BNL-NUREG--45693-Rev.1/91

DE91 009471

# USE OF PROBABILISTIC SAFETY ANALYSES IN SEVERE ACCIDENT MANAGEMENT*

BNL-NUREG-45693

P. Neogy and J. Lehner
Brookhaven National Laboratory
Department of Nuclear Energy
Building 130
Upton, NY 11973

*Work performed under the auspices of the U.S. Nuclear Regulatory Commission.

An important consideration in the development and assessment of severe accident management strategies is that while the strategies are often built on the knowledge base of Probabilistic Safety Analyses (PSA), they must be interpretable and meaningful in terms of the control room indicators.[1] In the following, the relationships between PSA and severe accident management are explored using ex-vessel accident management at a PWR ice-condenser plant as an example. Figure 1 provides representations of the Severe Accident Space (SAS) as viewed by the reactor operator and the analyst. Here and in what follows, the term "reactor operator" is used to indicate a group such as the accident management team; and the process under discussion is one of formulating and evaluating strategies rather than responding directly to a severe accident. The operator characterizes state vectors in SAS in terms of control room indicators (I) and the status of various systems (SS). The analyst characterizes SAS in terms of Plant Damage States (PDSs) and Accident Progression Bins (APBs). Let a state vector in the (I,SS) representation be denoted Observed State, |OS>; while a state vector in the (PDS,APB) representation is denoted Analyzed State, |AS>. In order that the operator can take advantage of available analytical results, it is necessary that |OS> be expressed in terms of the |AS>.

Formally, the |OS> may be expanded in terms of the |AS> on the assumption that the |AS> form a complete set:

$$|OS\rangle_i=\sum_j a_{ij}|AS\rangle_j . \qquad (1)$$

Since |OS> is labelled by {I}, {SS}, and is characterized by a time evolution factor F(t), say,

$$|OS\rangle_i=|\{I\}_i,\{SS\}_i,F_i(t)\rangle . \qquad (2)$$

Similarly, |AS> is characterized by a Plant Damage State, PDS, and several possible accident progression bins, APB:

$$|AS>_j = |PDS_j; \sum_k b_{jk} APB_k>, \tag{3}$$

where the coefficient $b_{jk}$ denotes the conditional probability that given the Plant Damage State $PDS_j$, the analyzed state $|AS>_j$ will evolve into the Accident Progression Bin $APB_k$. Assuming that the indicators (I) and the system status (SS) are sufficient to identify a PDS, Equation (2) may be re-written as

$$|OS>_i = |PDS_i; F_i(t)>. \tag{4}$$

Combining Equations (1), (3) and (4), and assuming that the PDSs are linearly independent, give

$$F_i(t) = \sum_k b_{ik} \, APB_k. \tag{5}$$

That is, the time evolution of the observed state is identical to that of the analyzed state, and can be expressed in terms of the same conditional probabilities and accident progression bins provided the following three conditions are satisfied: (1) the analyzed states form a complete set, (2) the PDSs are identifiable in terms of the control room indicators, and (3) PDSs are linearly independent. The assumption that the analyzed states form a complete set implies that all important accident sequences and phenomenology have been accounted for in the PSA, a central assumption in all probabilistic studies. The condition that the PDSs are linearly independent is met by ensuring that a given PDS does not evolve into another. Whether PDSs are identifiable in terms of control room indicators can be determined by an examination of the relevant Emergency Response Guidelines (ERGs). The Optimal Recovery Procedures (ORPs) and Emergency Contingency Actions (ECAs) applicable to ice-condenser plants are, in fact, oriented towards the recognition of accident initiators, and may be utilized to recognize PDSs. Table 1 presents basic indicators and system status monitors for seven broad-based PDSs. "H" and "L" indicate high and low levels, respectively, of pressure and radiation; "Y" and "N" indicate availability and non-availability, respectively, of the appropriate system; and "T" indicates the availability of the turbine-driven auxiliary feedwater system. As indicated, the PDSs are uniquely identifiable in terms of (1) the pressure of the containment atmosphere; (2) the radiation levels in the containment, at the steam generator secondary sides and in the auxiliary building; and (3) the status of the auxiliary feedwater, AC power and reactor trip systems. While the identification of the PDS can enable the accident management team to anticipate the likelihood and sequence of expected challenges, it should be emphasized that a requirement that the PDS be identified in terms of control room indicators is not being recommended. Such a requirement would be justifiably criticized as regression to event oriented procedures. However, as guidance to, and as part of the

