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A TIME-DEPENDENT EVENT TREE

TECHNIQUE FOR MODELLING RECOVERY OPERATIONS[a]

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ABSTRACT

The development of a simplified time dependent event tree methodology is presented. The technique is especially applicable to describe recovery operations in nuclear reactor accident scenarios initiated by support system failures. The event tree logic is constructed using time dependent top events combined with a damage function that contains information about the final state time behavior of the reactor core. Both the failure and the success states may be utilized for the analysis. The method is illustrated by modelling the loss of service water function with special emphasis on the RCP seal LOCA scenario.

INTRODUCTION

Accident sequences that potentially could occur during the operation of nuclear power plants are usually analyzed by static event-tree methods. The incorporation of time dependent information, especially in the numerous recovery processes, is cumbersome and normally neglected for calculational purposes. These methods do not easily allow considerations for diverse and time varying hardware and human recovery actions and usually exclude backward looping logic.

The limitation of the static event tree approach has been recognized in the past and various approximations were utilized to simulate dynamic plant response. The majority of these techniques predefine accident-progression phases in relatively large time periods and the event trees are constructed with separate considerations for the different success criteria and mitigating system responses in the different time phases[1].

The treatment of accident progression as modelled in NUREG-1150[2] may also be viewed as an implicit dynamic event tree technique by incorporating time dependent branchings for specific accident phases which include recovery considerations. The recovery processes are treated by considering the explicit time behavior of the initiating event, that may include potential or experienced recovery behavior (loss-of-off-site power, etc.), in combination with the expected core damage mechanism.

Another approach treating dynamic effects is found in the DYLAM[3] methodology which is capable of process simulation of detailed systems with many components incorporating component reliability information. The GO-FLOW methodology[4] is a success path oriented technique which is able to analyze complex sequences of system operation and changes accounting for multi-phase mission timing.

In this paper, a simple time dependent event tree methodology is described that may be applied to various accident sequences where time variation may be critical and the potential for

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diverse actions is envisioned. The technique is especially applicable to accident scenarios which are initiated by support system failures leading to the potential degradation or malfunction of required front-line systems or components.

The method may be viewed as a more systematic and general approach to recovery operations, however, it is limited to relatively simple systems and is not considered as a substitute for large scale system analysis due to the inherent increase in the complexities of such problems. It is intended to analyze support system recovery scenarios where the time dependency is critical and many alternative options are available for the operator.

Essentially, the technique corresponds to a simplified phased-mission analysis of the specific accident event and the corresponding systems. The minimal cut-sets from the different mission time periods are all collected and evaluated depending on their temporal behavior. The method takes the static event tree logic to its logical generalization to time dependent problems assigning time functions to top events and generating end-sequences that have instantaneous time dependency.

The initial construction of the process event trees resembles a static approach. Based on the accident initiator, a system oriented event tree is constructed with explicit recovery actions. The top events can further be specified in sub-system event trees that describe the evolutionary process of the system in question. The logic structure of these sub-system event trees always refer to an instantaneous time period, $[t,t+\Delta t]$, and consequently the top events do not represent consecutive operating actions, but rather the time dependent behavior.

The end-states of the time dependent event-trees describe the collection of failures or successes of the recovery actions at the respective time period. The core damage frequency (CDF) contribution in time period $[t,t+\Delta t]$ is obtained by combining the event tree end-state functionals with a conditional core damage probability (CCDP). The CCDP reflects the time dependent behavior of the core damage probability given the total failure of all mitigating systems and actions. The definition of the CCDP naturally provides a simple mechanism to incorporate previous knowledge about the potential spectrum of core damaging mechanisms. For example, in a LOCA scenario this may constitute the distribution of expected break sizes or leakage rates.

The recovery models may be formulated in two alternate ways; a) based on the failure paths

Model 1; $$P(\lambda) = \int_0^T p_\lambda(s(t),t)\, NR(t)\,dt ,$$

where

$$NR = 1 - \int_0^t r(t')\,dt',$$

b) using the success states

Model 2; $$P(\lambda) = \int_0^T r(t) \int_S^\infty p_\lambda(s,t)\,ds\, dt .$$

Here, $P(\lambda)$ is the conditional core damage probability given a specific accident initiator, λ. The recovery probability density, $r(t)$, and the integrated non-recovery fraction, NR, actually represent the end-states of the recovery event tree development. The term, $p_\lambda(s,t)$, is the conditional probability of core damage during time $[t,t+\Delta t]$, which may depend on a number of factors other than elapsed time (for example: heat generation and leak flow rate in a loss-of-coolant accident). These additional factors are lumped into the function $s(t)$.

