A Comparison of Scenario Binning Methods for Dynamic Probabilistic Risk Assessment

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ABSTRACT: Dynamic Event Tree (DET) analysis is an effective approach for evaluating plant response during the course of a transient in the presence of modeling or stochastic uncertainties. DET analysis produces very large output datasets, which creates challenges for data management and interpretation. In classical Level 1 PRA, scenarios are grouped mostly according to the states of various active plant systems. However, it is possible that scenarios with similar active component states have quite different physical histories. The Mean-Shift-Methodology (MSM) is proposed as a means to group DET scenarios based on their physical characteristics. A DET analysis was performed for a Station Blackout (SBO) scenario of a pressurized water reactor with possible AC power recovery using the MELCOR code coupled to the ADAPT DET generation tool. The advantages of scenario grouping using MSM are illustrated versus the conventional Level 1 PRA binning methodology.

1 INTRODUCTION

A large number of accident sequences can result from a Level 1 probabilistic risk assessment (PRA) representing the combinations of the various events on the system event trees. In the traditional approach to PRA, Level 1 accident sequences are binned according to the similarity of the state of various active systems or plant components and these bins are used as entry points into the Level 2 analysis. The binning generally has two purposes: 1) to limit the number of Level 2 initial conditions that must be considered, and, 2) to aid analysts in the processing and analysis of Level 1 results.

The traditional PRA suffers from its limited ability to address changes in the ordering of events resulting from variability in the timing of processes or the uncertainties associated with the knowledge of the plant state. These processes can include (but are not limited to) various accident phenomena, operator action or the response of digital control systems. In order to address some of these deficiencies, dynamic PRA methods have been developed (e.g., (Amendola, 1984), (Hakobyan, 2008), (Hofer, 2002)) which utilize physical simulation of system evolution to explicitly model accident sequences to allow for the direct accounting of the interactions among such processes.

Dynamic PRA methods suffer from difficulties similar to those of the traditional PRA with regards to the amount of scenarios that can be generated. In addition, when considering the post-core damage behavior, it may be impractical to perform a dynamic Level 2 analysis for all Level 1 sequences which are generated due to long simulation times required with codes such as MELCOR (Gauntt, 2005). Hence, binning methods are required to make the dynamic analysis manageable from both a computational and phenomenological viewpoint.

In this work, two different scenario binning methodologies are examined for a dynamic analysis of a station blackout (SBO) at a typical U.S. 4-loop pressurized water reactor (PWR). The first binning method considered is the classical binning methodology utilized in NUREG-1150 (U.S.N.R.C., 1991) which uses the states of various active systems and plant components to classify scenarios. The second method used is the Mean-Shift Methodology (MSM) (Fukunaga, 1975) which classifies the data based upon the time-dependent response of system variables (e.g., pressure and temperature at various points in the reactor coolant system) in addition to system states.

This paper will be broken down as follows: Section 2 will give an overview of the system and initiating event considered, Section 3 will give a description of the binning methodologies examined, Section 4 will describe the dynamic PRA methodology used, Section 5 will present the results of the two binning methods used. Finally, Section 6 will discuss the conclusions of this work.

2 SYSTEM AND INITIATING EVENT CONSIDERED

In a SBO accident, all offsite AC power is lost as well as AC power from emergency diesel generators. Under these conditions, heat removal from the primary system is provided by the turbine-driven auxiliary feedwater (AFW) system. However, this system will also fail if AC power is not restored before station batteries deplete (assumed to be six hours in this case).

Also considered in this scenario is the possibility that a small loss of coolant accident (LOCA) can develop from one of two possible sources: 1) failure of pressurizer valves to close on demand, and, 2) failure of reactor coolant pump (RCP) seals. RCP seals are designed to prevent the leakage of reactor coolant system (RCS) water from the primary system out of the RCPs during normal operation. When exposed to the conditions expected in a SBO, RCP seals can degrade, potentially leading to large leakages (Sankatar, 2003). The binning characteristics used for this work discussed in Section 3.1 come from the NUREG-1150 report for the Zion Nuclear Power Plant (NPP) (Stattison, 1990). At the time of the writing of NUREG-1150, RCP seal failure was an important event considered in the evolution of a SBO as it could lead to a significant loss of reactor inventory. While the likelihood of a hypothetical RCP seal failure is considered to be smaller today due to enhancements in RCP seal materials (NRC, 1991), RCP seal failure was treated in this paper in a manner consistent with that in NUREG-1150 in order to enable a comparison between a traditional approach and a dynamic approach. To that end, a model which predicts the probability of RCP seal failure as a function of the stress and temperature was developed from data in NUREG-1150, as well as experimental data from (Kittmer, 1985) representative of the RCP seal materials of the time.

