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TOWARD QUANTIFICATION OF THE UNCERTAINTY IN ESTIMATING FREQUENCY OF CRITICAL STATION BLACKOUT

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ABSTRACT

A formal statement of the critical station blackout problem is provided, and a solution given, up to evaluation of an n-dimensional "nonrecovery integral" n =number of trains (parallel backup sources of electrical power). Several approaches that have been developed in the industry to estimate probability of critical station blackout are shown to be interpretable as special cases of such integrals. Computational results, for a simple model problem, suggest there is yet a very substantial overconservatism in current state-of-the-art techniques for estimating probability of critical station blackout. Research issues associated to possibly meeting this need via computational evaluation of the nonrecovery integral are discussed.

Key Words: Core damage frequency, nonrecovery integral, reactor safety, station blackout, uncertainty quantification.

1. INTRODUCTION

Fully 25% of core damage frequency, as analyzed in the South Texas Project Nuclear Operating Company (STPNOC) Probabilistic Risk Assessment (PRA), is from Loss of Offsite Power (LOOP). Existing models of LOOP recovery are understandably very conservative. Improved models of LOOP recovery conceivably could have direct benefit for the accuracy of a major contributor to the STPNOC PRA. The work described here constituted a preliminary effort to quantify the uncertainty stemming from this conservatism, and therefore determine the extent of the benefit that might be available from such improved models.

This situation is by no means unique to the two STPNOC light-water reactors. To the contrary, a relatively recent US Nuclear Regulatory Commission report states that:

"… risk analyses performed for NPPs (nuclear power plants) indicate that the loss of all ac power can be a significant contributor to the risk associated with plant operation, contributing more than 70 percent of the overall risk at some plants. Therefore a loss of offsite power (LOOP) and its subsequent restoration are important inputs to plant risk models, and these inputs

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must reflect current industry performance in order for plant risk models to accurately estimate the risk associated with LOOP-initiated scenarios." [1]

The structure of this paper is as follows: In the following Section 2 (*Problem Statement and Formal Solution*) a precise formulation of what is termed here as the "critical station blackout problem" is given, and a formal solution of that problem is provided, in the form of an *n*-dimensional "nonrecovery integral," where *n* is the number of parallel backup sources of electrical power ("trains"). In Section 3 (*Special Cases*) various special cases of the critical station blackout problem are introduced, and the evaluations of the nonrecovery integral for those cases are shown to correspond to various (conservative) approximate solutions to the critical station blackout problem that have been employed in practice. Section 4 (*A Computational Comparison*) is devoted to a comparison of these various approximations to the exact solution, for a simple example. The results illustrate that there may yet be significant gain to be realized from relaxing the degree of conservatism imposed by the various approximations currently used in practice. Unfortunately the methodology (Markov models) employed to demonstrate this potential gain is applicable only to the case that failures and repairs of onsite emergency backup power trains are exponentially distributed at constant rates. The final Section 5 (*Conclusions*) primarily contains a discussion of possible approaches to extending this best estimate to more general classes of failure and repair distributions.

2. PROBLEM STATEMENT AND FORMAL SOLUTION

Subsection 2.1 contains a precise formulation of what is termed here as the "critical station blackout problem." A formal solution of that problem is developed in Subsection 2.2.

2.1. Formulation of the Critical Station Blackout Problem

A plant power system is considered to consist of offsite power plus *n* emergency power trains, indexed by *1, 2, … n*. LOOP is assumed to occur at some initial time t=0. Following that event various subsequent events occur at random times having presumed known statistical distributions, as follows:

