Thermal-Hydraulic Unreliability of Passive Systems

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Advanced light water reactor designs like AP600 and the simplified boiling water reactor (SBWR) use passive safety systems for accident prevention and mitigation. Because these systems rely on natural forces for their operation, their unavailability due to hardware failures and human error is significantly smaller than that of active systems. However, the coolant flows predicted to be delivered by these systems can be subject to significant uncertainties, which in turn can lead to a significant uncertainty in the predicted thermal-hydraulic performance of the plant under accident conditions. Because of these uncertainties, there is a probability that an accident sequence for which a best estimate thermal-hydraulic analysis predicts no core damage (success sequence) may actually lead to core damage. For brevity, this probability will be called thermal-hydraulic unreliability. The assessment of this unreliability for all the success sequences requires very expensive computations. Moreover, the computational cost increases drastically as the required thermal-hydraulic reliability increases. The required computational effort can be greatly reduced if a bounding approach can be used that either eliminates the need to compute thermal-hydraulic unreliabilities, or it leads to the analysis of a few bounding sequences for which the required thermal-hydraulic reliability is relatively small. The objective of this paper is to present such an approach and determine the order of magnitude of the thermal-hydraulic unreliabilities that may have to be computed.

The core damage frequency, f, due to the thermal-hydraulic unreliability of a best-estimate success sequence can be written as

$$f = f_I f_h f_t \qquad (1)$$

where

f_I = frequency of initiating event

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f_h = product of unavailabilities of all failed systems (hardware and humanware failures) in the sequence under consideration

f_t = sequence thermal-hydraulic unreliability.

If f_c is the core damage cutoff frequency, that is, core damage frequencies lower than f_c are considered negligible, then the cutoff value of f_t would be

$$f_{tc} = \frac{f}{f_I f_h} \qquad (2)$$

For best-estimate success sequences having a thermal-hydraulic unreliability that is less or equal to f_{tc}, their contribution to core damage is considered negligible. Equation (2) shows that success sequences which have high accident initiator frequencies and high failed system unavailabilities impose higher demands on thermal-hydraulic reliability. On the other hand the thermal-hydraulic unreliability of a given sequence is a function of the margin between the limiting value of the variable used as core damage criterion (e.g., peak clad temperature) and its best estimate prediction, and of the uncertainty in this prediction. For example, if a peak clad temperature of 2200°F is used as a core damage criterion, the thermal-hydraulic unreliability will be lower as the predicted peak clad temperature is further below 2200°F and the uncertainty of this prediction is smaller.

The process of identifying sequences to be considered in a thermal-hydraulic unreliability assessment will be illustrated by using as an example the Medium LOCA (MLOCA) event in an AP600 type advanced LWR design. In this design, the relevant safety-grade safety systems are[1] two core makeup tanks (CMT) and two accumulators (ACC) for high pressure injection, the automatic depressurization system (ADS), and two low pressure injection lines from the in-containment refueling water storage tank (IRWST). In addition to these passive coolant injection systems, injection can be provided by the normal residual heat removal system which is active and not safety-grade and will not be considered here. The success criteria are one IRWST line, one CMT or one accumulator, and only a fraction of the available depressurization lines is required for successful depressurization. Under the above conditions, the MLOCA event tree would show the following three-success sequences.

Sequence	Frequency,	f_{tc}
1. $MLOCA/\overline{CMT}/\overline{ADS}/\overline{\overline{ACC}}/\overline{IRWST}$	1.0E-4	1.0E-5
2. $MLOCA/CMT/\overline{ADS}/\overline{ACC}/\overline{IRWST}$	1.0E-8	1.0E-1
3. $MLOCA/\overline{CMT}/\overline{ADS}/ACC/\overline{IRWST}$	1.0E-8	1.0E-1

In the sequence notation used above, no bar above the system name means that the system is unavailable, one bar means the system is available and two bars mean that successful operation of the system is not necessary for sequence success. The thermal-hydraulic unreliability cutoff f_{tc} has been calculated using a core damage cutoff frequency of 10^{-9}, and the sequence frequencies have been calculated using the approximate value of 10^{-4} for the initiator frequency and the unavailabilities of ADS, two CMTs, and two accumulators.