During the course of this hypothetical SBO event, AC power may be recovered which can allow the actuation of emergency core cooling system (ECCS). Both low-pressure injection systems (residual heat removal pumps and passive accumulators) and high-pressure injection systems (safety injection pumps and charging pumps) may become available if needed. When ECCS is recovered, pump systems initially take suction from the refueling water storage tank (RWST). However, if ECCS runs for a long enough period, the RWST may deplete and the ECCS will need to switch to recirculation mode where pump suction is taken from the containment sump.

When AC power is recovered, however, ECC systems will not be immediately recovered as operating procedures must be followed to allow the activation of safety systems. For this work, a time delay was assumed between the recovery of AC power and the possible actuation of safety systems to simulate a delay in the recovery of safety systems due to procedure following. While the modeling of procedures was not rigorous, it was meant to be a more realistic representation of system response as compared to recovering ECCS immediately after power is restored. The duration of the time delays were estimated using Westinghouse emergency operating procedures (Westinghouse, 1996) and conversations with Westinghouse personnel (Lutz, 2010).

When plant systems are recovered after the initiating event, the possibility of failure upon demand of the following systems is considered:

1. Turbine-driven AFW (TDAFW) and motor driven AFW systems
2. Safety injection and charging pumps
3. Residual heat removal pumps
4. Recirculation system

Only the TDAFW systems is available before AC power is recovered and all others listed above may become available when AC power is recovered.

3 SCENARIO BINNING METHODOLOGIES CONSIDERED

3.1 *Classical scenario binning approach*

For Level 1 analysis, these scenario bins are known as plant damage states (PDSs). For this work, the binning characteristics used were taken from the NUREG-1150 analysis of the Zion Unit 1 NPP since the system under consideration is a Westinghouse-type 4-loop PWR. These bin characteristics are shown in Table 1. For each characteristic a certain number of pre-defined values are considered which cover the range of event sequences on the event tree. For example, the first characteristic listed in Table 1, "Status of RCS at Onset of Core Damage" deals with the presence or lack of a break in the RCS. Table 2 gives a listing of the possible values that this binning characteristic can take on.

Table 1. Binning characteristics used for Classical PRA scenario binning

Binning Characteristics	
1.	Status of RCS at Onset of Core Damage
2.	Status of ECCS
3.	Status of Containment Spray
4.	Status of AC Power
5.	RWST Injection Status
6.	Steam Generator Heat Removal Capability
7.	Status of RCP Cooling
8.	Status of Containment Fan Coolers

Table 2. Values considered for Binning Characteristic 1: "Status of RCS at Onset of Core Damage"

Value	Description
T	No break (Transient)
A	Large LOCA
S1	Medium LOCA
S2	Small LOCA
S3	Very Small LOCA
G	Steam Generator Tube Rupture
H	Steam Generator Tube Rupture, no SG depressurization
V	Interfacing system LOCA

The values of each binning characteristic are assumed to cover all of the possible states of each characteristic on the event tree and it is also assumed that all values within a binning characteristic are mutually exclusive. For each scenario on the event tree, a value is assigned for each binning characteristic resulting in the appropriate bin or PDS for that scenario. An example PDS might be "S2RRRRYRR", which implies scenarios with small LOCAs, no AC power available (and thus no ECCS or containment heat removal – R's in positions 2-5,8), RCP seal cooling is unavailable (R in position 7), and AFW is operating (Y in position 6).

For this work, only the "S2" (RCP seal LOCA or pressurizer valve failure) and "T" (no LOCA) values of characteristic 1 were possible. The binning characteristics "Status of ECCS", "Status of Containment Spray", and "Status of Fan Coolers", (characteristics 2, 3, and 8) characterize the status of the ECCS, containment spray system, and the fan cooler system, respectively, and whether or not the systems are available, recoverable with AC power recovery, or not recoverable. Characteristic 4 describes the availability of AC power for a scenario, stating whether it is available, recoverable, or not recoverable. Characteristic 5, "RWST Injection Status" states whether or not the inventory or the RWST has been injected into the containment. The characteristic "Steam Generator heat Removal Capability" describes the availability of AFW systems and whether or not operators have depressurized intact steam generators to enhance primary system cooldown. Finally, Characteristic 7 states the availability of RCP seal cooling. If RCP seal cooling is unavailable, an RCP seal LOCA may develop.