For ex-vessel accident management, the accident progression bins define the challenges to the containment, and the conditional probabilities are the ones for containment failure. The conditional probabilities for containment failure for seventeen plant damage states, corresponding to thirteen containment challenge mechanisms at the ice-condenser plant are presented in Table 2. The probabilities of containment failure were obtained from Reference 2 using the results of a central walkthrough with direct containment heating and in-vessel steam explosion included, and collapsing 34 containment release modes to the 13 challenges indicated in Table 2. These analytical results provide simulations of the containment response to various severe accident challenges, and thereby supply the framework within which accident management strategies may be developed and evaluated.

A quantitative assessment of an accident management strategy can be made by including the strategy explicitly in the probabilistic safety analysis. Equation (5) shows that the time evolution of a plant damage state, $PDS_i$, that has been identified can be expressed in terms of the conditional probabilities, $b_{ik}$, and accident progression bins, $APB_k$. The impact of a strategy S which is intended to maintain containment integrity will be manifested in the analysis by a shift in the distribution of the conditional probabilities:

$$SF_i(t) = \sum_k b'_{ik} \, APB_k . \tag{6}$$

The altered conditional probability, $b'_{ik}$, which corresponds to the containment failure mode "k" the strategy "S" guards against, will show a decrease, while the conditional probability for no failure, and possibly, those for other failure modes will show an increase. The change in the conditional probability $b_{ik}$ is a measure of the effectiveness of the strategy "S" against the challenge "k" for the plant damage state $PDS_i$. This process is readily extended to a series of strategies that are implemented in the course of a given accident sequence until the conditional probabilities for all important containment failure modes are significantly reduced.

Although probabilistic safety analyses that explicitly account for the implementation of severe accident management strategies are unavailable at present, considerable insight into the effectiveness of selected strategies can be gained by referring to available analytical results. Table 3 presents conditional probabilities for containment failure corresponding to three plant damage states selected out of the seventeen included in Table 2. S2NNNN is a station blackout with PORV and pump seal LOCA, and with safety injection, containment heat removal, containment sprays and AC power unavailable. The loss of the distributed igniter system (due to the loss of AC power) leads to a high probability (85%) of early containment failure due to hydrogen burn, and may contribute to the failure probability (7.7%) due to DCH and steam spike at vessel breach. Clearly, a strategy (S1) that ensures that the power supply to the igniters is maintained even in SBO sequences is likely to be highly effective in preventing early containment failure. A measure of the effectiveness of S1 can be obtained by comparing the conditional probabilities for S2NNNN with those for S2NNNY, the latter plant damage state being identical to S2NNNN except that AC power, and therefore the igniters, are available in S2NNNY. The probability for early containment failure is seen to be reduced from 85% to 1.7%, the reduction being attributable to S1, a strategy that ensures a backup power supply to the igniters in SBO sequences.

The reduction in the probability for early containment failure through the application of S1 is obtained at a price. The containment heat removal system is still unavailable, and while early containment failure is averted, late overpressure failure due to the accumulation of steam and non-condensable gases is now a virtual certainty. A second strategy S2 that effectively restores the containment heat removal function may succeed in maintaining containment integrity. A measure of the effectiveness of S2 may be found by comparing the conditional probabilities for S2NNNY and S2NYBY, the latter plant damage state having containment heat removal and containment sprays, as well as AC power, available. The comparison indicates that the implementation of S2 reduces the probability of late overpressure failure from 97.8% to 17.7%, while the probability of avoiding containment failure increases to 77%. The net impact of applying the strategies S1 and S2 during a station blackout sequence is to reduce the conditional probability for early containment failure through hydrogen burn from 85% to 1.7%, increase the probability that containment failure can be averted to 77%, and maintain a residual probability of 17.7% for late overpressure failure.

Probabilistic safety analyses can promote the formulation and evaluation of severe accident management strategies by providing a framework within which severe accidents and the impact of severe accident management strategies may be simulated. The results of PSA may also be useful in the actual application of severe accident management strategies because they allow the accident management team to anticipate the likely course of a given accident and the challenges associated with it. While severe accident management is properly regarded as being intimately related to emergency operating procedures, utilization of its links to PSA can ensure completeness and proper evaluation of accident management strategies.

