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Core Damage Frequency Estimation Using Accident Sequence Precursor Data: 1990-1993

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1 Introduction

The Nuclear Regulatory Commission's (NRC's) ongoing Accident Sequence Precursor (ASP) program uses probabilistic risk assessment (PRA) techniques to assess the potential for severe core damage (henceforth referred to simply as core damage) based on operating events. The types of operating events considered include accident sequence initiators, safety equipment failures, and degradation of plant conditions that could increase the probability that various postulated accident sequences occur. Such operating events potentially reduce the margin of safety available for prevention of core damage and thus can be considered as precursors to core damage. The current process for identifying, analyzing, and documenting ASP events is described in detail in Vanden Heuval et al[1]. The significance of a Licensee Event Report (LER) event (or events) is measured by means of the conditional probability that the event leads to core damage, the so-called *conditional core damage probability* or, simply, CCDP.

When the first ASP study results were published in 1982[2], it covered the period 1969-1979. In addition to identification and ranking of precursors, the original study attempted to estimate core damage frequency (CDF) based on the precursor events. Subsequent to the release of this study in 1982, the ASP methodology and its results became the subject of much controversy and a number of independent reviews were initiated. For example, reviews by INPO[3], Ebersole[4], Minogue[5], Modarres[6] and Science Applications, Inc.[7] were performed following the release of the 1969-1979 ASP study. When the ASP program was transferred from the NRC's Office of Nuclear Regulatory Research (RES) to the Office for Analysis and Evaluation of Operational Data (AEOD) in 1985, the focus of the ASP program changed and an attempt was no longer made to estimate CDF.

The 1969-1979 ASP study used only one set of generic accident sequence models. However, based on the recommendations from its review, the decision was made to utilize generic, but plant-class specific, accident sequence models. That is, specific event trees were developed for various plant-classes in order to account for marked differences between various plants. The plants were categorized such that each category would respond similarly to an initiating event. Accordingly, eight sets of event trees were developed corresponding to a total of eight plant-classes (five PWR and three BWR).

A number of new developments and applications regarding accident precursors have emerged since the release of the original study in 1982. Research by Bier and Mosleh[8], Modarres et al[9], Lois[10], Hoertner et al[11],[12], Ballard[13], IAEA[14], Cooke et al[15],[16], Bier[17], Abramson[18], Johnson and

Rasmuson[19], and Modarres et al[20] has significantly contributed to the proper treatment and use of accident precursors. A special issue of the journal *Reliability Engineering and System Safety* in November of 1990[21] was devoted to the ASP issue and discussed a number of new developments. Also, an AEOD-sponsored workshop[22] on accident precursors was held in 1992 in which some recommendations for improving the methodology were generated. Another workshop on accident precursors was recently held in May 1995 in Wisconsin.

While the emphasis of AEOD has been on the identification of significant precursors from LERs, the use of ASP results has become more widespread at the NRC. The NRC staff response[23] to Chairman Selin's request[24] to study industry comments on the trend in core melt probability concludes that: "The staff notes, on the basis of actual events, that the trend in the sum of the estimated conditional core damage probabilities shows an overall decrease since 1970's. This can be used as an indicator of a corresponding downward trend in the probability of occurrence of a core damage." Thus, the estimation of CDF based on ASP results continues to be a subject of important and ongoing interest.

The simple sum of the CCDPs as an estimator of CDF (see Section 2) is known to be positively biased due to overcounting[18],[20], while the estimators proposed by Cooke et al[15],[16] (henceforth referred to as the Cooke-Goossens estimator) and Bier[17] have been developed to specifically reduce such bias. On the other hand, Abramson[18] has developed an estimator which essentially removes the positive bias, thus yielding an approximately unbiased estimator.

The purpose of this paper is to compare the average annual CDF estimates calculated using the CCDP sum, Cooke-Goossens, Bier, and Abramson estimators for various reactor classes using the combined ASP data for the four years, 1990-1993. An important outcome of this comparison is an answer to the persistent question regarding the degree and effect of the positive bias of the CCDP sum method in practice.

Note that this paper only compares the estimators with each other. Because the true average CDF is unknown, the estimation error is also unknown. Therefore, any observations or characterizations of bias are based on purely theoretical considerations.

2 Estimating Average Core Damage Frequency

Suppose that m different types of precursors have been observed in operating time T for a given accident sequence within a given plant-class, where the operating time T denotes the total critical reactor-years of operation. Further, let N_i denote the total number of occurrences of the i th type of precursor, $i = 1, \dots, m$. In the common case in which all the precursors are unique, m simply denotes the total observed number of precursors for the given sequence, and $N_i = 1$ for all i .

Apostolakis and Mosleh[25] somewhat casually suggested estimating the average CDF λ for the sequence as

$$\tilde{\lambda} = \frac{\sum_{i=1}^m N_i p_i}{T}, \quad (1)$$

where p_i denotes the CCDP corresponding to the i th precursor type. In (1), the worth (contribution) of the i th type of precursor is represented as its CCDP, p_i , that the event would have subsequently led to core damage. Obviously, if the event represents core damage, then $p_i = 1$; otherwise, $0 < p_i < 1$.