3.2 *Scenario binning or aggregation using MSM*

The MSM (Fukunaga, 1985) considers each point x_i (i =1, …, N) of the data set as an empirical distribution density function $K(x_i)$ distributed in a d-dimensional space (overlapping curves in Figure 1 for the 1-D case) where regions with high data density (i.e., modes) correspond to local maxima of the global probability density function $f_N(x)$ defined as (red line in Fig. 2 for the 1-D case)

$$f_N(x) = \frac{1}{Nh^d}\sum_{i=1}^{N} K\left(\frac{x-x_i}{h}\right) \qquad (1)$$

where each point $x_i \in \mathbb{R}^d$ and h is a scalar parameter called the bandwidth which indicates the level of refinement of the cluster analysis. The function $K(x)$: $\mathbb{R}^d \mapsto \mathbb{R}$ is the distribution density associated to each data point which is also called the kernel. The steps in the implementation of MSM are as follows:

1. Starting from a data point x search all points x_i within bandwidth radius and determine the average data point $\underline{x}$ as following:

$$\underline{x} = \frac{\sum_{i=1}^{N} x_i K\left(\frac{x-x_i}{h}\right)}{\sum_{i=1}^{N} K\left(\frac{x-x_i}{h}\right)} \qquad (2)$$

2. Next, move from x to $\underline{x}$ and repeat Step 1
3. Repeat Step 1 and 2 until convergence is met:

$$\left|\underline{x}^{(r+1)} - \underline{x}^{r}\right| < \varepsilon \qquad (3)$$

   where $\underline{x}^{(r)}$ indicates $\underline{x}$ at iteration r
4. Repeat Steps 1 through 4 for each data point

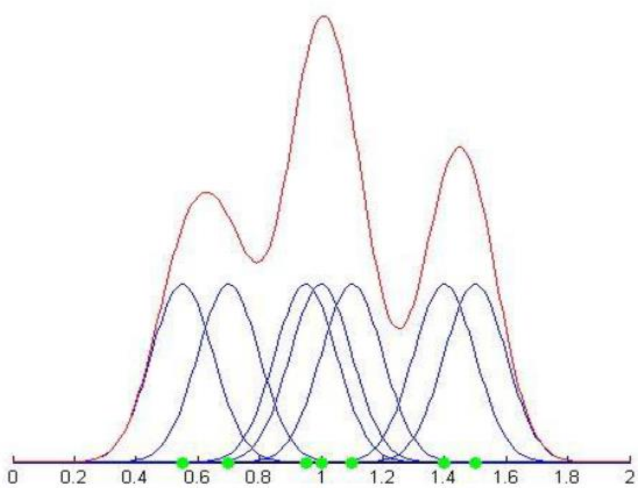

Figure 1: Density function (bounding, top curve) for points distributed in a 1-dimensional space modeled using kernels

The advantage of MSM is that it is able to identify clusters with arbitrary shapes, hence, it is not limited to topological figures such as spheres or ellipsoids. Moreover, compared to, for example, K-Means and Fuzzy C-Means (Jain, 1988) the number of clusters is not specified a-priori by the operator but is determined by the algorithm based on the areas with higher point concentration using the value of the bandwidth, h, chosen.

4 ADAPT DYNAMIC EVENT TREE METHODOLOGY

The ADAPT (Analysis of Dynamic Accident Progression Trees) methodology is a DET methodology developed by Hakobyan et al. (Hakobyan, 2006). DETs are similar in structure to their classical analogs with the exception that DETs base possible branching of system evolution on a phenomenological system model output. The horizontal axis of a DET directly corresponds to time.

In the ADAPT methodology, branching occurs at fixed points in the system state space. The success or failure of plant active systems is questioned when system set points are reached as determined by the dynamic system model used and when allowed by plant procedures. ADAPT tracks the case where the system fails and the case where the system succeeds. Intermediate states of failure can also be considered (i.e. 1 of 2 pumps successfully operate). For the purposes of this study, the MELCOR (Gauntt, 2005) code was linked to ADAPT as the dynamic system model.