- Offsite power is recovered at time t_0, distributed as the cumulative distribution function (cdf) $G,\ G(t) = \text{Prob}\{t_0 \le t\}$. Recoveries of offsite power prior to or at t=0 are respectively irrelevant to or incompatible with LOOP at t=0, so that this cdf is assumed to be identically zero on the closed left half-line $t \le 0$.
- Emergency power train *i* fails at random time τ_i, which is assumed to be distributed as the cdf F_i. These cdfs are identically zero on the open left half-line $\tau < 0$ (failures prior to loss of offsite power are irrelevant), and are assumed to be absolutely continuous on the open right half-line $\tau > 0$; however, in order to incorporate the important phenomenon of failure on demand it is necessary to allow for the possibility that $F_i(0)>0$, and hence F_i has a (left) jump discontinuity at $\tau = 0$. (The assumption here is that at time 0 all emergency power trains attempt to go into an operating state, so that all failures to start occur at that time. Other workers have considered a finer classification of failures to start (e.g., [2]). Inclusion of such

considerations could be an important element of future development.) The corresponding probability density function (pdf) f_i is then an integrable function such that

$$F_i(\tau) = \int_{-\infty}^{\tau} [F_i(0)\delta(\tau') + f_i(\tau')]d\tau' = \int_{0-}^{\tau} [F_i(0)\delta(\tau') + f_i(\tau')]d\tau' = \mathrm{Prob}\{\tau_i \le \tau\},$$

where $F_i(0)$ is the probability that emergency power train i fails on demand, and the "delta function" δ formally satisfies

$$\int_{-\infty}^{\tau} \delta(\tau')d\tau' = \int_{0-}^{\tau} \delta(\tau')d\tau' = \begin{cases} 0, & \text{if } \tau < 0, \\ 1, & \text{if } \tau \ge 0. \end{cases}$$

(In the present initial problem formulation common-cause failures between the different emergency power trains are neglected.)

- Given that emergency power train i fails at time $\tau_i \ge 0$, it recovers at some subsequent random time $t_i > \tau$ that is distributed according to the cdf $t \to R_i(t; \tau_1, \tau_2, ..., \tau_n)$, where R_i is a cdf that is zero on the closed left half-line $t \le \tau_i$ (i.e., no "instantaneous" repairs, because a recovery coincident with failure is no failure at all). This very general form of the recovery function for emergency power trains seems necessary in order to accommodate the full range of repair policies that might be adopted by plant management. Some more specific concrete instances of this very general form of a recovery cdf for an emergency power train appear in the following discussion.

Given these various distribution functions, the associated problem is to compute the corresponding cdf for the random time T_{CSBO} of occurrence of a critical station blackout (CSBO), which is to say a station blackout that lasts as long as some specified "critical time" T_c. The solution to that problem is developed in the following subsection.

2.2. Formal Solution of the Critical Station Blackout Problem

A station blackout occurs at $t = 0$, and recovery occurs only after time greater than the critical time T_c, if, and only if: *i)* all emergency power trains fail on demand, and *ii)* neither offsite power nor any of the emergency power trains subsequently recover within elapsed time T_c. The probability of the former occurring is $\prod_{i=1}^{n} F_i(0)$. That of the latter occurring is $[1 - G(T_c)]\prod_{i=1}^{n}[1 - R_i(T_c; 0, 0, ..., 0)]$. Therefore the pdf for station blackout at a random time T_{SBO} contains a failure-on-LOOP contribution of the form

$$F_{\mathrm{CSBO}}(0)(T)\delta(T) = \left\{\prod_{i=1}^{n} F_i(0)\right\}[1 - G(T_c)]\left\{\prod_{i=1}^{n}[1 - R_i(T_c; 0, 0, ..., 0)]\right\}\delta(T).$$

For station blackout to occur between times T and $T + dT$, for some $T > 0$, and subsequently extend for a time interval T_c, a number of events describable in terms of the known distribution functions must occur. These events, and their respective probabilities, can be enumerated as follows:

- Offsite power must have not been recovered by time $T+T_c$. (The associated probability is $1-G(T+T_c)$.)
- Some emergency power train, say the ith, must fail between T and $T + dT$. (Associated probability $f_i(T)dT$.)
- All emergency power trains other than the ith must have failed prior to time T. (The probability of the jth such train, $j \neq i$, failing at $t=0$ is $F_j(0)$. The probability of the same train failing within $d\tau'_j$ at τ'_j is $f_j(\tau'_j)d\tau'_j$.)
- The ith emergency power train must not have recovered by subsequent elapsed time T_c. (The corresponding probability is $1-R_i(T+T_c;\tau'_1,..,\tau'_{i-1},T,\tau'_{i+1},...,\tau'_n)$, in the notation of the preceding item.)
- None of the previously failed emergency power trains must have recovered by time $T+T_c$. (If the jth such train fails at time τ'_j, then the probability it has not recovered by time $T+T_c$ is $1-R_j(T+T_c;\tau'_1,..,\tau'_{i-1},T,\tau'_{i+1},...,\tau'_n)$.)

If one sums, multiplies or integrates over all of these possibilities, as appropriate, then the pdf for station blackout is revealed as

$$
\begin{aligned}
f_{\mathrm{CSBO}}(T) = {} & \left[\prod_{i=1}^{n} F_i(0)\right]\left[1-G(T_c)\right]\left\{\prod_{i=1}^{n}\left[1-R_i(T_c;0,0,...,0)\right]\right\}\delta(T) + \left[1-G(T+T_c)\right]\times \\
& \sum_{i=1}^{n} f_i(T)\left[1-R_i(T+T_c;\tau'_1,..,\tau'_{i-1},T,\tau'_{i+1},...,\tau'_n)\right]\times \\
& \int_{0-}^{T}\cdots\int_{0-}^{T}\prod_{j=1,\,j\neq i}^{n} f_j(\tau'_j)\left[1-R_j(T+T_c;\tau'_1,..,\tau'_{i-1},T,\tau'_{i+1},...,\tau'_n)\right]d\tau'_1...d\tau'_{i-1}d\tau'_{i+1}...d\tau'_n.
\end{aligned}
$$

The associated cdf for onset of critical station blackout is then zero for negative values of T and is given by

$$
\begin{aligned}
F_{\mathrm{CSBO}}(T) &= \int_{0-}^{T} f_{\mathrm{SBO}}(T')dT' = \left[1-G(T_c)\right]\left\{\prod_{i=1}^{n} F_i(0)\left[1-R_i(T_c;0,0,\ldots,0)\right]\right\} + \int_{0}^{T}\left[1-G(T'+T_c)\right]\times \\
&\sum_{i=1}^{n} f_i(T')\left[1-R_i(T'+T_c;\tau_1',\ldots,\tau_{i-1}',T',\tau_{i+1}',\ldots,\tau_n')\right]\times \\
&\int_{0-}^{T'}\cdots\int_{0-}^{T'}\prod_{\substack{j=1,\\ j\neq i}}^{n} f_j(\tau_j')\left[1-R_j(T'+T_c;\tau_1',\ldots,\tau_{i-1}',T',\tau_{i+1}',\ldots,\tau_n')\right]d\tau_1'\ldots d\tau_{i-1}'d\tau_{i+1}'\ldots d\tau_n'dT' = \qquad (1) \\
&\int_{0-}^{T}\cdots\int_{0-}^{T}\left[1-G(\hat{\tau}+T_c)\right]\prod_{j=1}^{n} f_j(\tau_j')\left[1-R_j(\hat{\tau}+T_c;\tau_1',\ldots,\tau_n')\right]d\tau_1'\ldots d\tau_n' = \\
&\mathrm{Prob}\left\{T_{\mathrm{CSBO}} \le T\right\}, \text{ for } T \ge 0,
\end{aligned}
$$

where $\hat{\tau} := \max_{1\le i\le n}\left\{\tau_i'\right\}$.

Lloyd and Anoba [3] have given special cases of this general solution. Vaurio and Tammi [4] have given a recursive solution for the case in which the various trains start sequentially, each as its predecessor fails, rather than all starting at time of LOOP.