Both formulas describe the conditional core damage frequency contribution due to an accident scenario, represented by P(SL), as the integrated sum of time dependent probabilities. The first model sums up those fractions of the failure sequences which are unable to recover by time $[t,t+\Delta t]$ and lead to core damage in this period with probability p_λ. The second or success model integrates those sequences which recover with the rate $r(t)$, but lead to core damage in the previous time periods.

Figure 1 illustrates the difference between the two models, where the areas under the curve represent the conditional CDF if recovery is not taken into account.

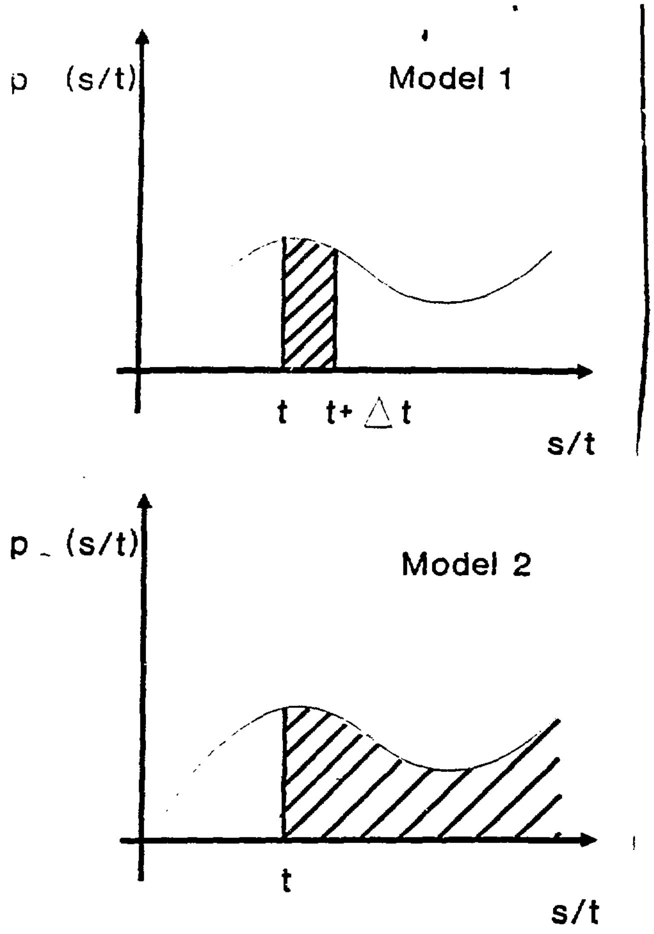


Fig. 1 Conditional core damage probability density function

The non-recovery function is obtained through the event tree analysis and this part corresponds to the development of the recovery failure sequences for the particular time phase. The dynamic effects involving system configuration changes and/or operator actions may be incorporated through the sub-system event tree analysis.

The structure of the sub-system event tree method allows dividing a complex event tree into several sub-systems, which are easier to analyze. This approach essentially relies upon the folowing identity,

$$P(A)=P(A_1+A_2)=P(A_1)+P(A_2)-P(A_1)P(A_2) ,$$

where A_1 and A_2 represent top event probabilities or the sub-system event tree which is coalesced into top event A.

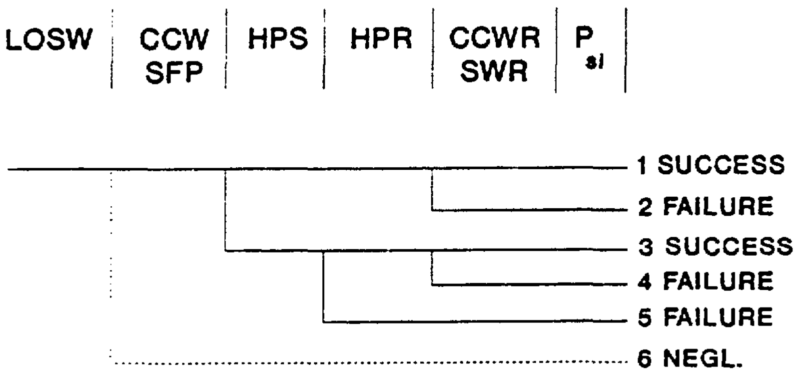
The dynamical diversity of the complex time dependent problem is approximately mapped by the sub-system event trees. This particular approach is most suitable for limited system analysis with failures dominated by specific components. In this sense, recovery operations due to support system failures are easily tractable, since the random failures of the supported system may be neglected. The total time dependent analysis of a full scale event tree/fault tree model is presently beyond the capability of the present approach.