As mentioned in Section 2, a probability distribution for the failure of RCP seals was developed based upon models available in NUREG-1150 and historical data on O-ring performance. The developed failure distributions were discretized for use in ADAPT (physical values corresponding to discrete probability points were used as branching conditions). For the failure of pressurizer relief valves, a probability of failure of 6.8e-3 per valve per demand (Bickford, 1985) was assumed (both PORVs and SRVs). The probability of failure of at most one pressurizer valve with a probability of failure per demand of λ after k cycles is taken to be

$$p(k) = (2\lambda - \lambda^2)(1 - [2\lambda - \lambda^2])^{k-1} \qquad (4)$$

Failure of pressurizer valves is questioned when the cumulative probability of valve failure reaches certain analyst-specified probabilities.

For plant active systems, failure of a system is questioned when it is called upon. The timing of system actuation is dependent upon process conditions (whether or not a system's actuation setpoint has been reached), the availability of AC power and progression of plant procedures. Probabilities for the failure of active systems were taken from the NUREG-1150 analysis of the Zion NPP.

In order to prevent an exponential growth in DET size, a conditional probability truncation of 1e-6 was used (those branches which fell below a conditional probability of 1e-6 were not executed). This value was used to maintain consistency with the NUREG-1150 analysis of a SBO accident which only considered scenarios with an absolute frequency greater than 1e-9 per year and an assumed SBO frequency of 3e-4 per year.

5 RESULTS

The probabilistic model coupled with the MELCOR system model for the initiating event discussed in Section 2 was executed using the ADAPT methodology discussed in Section 4. The resulting DET generated 614 scenarios, 132 of which led to core damage. All scenarios which led to core damage were binned according to both the classical PDS definitions discussed in Section 3.1 as well as the using MSM (discussed in Section 3.2). Section 5.1 will discuss the DET results using the classical PDS definitions to bin the results and Section 5.2 will discuss the results using MSM to bin the results.

5.1 *Results Using Classical Binning Methodology*

The binned results of the DET experiment using the classical PDS definitions are shown in Table 2. Table 2 shows that the RCS experiences only transient conditions (no LOCA – "T" for the first PDS characteristic) or a small break LOCA resulting from either an RCP seal LOCA or a pressurizer valve failure (an "S2" for the first PDS characteristic). In addition, 112 of the 132 core damage scenarios identified were cases in which AC power was never recovered. However, in 20 scenarios, namely those in PDSs S2RRYRYRR and S2IRYYYNY, AC power was recovered but core damage still occurred. For those scenarios in S2RRYRYRR, AC power was recovered but ECCS injection was not recovered before core damage occurred. For the scenarios in PDS S2IRYYYNY, AC power was recovered and ECCS operated in injection mode only but again, core damage still occurred. The last PDS is a mixture of cases where: a) ECCS injection was restored but core damage occurred shortly after (ECCS not restored in time to prevent core damage – Category A), and, b) ECCS injection was restored, core damage was initially prevented but the ECCS failed when it entered recirculation mode leading to core damage – Category B). These two categories represent very different scenarios histories but were placed into the same PDS because of the definition of the "I" value of the second PDS characteristic. The reason was that "ECCS injection operated in injection mode only". While this statement is true of all scenarios in S2IRYYYNY, it is true for different reasons. It is possible, that when using this type of binning methodology in a dynamic analysis, that the initial binning scheme should be redefined based on DET outcome. For example if the "I" value of the second PDS characteristic were split into two categories, 1) "ECCS operated in injection mode but recirculation mode not called upon", and, 2) "ECCS operated in injection mode but recirculation mode failed", the scenarios in S2IRYYYNY would have been more properly characterized. Next, it is instructive to look at the scenario histories for all of the scenarios in PDS S2IRYYYNY. Figure 2 gives a plot of the system pressure vs. time for the entire scenario in this PDS. Those belonging to categories A and B are marked on the plot.