Eq. (1) is, except for the important consideration of common-cause failures, a formal solution of the station blackout problem. (The value at a "mission time" of $T = 24$ hours and for a critical time T_c, depending on the particular system but typically on the order of an hour, often is used as a basis for input to fault-tree calculations.) Any practical application of this formal solution will require computational methods to evaluate the n-fold "nonrecovery integral" in (the last line of) Eq. (1). This could be a formidable task, as evaluation of multiple integrals is computationally costly. Partially for this reason the standard that has evolved in the nuclear industry is based on evaluation of various overestimates (i.e., conservative bounds). Some of these will be illustrated in the discussion of various special cases derived from (1) that appear in the following subsection.

3. SPECIAL CASES

The presumed importance of loss of offsite power goes back to the very early days of probabilistic safety analysis. For example, Keller and Modarres [5, p. 276] say, in regard to the well-known early 1970's study WASH-1400), the following: "Preliminary results indicated that the most important transients involved the *loss of offsite power* and the loss of plant heat removal systems." (Emphasis added.)

As a consequence there has been much prior work on various aspects of this issue, much of it supported by the NRC itself. (See, for example, [1] and additionally Vol. 2 of that same report [6].) The work reported here is directed toward exploring the potential benefits from development of a methodology that moves toward replacing some of the prior conservatism by best-estimate calculations, especially in regard to recovery of emergency power trains from potential failures during a LOOP event; however it is evolutionary, in that it intends to build upon but extend well-developed and widely understood methodologies currently employed in the industry. The connections of these various methodologies to the formal solution provided by the nonrecovery integral (1) are explored in the various subsections of this section.

3.1. Single Train, No Recovery

This is the case n=1, $R_1 = G \equiv 0$. In this case the general solution (1) evaluates as

$$F_{\text{CSBO}}(T) = \int_{0-}^{T} f_{\text{SBO}}(T')dT' = F_1(0) + \int_{0}^{T} f_1(T')dT' = F_1(T),$$

or

$$\text{Prob}\left\{T_{\text{CSBO}} \le T\right\} \equiv \text{Prob}\left\{\tau_1 \le T\right\}.$$

This is exactly what one would expect intuitively in this simplest of all possible cases. This result is useful primarily as a check on the validity of the general form (1) of the solution to the critical station blackout problem.

3.2. Multiple Trains, No Recovery

In the case of general $n > 1$, but $G = R_i \equiv 0, i = 1, ..., n,$ the general solution (1) evaluates as

$$\begin{aligned} F_{\text{CSBO}}(T) = \int_{0-}^{T} f_{\text{SBO}}(T')dT' = \int_{0}^{T} ... \int_{0-}^{T} \prod_{j=1}^{n} f_j(\tau'_j)\, d\tau'_1 ... d\tau'_n = \\ \prod_{i=1}^{n} F_i(T) = \text{Prob}\left\{\max_{1 \le i \le n}\left\{\tau_i\right\} \le T\right\} = \text{Prob}\left\{T_{\text{CSBO}} \le T\right\}, \text{ for } T \ge 0. \end{aligned} \qquad (2)$$

This case is of interest as an upper bound for the general result (1); in other words a conservative estimate of the probability that critical station blackout occurs by time T. It is generally deemed excessively conservative, because the impact of recovery of neither offsite power nor any of the emergency power trains is considered. Any account taken of these recoveries of course must reduce the corresponding estimate of the probability of critical station blackout within any fixed mission time T.

3.3. The Fault-tree Approach

The description here of the "fault-tree approach" closely follows that of Lloyd and Anoba [3]. In this approach the (offsite and emergency power train) "nonrecovery factors" in the general solution (1) are assigned constant values,

$$1 - G(T' + T_c) \equiv \widehat{G} = \text{constant}, \; 1 - R_j(T' + T_c; \tau'_1, .., \tau'_{i-1}, T', \tau'_{i+1}, ..., \tau'_n) = \widehat{R}_i = \text{ constant}. \quad (3)$$

The solution (1) then becomes

$$F_{\mathrm{CSBO}}(T) = \widehat{G} \times \left\{ \prod_{i=1}^{n} \left[F_i(T) \widehat{R}_i \right] \right\} = \mathrm{Prob}\left\{ T_{\mathrm{CSBO}} \le T \right\}. \tag{4}$$

The assignment of point values to nonrecovery events is consistent with the point-estimate of probabilities that underlies fault-tree analysis. It is inconsistent with the true dynamic nature of the recovery process; indeed G and R_j as defined by (3) cannot even be cdfs, except in the (obviously overconservative) prior cases that they are identically equal to 1; i.e., recovery is neglected altogether.