## References

1. P. Neogy and J. Lehner, "Application of Containment and Release Management to the Sequoyah Nuclear Plant," to be published.

2. V.L. Behr, et al., "Containment Event Analysis for Postulated Severe Accidents: Sequoyah Power Station, Unit 1," Sandia National Laboratories, NUREG/CR-4700, Vol.2, February 1987.

# ALTERNATE REPRESENTATIONS OF SEVERE ACCIDENT SPACE

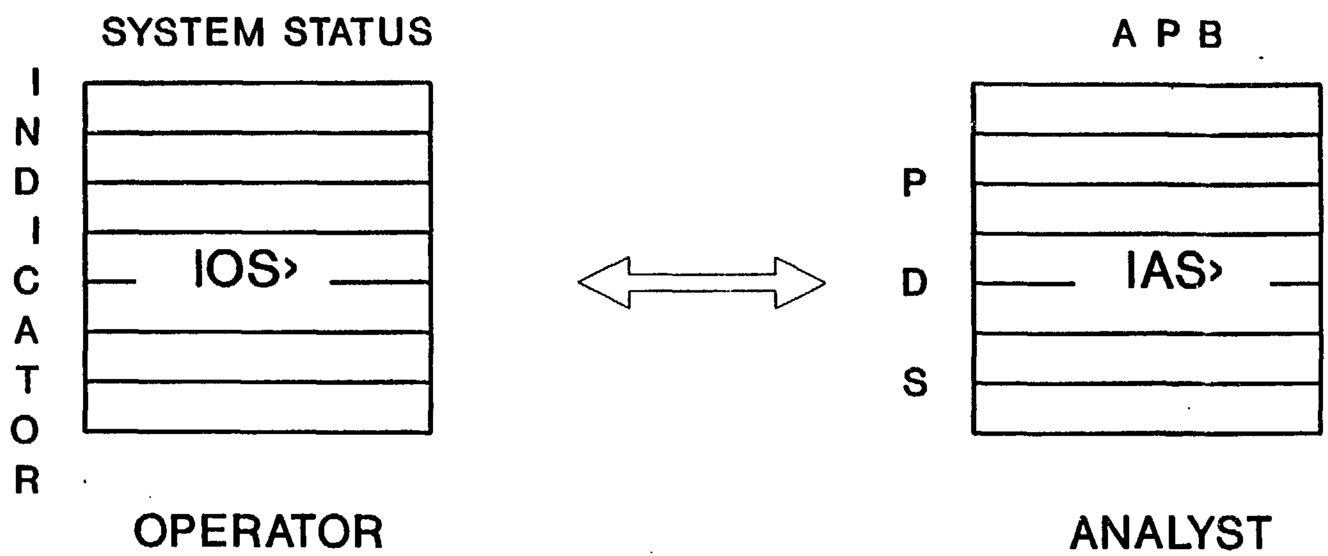


Figure 1 Alternate Representations of Severe Accident Space

# IDENTIFICATION OF PLANT DAMAGE STATES

| INDICATORS / SYSTEM STATUS | | | | | | | P D S |
|---|---|---|---|---|---|---|---|
| CONT RAD | S S RAD | A B RAD | CONT PRESS | A/C POWER | AFWS | SCRAM | |
| L | L | L | L | N | T | Y | SLOW SBO |
| L | L | L | L | N | N | Y | FAST SBO |
| H | L | L | H/L | Y | Y | Y | LOCAS |
| L | L | H | L | Y | Y | Y | V-SEQUENCE |
| L | L | L | L | Y | N | Y | TRANSIENT |
| H/L | H/L | L | L | Y | Y | N | ATWS |
| L | H | H/L | L | Y | Y/N | Y | SGTR |