It can be seen from Figure 2 that there is a large difference between the scenario histories observed for the scenarios in Categories A and B. However, even for those scenarios in Category B, a large variation in the observed core damage times is seen (~27000s or 8.5 hours). The variability arises from timing and type of induced LOCA which occurs. For some cases large enough RCP seal LOCAs occur to preclude the challenging of pressurizer relief valves. However, in some cases valve failures occur which leads to a faster RCS depressurization and earlier core damage time.

Aside from those PDSs in which AC power was recovered, significant differences in scenario history are also seen in those PDSs where AC power is never recovered. For example, Figure 3 gives a plot of the system pressure vs. time for the scenarios in PDS S2RRRRDRR. In this PDS, an S2-sized LOCA developed, AFW initially succeeded but failed after station batteries depleted, and AC power was never recovered. In addition, RCP seal cooling is not available so that RCP seal LOCAs have the potential to develop.

It can be seen in Figure 3 that there are two general trends that are observed. Trend A consists of scenarios with core damage times between 30-34000s and Trend B consists of scenarios whose core damage times lie between 42-56000s. Those scenarios in Trend A developed an RCP seal LOCA (~1000 gpm) early in the transient which led to earlier core damage times. However, for those scenarios in Trend B, no RCP seal LOCA initially developed but either: a) one developed late in the accident after the RCS repressurized after AFW failure, or, b) no RCP seal LOCA developed but a pressurizer valve failed when challenged. It can be seen that that there are two cases observed in Trend B with a fast rate of depressurization resulting from pressurizer valve failure. These scenarios exhibit much different behavior than the remainder of the scenarios in Trend B which depressurized much more slowly due to the smaller size of RCP seal LOCAs.

Table 2: Binned results of DET experiment using classical PDS definitions

Bin	Number of Scenarios	Description
S2RRRRDYR	8	Small break LOCA, TDAFW runs until batt. depletion, RCP seal cooling available, No AC power
TRRRRDYR	3	No LOCA, TDAFW runs until batt. depletion, RCP seal cooling available, No AC Power
S2RRRRSYR	7	Small LOCA, no AFW, RCP seal cooling available, No AC Power
TRRRRSYR	6	No LOCA, no AFW, RCP seal cooling available
S2RRRRYRR	17	Small LOCA, TDAFW operable, no RCP seal cooling
GRRRRDYR	17	Steam generator tube rupture, AFW runs until batt. depletion, RCP seal cooling available, No AC power
S2RRYRYRR	2	Small LOCA, AC power available, ECCS injection not yet recovered, TDAFW operable
S2IRYYYNY	18	Small LOCA, TDAFW operable, AC Power available, ECCS operates in injection mode only, sprays and fan coolers operable
S2RRRRDRR	26	Small LOCA, TDAFW runs until batt. depletion, no RCP seal cooling, No AC Power
S2RRRRSRR	28	Small LOCA, no AFW available, no RCP seal cooling, no AC Power