In regard to the offsite nonrecovery, Lloyd and Anoba [3] say the following:
".. it must be supplied by the analyst. If the term has a mission-time dependence, establishing a probability value for the term may be difficult. As a result, this value may be significantly overconservative."

It appears that much the same concern holds for the nonrecovery factors for the individual emergency power trains, especially in view of the additional complication that in the general solution (1) these appear with arguments offset by the associated (variable) time of failure. These considerations are the two major obstacles to realistic best estimates of CSBO that take adequate account of the dynamic nature of recovery processes. Most efforts to account for these dynamic effects customarily are formulated as computation of a "recovery factor" to be applied to (4), or some similar relatively easily computed conservative estimate of the probability of CSBO within some accepted mission time. The former (dynamics of nonrecovery of offsite power) is somewhat easier, because the corresponding nonrecovery complementary cdf in (1) depends on time variables other than elapsed time since LOOP only in the relatively simple form of an offset by the constant critical time. By contrast the nonrecovery (complementary) cdfs for the emergency power trains depend upon that plus the variable times of failure of the different emergency power trains, in a manner that depends upon the repair policy (and resources) at the particular plant of interest. The following two subsections are devoted to brief descriptions of the current state-of-the-art in the nuclear industry for dealing with these two respective issues.

3.4. Dynamic Offsite Recovery

Lloyd [6] demonstrated how to incorporate the dynamic variation in offsite recovery into the solution. If constancy of the nonrecovery factors (i.e. (3)) now is assumed only for nonrecovery of the emergency power trains, then the general solution (1) becomes

$$F_{\mathrm{CSBO}}(T)=\prod_{i=1}^{n}\widehat{R}_i\left\{\left[1-G(T_c)\right]\prod_{i=1}^{n}\widehat{F}_i(0)+\int_0^T\left[1-G(T'+T_c)\right]\times\right.$$
$$\left.\sum_{i=1}^{n}f_i(T')\int_{0-}^{T'}\cdots\int_{0-}^{T'}\left[\prod_{\substack{j=1,\\ j\neq i}}^{n}f_j(\tau_j')\right]d\tau_1'\ldots d\tau_{i-1}'d\tau_{i+1}'\ldots d\tau_n'dT'\right\}=$$
$$\prod_{i=1}^{n}\widehat{R}_i\left\{\left[1-G(T_c)\right]\prod_{i=1}^{n}\widehat{F}_i(0)+\int_0^T\left[1-G(T'+T_c)\right]\prod_{\substack{j=1,\\ j\neq i}}^{n}F_j(T')dT'\right\}=\mathrm{Prob}\left\{T_{\mathrm{CSBO}}\le T\right\}.$$

Approaches based on numerical integration of the (convolution) integral appearing in this form of the solution are described in Lloyd and Anoba [3], Lloyd [6], and Read and Fleming [7].

3.5. Repair Only After SBO

This is essentially the prior case, except that now the nonrecovery cdfs for the emergency power trains satisfy

$$R_j(T';\tau_1',..,\tau_{j-1}',\tau_j',\tau_{j+1}',...,\tau_n')=\widetilde{R}_j\left(T'-\max_{k=1}^{n}\left\{\tau_k'\right\}\right),$$

where each $\widetilde{R}_j$ is a cdf that is identically zero on the closed left half line (i.e., for arguments that are not positive).

The underlying model of repair is that no attempts are made to repair any emergency power train until SBO occurs. At that time repairs begin on each of the emergency power trains, in a manner consistent with the respective recovery cdfs $\widetilde{R}_j$.