In order to illustrate the technique, the loss of emergency service water function (ESW) is modelled. There are a number of different safety function related components cooled by the ESW system such as the component cooling water system, station diesel-generators and, indirectly, the reactor coolant pump (RCP) seals. This latter item is especially important, since the failure of the RCP seals leads to a small LOCA with a concurrent loss of any mitigating capability due to the disabling of the high pressure injection function (HPI pumps are also cooled indirectly by ESW).

In the following example this particular accident sequence is analyzed, that is, the loss of ESW (LOSW) with a subsequent RCP seal LOCA event. After an LOSW event, the operators primarily respond to the temperature behavior of the CCW system. Based on the temperature rise of the CCW system and the subsequent loss of cooling at the various equipment, such as, charging pumps (RCP seal injection/cooling function), CCW pump and/or RCP seals (thermal barrier), the operators may start reducing the reactor power and, for excessively high temperatures, may shut down the affected equipment.

If the unit is brought to hot standby conditions, it may be maintained there utilizing the auxiliary feedwater system. However, the RCP seals may still loose their cooling during this time and become vulnerable to failure. In Reference 5, an RCP seal failure model was developed based on an expert judgement process. It was indicated that seal failure is expected in about 1.5 hours after loss of seal cooling.

A simple recovery event tree was used to include the possible recovery actions and is indicated in Figure 2a. The potential recovery events modelled are 1) the availability of the CCW and the spent fuel pool (SFP) systems for heat removal, 2) the availability of the SW/CCW cooling function and 3) the preservation and/or recovery of the high pressure injection function. The final top event is the probability that the leak rate of the seal LOCA is such that it leads to core uncovery (p_{sl}).



LOSW - Loss of SW

CCW/SFP - alternate heat sink by CCW/Spent Fuel Pool

HPS - HP injection secured /not damaged

HPR - HP injection recovered

CCWR/SWR - CCW/SW cooling recovered

P_{sl} - Probability of RCP seal LOCA leading to core uncovery

Fig. 2a. Seal LOCA Recovery Event Tree (at time t)

The sub-system event tree for the CCW system is indicated in Figure 2b. This reflects the initial assumption that random failures of the system are neglected and only the supported function is included i.e., failure of heat removal from the CCW heat exchangers. The expected effects due to the increase in system temperatures are indicated in Table 1.

This simple model includes the potential use of the spent fuel pool as an alternate heat sink by transferring heat from the CCW system to the SFP. The potential operator response is represented by the CCW feed and bleed action that may include any ad hoc or temporary arrangements.