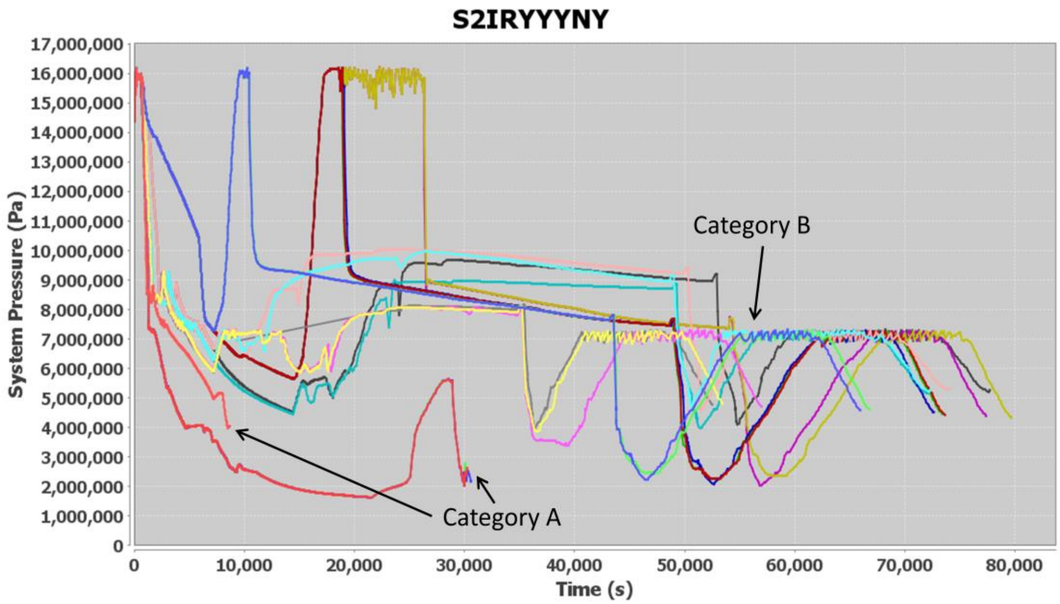

Figure 2: Plot of system pressure vs. time for PDS S2IRYYYNY. The scenarios belonging to both Category A and Category B are noted.

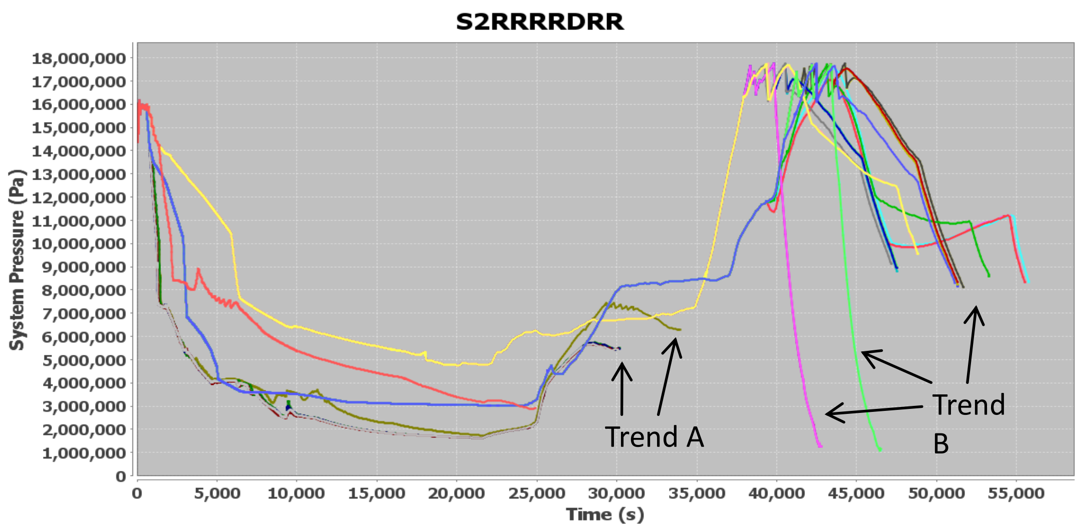

Figure 3: Plot of system pressure vs. time for PDS S2RRRRDRR. The sceanrios belong to both Trend A and Trend B are noted.