The corresponding cdf for CSBO is

$$\begin{aligned}F_{\mathrm{CSBO}}(T)=&\left[1-G(T_c)\right]\left\{\prod_{i=1}^{n}F_i(0)\left[1-\widehat{R}_i(T_c)\right]\right\}+\int_0^T\left[1-G(T'+T_c)\right]\times\\&\sum_{i=1}^{n}f_i(T')\left[1-\widehat{R}_i(T_c)\right]\int_{0-}^{T'}\cdots\int_{0-}^{T'}\prod_{\substack{j=1,\\ j\neq i}}^{n}f_j(\tau_j')\left[1-\widehat{R}_j(T_c)\right]d\tau_1'\ldots d\tau_{i-1}'d\tau_{i+1}'\ldots d\tau_n'dT'=\\&\prod_{i=1}^{n}\left[1-\widehat{R}_i(T_c)\right]\left\{\left[1-G(T_c)\right]\prod_{i=1}^{n}F_i(0)+\int_0^T\left[1-G(T'+T_c)\right]\sum_{i=1}^{n}f_i(T')\prod_{\substack{j=1,\\ j\neq i}}^{n}F_j(T')dT'\right\}=\\&\mathrm{Prob}\left\{T_{\mathrm{CSBO}}\le T\right\},\ \text{for } T\ge 0.\end{aligned}\tag{5}$$

This form of the solution is that employed by Read and Fleming [7]. It clearly is somewhat conservative, in that it assumes no repair work begins on any emergency power train until all trains have failed. To some extent this conservatism is reduced by the parallel "infinite workforce" assumption that once repair does begin it can proceed on all trains simultaneously, with no loss of effectiveness. In Lloyd and Anoba [3] this innate conservatism also is somewhat overcome by the use of a recovery time distribution that "applies to situations involving a high urgency for diesel generator repairs."

In any event the expression (5) for the distribution of CSBO events, as implemented in the STADIC code, is state-of-the-art in the nuclear industry. The question of interest here is whether there might be significant gain (i.e., reduction in estimate of core damage frequency) from even further improvements in estimating the nonrecovery integral. In the following section an example is given that suggests the potential for considerable gain.

4. A COMPUTATIONAL COMPARISON

The simple model system underlying the preliminary exploration of possible reduction in estimated probability of CSBO consisted of a plant with two identical emergency diesel generators, A and B. Such a model plant can, at any time, lie in any of five states: State 0, offsite power is available; State 1, only Diesel A is available; State 2, only Diesel B is available; State 3, both Diesels A and B are available, but offsite power is not; and State 4, no power is available (SBO). In the "exact" model transitions are assumed to occur between the various states as shown in Figure 1, with the following parametric values for the indicated transition rates: diesel failure rate = $\lambda_D = 8.35\text{e-}4 \text{ hour}^{-1}$; probability that a diesel failure stems from a common cause that would affect both diesels (if operating) = $\rho_2 = .0115$; $\rho_1 = 1 - \rho_2$; diesel repair rate = $\mu_D = 1/12 \text{ hour}^{-1}$; and recovery rate for offsite power =

$$\mu_0(t) = f_T(t;.3,1.064)/(1\text{-}F_T(T;.3,1.064)) \text{ hour}^{-1};$$

where f_T and F_T are respectively the lognormal pdf and cdf. (Cf. Table 4.1, pp. 27-28 of [1].)

The initial values shown in Figure 1 for the various states were obtained by assuming LOOP at $t = 0$, a probability of failure on demand for the diesels of .0132, and a probability of $\rho_2 = .0115$ that the failure on demand results from a common cause (of failure of both diesels), given that it does occur. The corresponding results, for the Markov model taken here as exact, are shown as the solid black curve (labeled "full recovery") in Figure 2.