Table 1 Identification of Plant Damage States

| PLANT DAMAGE STATE -> | AIYBY | AINBY | AINIY | ANYBY | ABNBY | S2IYBY | S2NNNY | S2NNNN | S2INIY |
|---|---|---|---|---|---|---|---|---|---|
| --------------------------- | (1.3E-6) | (1.9E-7) | (1.9E-7) | (1.6E-7) | (6.0E-7) | (2.2E-6) | (1.9E-5) | (1.1E-5) | (2.0E-7) |
| ***** CHALLENGES ***** | | | | | | | | | |
| NO CONT FAILURE | 0.51 | - | - | 0.51 | - | 0.77 | - | 0.005 | - |
| CF BEFORE CORE MELT | - | - | - | - | 1.00 | - | - | - | - |
| VE HYDROGEN BURN | - | - | - | - | - | - | - | - | - |
| IN-VESSEL ST EXPL | - | - | - | - | - | - | - | - | - |
| E HYDROGEN BURN | - | - | - | - | - | - | - | 0.10 | - |
| E HYDR BURN + ST SPIKE | - | - | - | - | - | 0.017 | 0.017 | 0.75 | 0.003 |
| ST SPIKE AT VB | - | - | - | - | - | - | - | - | - |
| DCH + ST SPIKE | - | - | - | - | - | - | - | 0.077 | - |
| LATE OP/HYDR BURN | - | - | - | - | - | - | - | 0.004 | 0.015 |
| LATE OP/ST + NCG | 0.434 | 1.00 | 1.00 | 0.434 | - | 0.177 | 0.978 | 0.063 | 0.979 |
| BASEMAT MELT | 0.036 | - | - | 0.036 | - | 0.009 | - | 0.005 | - |
| BYPASS | - | - | - | - | - | - | - | - | - |
| LOSS OF ISOLATION | 0.021 | - | - | 0.021 | - | 0.029 | 0.002 | 0.001 | 0.002 |
| INDUCED SGTR | - | - | - | - | - | - | - | - | |

| PLANT DAMAGE STATE -> | S2NYBY | S3IYBYB | S3INIYB | S3INBYB | TNNNNN | TNYBYR | TNYBYB | V |
|---|---|---|---|---|---|---|---|---|
| --------------------------- | (1.3E-6) | (4.1E-5) | (3.8E-6) | (3.0E-7) | (8.9E-6) | (2.6E-6) | (7.0E-7) | (1.2E-6) |
| ***** CHALLENGES ***** | | | | | | | | |
| NO CONT FAILURE | 0.77 | 0.68 | - | - | 0.01 | 0.52 | 0.68 | - |
| CF BEFORE CORE MELT | - | - | - | - | - | - | - | - |
| VE HYDROGEN BURN | - | - | - | - | - | - | - | - |
| IN-VESSEL ST EXPL | - | - | - | - | - | - | - | - |
| E HYDROGEN BURN | - | - | - | - | 0.086 | - | - | - |
| E HYDR BURN + ST SPIKE | 0.018 | 0.052 | 0.052 | 0.052 | 0.650 | 0.041 | 0.052 | - |
| ST SPIKE AT VB | - | - | - | - | 0.004 | - | - | - |
| DCH + ST SPIKE | - | - | - | - | 0.058 | - | - | - |
| LATE OP/HYDR BURN | - | - | 0.001 | - | 0.005 | - | - | - |
| LATE OP/ST + NCG | 0.177 | 0.226 | 0.95 | 0.955 | 0.043 | 0.172 | 0.228 | - |
| BASEMAT MELT | 0.009 | 0.014 | - | - | 0.003 | 0.01 | 0.014 | - |
| BYPASS | - | - | - | - | - | - | - | 1.00 |
| LOSS OF ISOLATION | 0.029 | 0.026 | 0.002 | - | 0.001 | 0.02 | 0.026 | - |
| INDUCED SGTR | - | - | - | - | 0.14 | 0.24 | - | - |

Table 2 Conditional Probabilities of Containment Failure for Indicated Plant Damage States

| PLANT DAMAGE STATES → / CHALLENGES ↓ | S2NYBY | S2NNNY | S2NNNN |
|---|---|---|---|
| NO CONT FAILURE | 0.77 | | 0.005 |
| C F BEFORE CORE MELT | | | |
| V E HYDROGEN BURN | | | |
| IN-VESSEL ST EXPL | | | |
| E HYDROGEN BURN | | | 0.10 |
| E HYDR BURN + ST SPIKE | 0.017 | 0.017 ← S1 | 0.75 |
| ST SPIKE AT V B | | | |
| DCH + ST SPIKE | | | 0.077 |
| LATE O P/ HYDR BURN | | | 0.004 |
| LATE O P/ ST + NCG | 0.177 ← S2 | 0.978 | 0.063 |
| BASEMAT MELT | 0.009 | | 0.005 |
| BYPASS | | | |
| LOSS OF ISOLATION | 0.029 | 0.002 | 0.001 |
| INDUCED SGTR | | | |

Table 3 Impact of Strategies on Containment Failure Probabilities