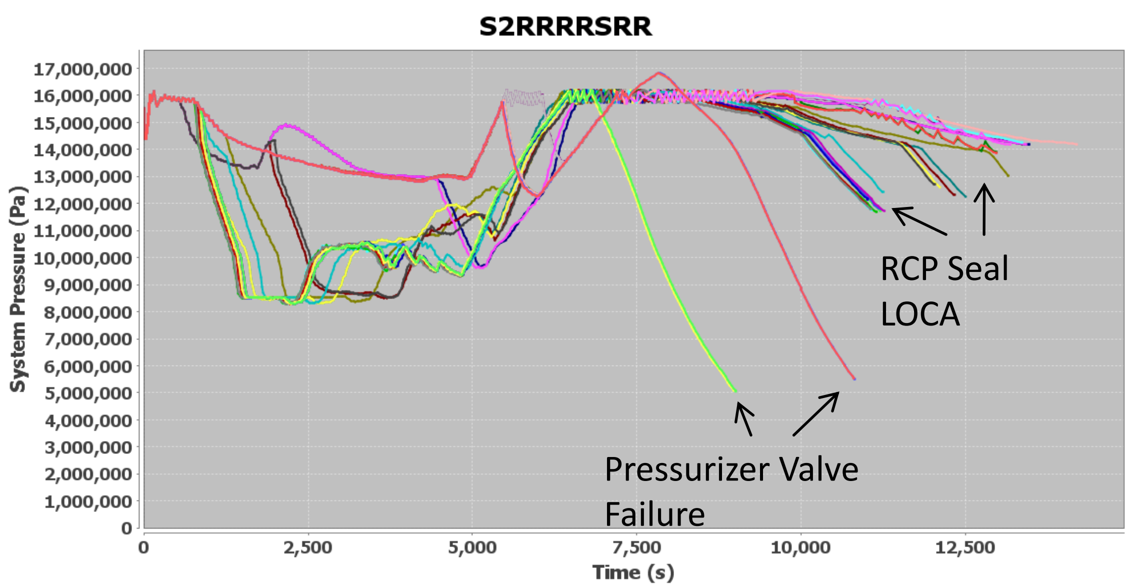

Figure 4: Plot of system pressure vs. time for PDS S2RRRRSRR.

The next PDS of interest is S2RRRRSRR (Figure 4). The scenarios in this PDS were those in which an S2-sized LOCA developed, AC power was never recovered, AFW initially failed, and RCP seal cooling is not available. In this situation, a competition develops between the two competing LOCA modes considered here (pressurizer valve failure and RCP seal LOCA). It can be seen that those sceanrios in which pressurizer valves fail enter the core damage phase of the accident with much lower system pressures and with faster depressurizaton rates than those scenarios in which an RCP seal LOCA occurs, which could have possible implications for the accident progression in the post-core damage phase of the accident.

For those PDSs in which there is a competition of failure modes or there is large variability in the timing of occurrence of a single failure mode, the classical binning procedure (as it is) has difficulty grouping scenarios of like physical history despite being similar in system configuration. This could, of course, be obviated by a redefinition of the binning characteristics based on DET results. However, it may not be intuitive how to redefine the bins as differences in observed trends may arise from multiple sources.

5.2 *Results Using MSM*

Each scenario (i.e., a point) x_i (see Equation 1) has been represented as a multidimensional vector where each dimension corresponds to the value of a specific state variable sampled at a specific time instant. For the scope of this work we chose 23 state variables sampled 200 times. Thus the dimensionality of each scenario is equal to 200·23=4600.

Clustering using MSM has been performed for different values of bandwidth *h*. It has been found that the 15 clusters obtained with *h*=25 are representative of the original data set. In this respect, Table 3 shows the results of the clustering using MSM, including the number of scenarios contained.

Table 3: Clustering results of DET experiment using MSM

Cluster	Number of Scenarios	Cluster	Number of Scenarios
1	33	9	1
2	7	10	2
3	1	11	2
4	19	12	5
5	15	13	14
6	28	14	2
7	1	15	1
8	1		

Figures 5, 6 and 7 show the scenarios contained in Clusters 1, 4 and 5, respectively. It is possible to note how the scenarios contained in each cluster have similar temporal behavior. This indicates how clustering can overcome the limitations of the classical binning shown in Section 5.1 regarding scenarios having different temporal behavior and located in the same bin. In general, the scenarios within a cluster generated using MSM exhibited more consistent temporal behavior than those scenarios grouped into bins using the classical methodology. In addition, scenarios in an MSM-generated cluster in general showed a much smaller spread in the estimated timing of core damage, whereas scenarios in a classically grouped bin showed a spread in the timing of core damage up to 20 hours.

A few discrepancies were noted, however, in the MSM grouping of the scenarios. The first noted relates to scenarios grouped into Cluster 1 (Figure 5). Of the 33 scenarios in Cluster 1, 32 of them were cases in which AC power was not recovered and an early RCP seal LOCA developed. However, in one case, a large RCP seal LOCA developed, AC power was recovered and ECCS injection began just at the time that core damage was initiated. Hence, while the temporal history for this scenario was very similar to the other scenarios in its cluster, the plant state was very different. However, there was not enough time for the change in plant state to affect the scenario evolution significantly.