For comparative purposes the probability of SBO (state 4), as a function of time, was computed for the following analogs of various approximations that were discussed in the preceding section:

1. No recovery, for which the recovery rates were changed to $\mu_D = \mu_0 \equiv 0$, and all else remained as in the assumed exact model.
2. Offsite recovery only, for which the diesel repair rate was changed to zero, but the offsite recovery rate and all else were as in the assumed exact model.

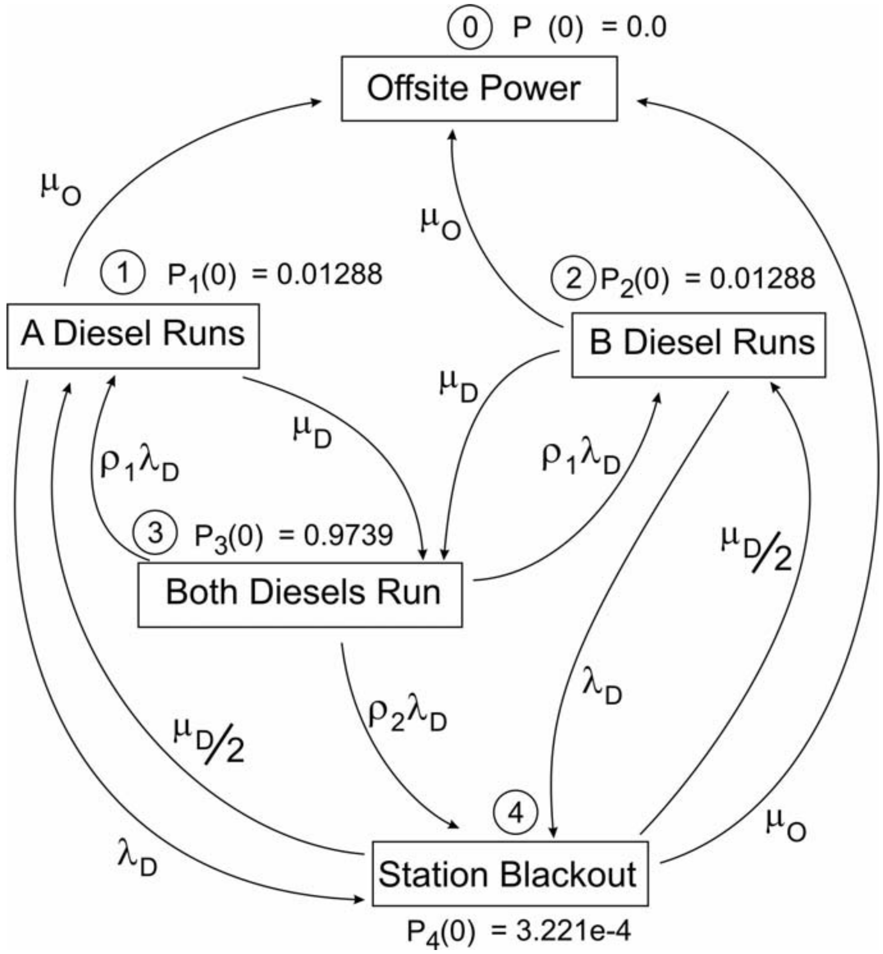

Figure 1. Block diagram of the Markov model

3. The Read-Fleming [7] model of diesel recovery, in which all was as in the assumed exact model, except that the transition rates from States 1 and 2 to State 3 were changed to zero

The results from the four approaches can conveniently be compared in terms of their respective estimates of probability of SBO at the end of the 24 hour mission time. The estimate without recovery is approximately 15e-3; consideration of offsite recovery (only) substantially reduces that, to about 3.5e-3; the Read-Fleming model (of onsite recovery only after SBO) approximately halves that, to approximately 1.5e-3; finally, full recovery halves that again, to about 0.8e-3. This certainly suggests the possibility that current methodologies could substantially overestimate the probability of core damage frequency from LOOP events, and therefore result in mitigating work that is less than optimally effective in guarding against the remote possibility of core damage.