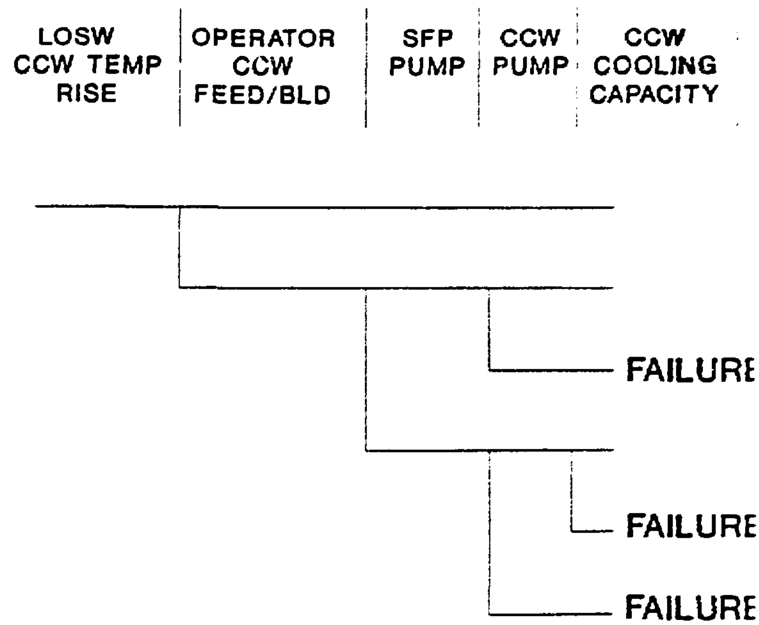


Fig. 2b. CCW Sub-system Event Tree

TABLE 1. CCW HEAT UP EFFECTS

CCW (T) F	EFFECTS	EXPECTED TIME MIN
105	NORMAL OPERATION	
120-130	REVERSE HEAT TRANSFER TO SFP	15-30
130-140	POTENTIAL DAMAGE TO SFP PUMPS	30-45
140-150	POTENTIAL DAMAGE TO CCW PUMPS	45-60
>200	LOSS OF RCP SEAL COOLING	~60

The time dependence of the various recovery actions is used to evaluate the final state sequences. The total time period is divided into convenient sub-intervals and the sequence terms are either represented as exponentials or constants in the respective intervals. For a piece-wise constant approximation, the expression for Model 1 becomes

$$P(\lambda) = \sum_i NR_i \int_{t_i}^{t_{i+1}} p_\lambda(s(t),t)\, dt \,.$$

The term under the integral expresses the average value of the CCDP over the respective time interval.

The total conditional CDF of a seal LOCA may be calculated by applying the above models to each sequence, the failure states (Seq. 2, 4, 5) for Model 1 and the success states (Seq. 1, 3) for Model 2.

The results of the two models differ by about 10% which is entirely due to the relatively crude numerical approximations both in the analysis and in the seal failure model. The uncertainty of the various failure modes, potential equipment behavior upon loss of cooling and the possibility of alternate operator actions do not warrant more explicit treatment of the time dependent behavior at this time.

The conditional seal LOCA probability that leads to core damage was calculated and the results are listed in Table 2. This in combination with the initiating frequency (loss-of-ESW) would result in a CDF prediction incorporating the time dependent behavior of the recovery actions and the core uncovery mechanism.

In summary, a simplified time dependent event tree methodology was presented that takes into account the time variations of the various recovery actions. The model is especially useful when the full time dependence of recovery actions and core damage mechanisms must be considered. It allows considerations for diverse recovery arrangements and operator actions.

REFERENCES

1. T.F.BOTT and D.W.STACK, "N Reactor Probabilistic Risk Assessment Methodology," *Proc. Int. Top. Mtg. Prob. Reliab. Safety Ass.*," Pittsburgh, PA., April 1989.

2. U.S. Nuclear Regulatory Commission, "Severe Accident Risk: An Assessment for Five U.S.Nuclear Power Plants," Second Draft, NUREG-1150, June 1989.

3. A.AMENDOLA, "Accident Sequence Dynamic Simulation vs. Event Trees," *Reliab. Engnr. Syst. Safety* 22, (1988), 3-25.

4. T.MATSUOKA, M.KOBAYASHI, "A Phased Mission Analysis by the GO-FLOW Methodology,"*Proc. Int. Top. Mtg. Prob. Reliab. Safety Ass.*," Pittsburgh, PA., April 1989.

5. T.WHEELER, S.C.HORA, W.R.CRAMOND, and S.D.UNWIN, "Analysis of Core Damage Frequency from Internal Events: Expert Judgement Elicitation," NUREG/CR-4550, Vol.2, April 1989.

TABLE 2. CONDITIONAL CORE DAMAGE
DUE TO RCP SEAL LOCA

TIME PERIOD AFTER SEAL LOCA (HR)	CORE DAMAGE	CONDITIONAL PROBABILITY MODEL 1		MODEL 2
0-1.5	Seq. 2	0	Seq. 1	0
	Seq. 4	0	Seq. 3	0
	Seq. 5	0		
1.5-3.0	Seq. 2	1.2E-03	Seq. 1	3.3E-04
	Seq. 4	5.4E-08	Seq. 3	1.6E-08
	Seq. 5	3.4E-06		
3.0-4.5	Seq. 2	6.8E-02	Seq. 1	4.2E-02
	Seq. 4	3.4E-06	Seq. 3	2.1E-06
	Seq. 5	5.0E-04		
4.5-24	Seq. 2	1.4E-02	Seq. 1	3.1E-02
	Seq. 4	2.6E-07	Seq. 3	9.2E-06
	Seq. 5	1.6E-04		
Total P(SL)		8.4E-02		7.3E-02