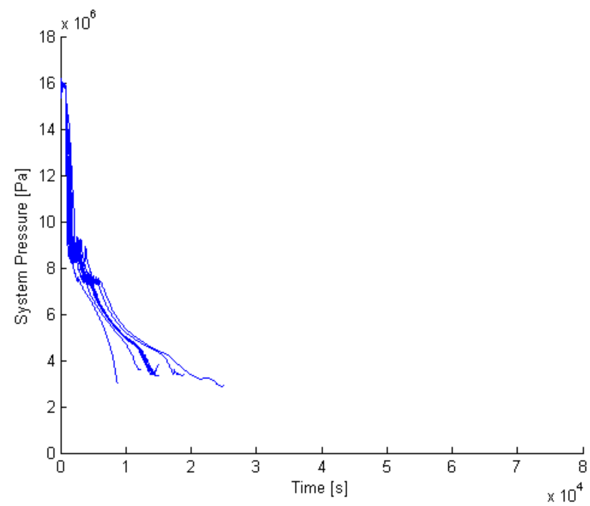

Figure 5: Plot of the scenarios contained in Cluster 1

Cluster 4 and Cluster 5 consisted of scenarios which had very similar core damage times. However, both clusters contained both LOCA and non-LOCA cases. Hence, the scenarios grouped in these cases could lead to very different scenario trajectories if continued into the post-core damage regime.

6 CONCLUSION

This paper presents a comparison of two different methodologies for grouping scenarios resulting from an ADAPT DET analysis. The classical binning methodology used in NUREG-1150 grouped scenarios which have similar plant states. However, scenarios with similar plant states may be very different with regards to their temporal evolution. The classical binning approach is useful for examining the variation in scenario evolution expected for a particular plant state, but the results of this study showed that they can be sensitive to the a priori definition of "similar" plant states.

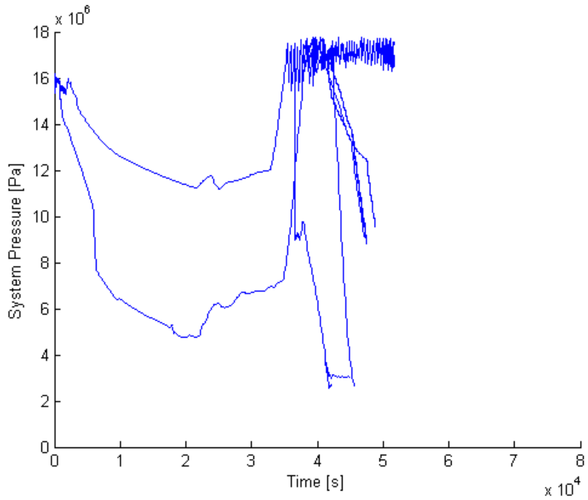

Figure 6: Plot of the scenarios contained in Cluster 4

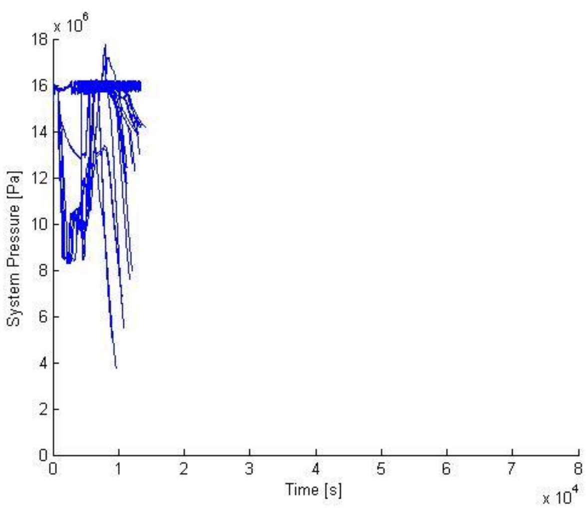

Figure 7: Plot of the scenarios contained in Cluster 5

The classical grouping approach can be improved to group scenarios of more similar physical history by updating the binning scheme based on DET results.

The MSM approach tended to yield groups with more similar temporal histories. However, MSM could not always capture the fact that although certain scenarios may exhibit similar behavior up to a certain point, some aspects of the scenarios may diverge if the analysis is continued to later times in the accident.

Clearly, a methodology which incorporates the benefits of both methods is needed. These two methods can be used in conjunction to better capture the nuances of the scenario. For example, MSM could be used to group scenarios by their physical history and sub groups could be generated by a classical methodology which could better take into account the effects of the plant state that have not yet significantly affected the dynamics.

It is expected that both plant state information as well as physical variable information should be accounted for when considering scenario similarity. Plant state variation will often have impacts on physical variable evolution, but the impact may be delayed or unknown depending on the scenario mission time and modeling scope. The exploratory analysis performed in this work has helped to provide insight into the types of situations where inconsistencies in scenario grouping may arise when considering plant state information only versus physical variable evolution only.

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