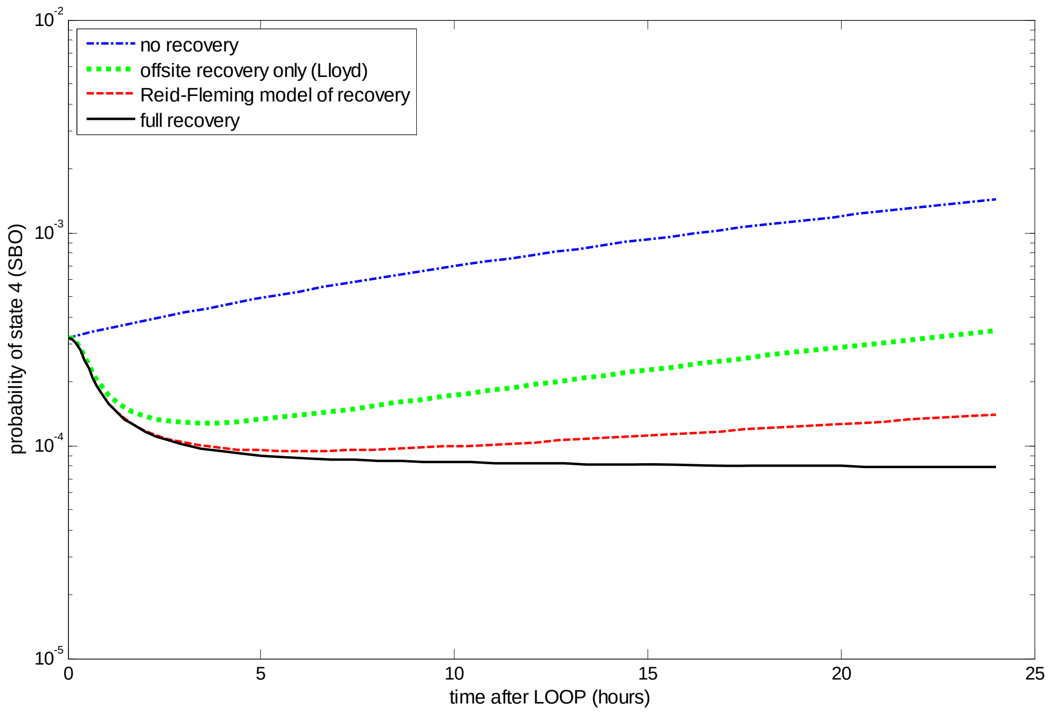

Figure 2. Probability of station blackout, as computed from the various models

5. CONCLUSIONS

Preliminary results reported here suggest that the current state-of-the-art in the nuclear industry for estimating probability of critical station blackout leaves substantial room for improvement (possible reduction by as much as two thirds) in estimating the contribution of station blackout to estimate of core damage frequency. We suggest this alone warrants a substantial effort toward effecting such improvements.

A different benefit from improved estimates of critical station blackout might ultimately prove even more beneficial to the nuclear industry as a whole. As the nuclear renaissance has progressed, some have suggested that it calls for a quantum improvement in the already extremely low estimates of core damage frequency. One approach to that, and perhaps the only available approach for existing NPPs, is to add additional backup systems to guard against the leading potential initiators of events that could lead to core damage. Retrofitted backup systems can be very expensive, and are likely to be undertaken only if there is substantial assurance they will lead to significant reductions in risk and corresponding enhancements to overall system reliability. Improved methods for estimating risk and reliability can help to provide that assurance.

Given the need for improvements in estimates of the probability of CSBO, how might this improvement be provided? One possibility is the very direct approach of numerical evaluation of nonrecovery integrals such as (1). This appears to be a significant research challenge, but computational evaluation of multidimensional integrals has been successfully employed in other areas of safety analysis (e.g., [8] is a work that is widely cited in the field of structural safety).

Yet another question that must be addressed before computational evaluation of nonrecovery integrals can become a practical tool for application in the nuclear industry is the extension to account for possible common-cause failures. This also appears likely to require a substantial research effort.

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