These success sequences can be split into a large number of sequences depending on whether one or both CMTs, one or both ACCs, one or both IRWST lines are available, and on how many depressurization lines above the minimum required are also available. Those additional sequences generated from sequence 2 and 3, because of the additional system failures, would have a frequency below the cutoff of 10^{-9} and can be neglected. For example, the sequence $MLOCA/CMT/\overline{ADS}$/one $\overline{ACC}/\overline{IRWST}$ would have a frequency of about 10^{-11}. From sequence 1, we get the sequence $MLOCA/\overline{CMT}/\overline{ADS}/\overline{\overline{ACC}}$/one $\overline{IRWST}$ and sequences which either have a frequency of less than 10^{-9}, or they have a higher safety system redundancy than sequences 2 and 3. The sequence $MLOCA/\overline{CMT}/\overline{ADS}/\overline{\overline{ACC}}$/one $\overline{IRWST}$ has a frequency of about 10^{-7} and an f_{tc} of about 10^{-2} and will be called here "sequence 4."

Significant computational effort can be saved if it is established that operation of additional equipment than the minimum required for path success does not lead to a worse transient, that is, to a higher peak clad temperature. This would be a good design feature because it would assure no adverse system interactions if more systems come into operation.

If no adverse system interactions are present, in the sense discussed above, the problem of thermal-hydraulic unreliability can be approached as follows. A conservative deterministic analysis can be performed with the sequences $MLOCA/CMT/\overline{ADS}/\overline{ACC}$/one $\overline{IRWST}$ and

MLOCA/$\overline{CMT}$/$\overline{ADS}$/ACC/ one $\overline{IRWST}$. In this analysis defendable "worst values" are used for all the uncertain parameters. If with such values these two sequences give a peak clad temperature below 2200°F, after the computer code modeling error has been accounted, then all other success sequences will also have a peak clad temperature below 2200°F. This is the case, because all other sequences with a frequency greater than 10^{-9} have a larger redundancy of safety systems. If this approach would fail, because it is overconservative, a combination of this approach with statistical analysis as discussed below will most likely be successful.

In terms of thermal-hydraulic reliability, sequence 1 is the most demanding. A very extensive computational effort is needed to determine an f_{tc} of 10^{-5}. However, this sequence has a very high redundancy of safety systems and most likely the deterministic approach, or an approach that uses statistical analysis only with the variable having the largest impact on peak clad temperature, while all other variables are given worst values, will be successful. Statistical analysis with only one variable does not impose any significant computational effort. All other sequences can be bounded with a statistical analysis of the sequences MLOCA/CMT/$\overline{ADS}$/$\overline{ACC}$/one $\overline{IRWST}$, and MLOCA/$\overline{CMT}$/$\overline{ADS}$/ACC/ one $\overline{IRWST}$ with an f_{tc} value of only 10^{-2} (f_{tc} value of sequence 4, which is the most demanding after sequence 1). All other sequences have either a frequency of less than 10^{-9} or a higher system redundancy than these sequences.

In conclusion, this work presented a bounding approach that can drastically reduce the required computational effort for thermal-hydraulic reliability assessment. If a statistical analysis has to be performed, most likely there would be no need to assure a thermal-hydraulic unreliability of less than about 10^{-2}. Although an MLOCA event was used as a reference, similar conclusions are derived for other events.

References

1. C. L. Haag and T. L. Schulz, "The Use of PRA in Designing the Westinghouse AP600 Plant," Proceedings of ARS '94 International Topical Meetings on Advanced Reactors Safety, Pittsburgh, PA, Vol. 1, p. 103 (April 17-21, 1994).

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