Because of the possibility of overlap in the precursor events, it has been claimed by Rubenstein[26], Cooke et al[15],[16], Bier[17], and Abramson[18] that there is potential overcounting in the numerator in equation (1). Consequently, equation (1) is a positively biased estimator of λ (that is, on average, it overestimates λ). In an attempt to either reduce or remove the positive bias in equation (1), Cooke et al[15],[16], Bier[17], and Abramson[18] proposed several alternative estimators. These estimators are further discussed and illustrated in Modarres et al[20].

For the class of all reactors, the NRC's Office of Nuclear Reactor Regulation (NRR) has in the past used the CCDP sum [the numerator in equation (1)] as an overall indicator of plant safety and for assessing safety trends. NRR subsequently normalized the sum of the CCDPs by dividing the sum in a given year by the total operating time (in reactor-years) for that year. While this normalized value is an indirect indicator of plant safety, it is *not* an unbiased estimator of λ (for reasons discussed above). The estimator in equation (1) will henceforth be referred to as the *CCDP sum estimator*.

Suppose we apply equation (1) to the set of observed ASP events for a given accident sequence within a specified plant-class. Further suppose that there are no overlapping (or laddered) precursors as described and illustrated in Modarres et al[20], and that all precursors are unique. In this case, $\bar{\lambda}$ is an approximately unbiased estimate of the average CDF for the given sequence (averaged over all the reactors within the specified plant-class). Such an average is consistent with the frequencies and failure probabilities used in the ASP calculations which are derived in part from data obtained across the light-water reactor population. In other words, the CCDPs determined for each ASP event cannot be rigorously associated with the probability of core damage resulting from the actual event at the specific plant at which it occurred. Thus, the estimate and use of average CDF is consistent with the ASP data.

Furthermore, in this case, the Cooke et al[15],[16], Bier[17], and Abramson[18] estimators all produce exactly the same estimates even though the estimators are different and have different performance properties (such as their biases). On the other hand, for those accident sequences in which overlapping is present, the estimates will generally be different. Also, the extent to which overlapping is present is a function of the operating time. The greater the operating time, the more likely that overlapping will be observed, and thus the greater the benefit in using an approximately unbiased estimator as opposed to a biased estimator such as $\bar{\lambda}$.

3 Results

We now consider the estimates obtained using the CCDP sum, Cooke-Goossens, Bier, and two Abramson estimators (Martz[27]). The estimates of the total industry-wide CDF per operating year are formed using the combined ASP data for 1990-1993. The details, as well as the ASP data used in the calculations, are presented in Martz[27].

Figure 1 gives the five estimates for each of the eight plant-classes. The major contributor to the risk of core damage is clearly seen to be PWR Class B and D plants. Overlapping precursors were observed in only seven accident sequences, all in BWR Class C. Thus, we see that the consideration and use of approximately unbiased CDF estimates makes relatively little difference overall and what little differences do exist are all confined to BWR Class C. The total CDF estimate for PWRs based on the combined 1990-1993 ASP data is calculated to be approximately $3.0E-4$ per operating year, while the total CDF estimate for BWRs is approximately $1.0E-4$. The industry-wide total CDF estimate based on the combined ASP data from 1990-1993 is thus approximately $4.0E-4$ per operating year.

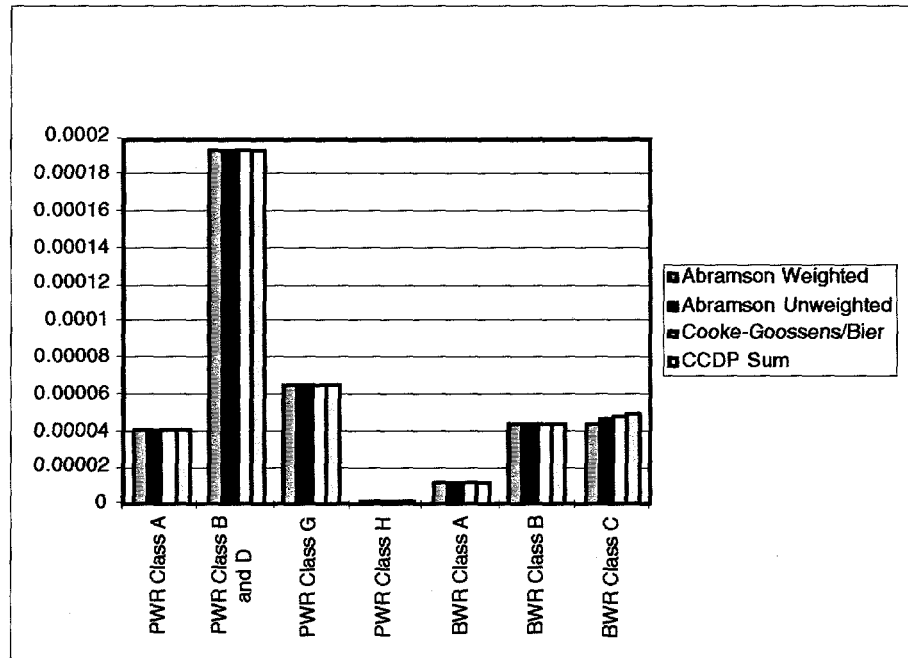


Figure 1. Total CDF Estimates by Plant-Class Using 1990-1993 ASP Data

In order to identify trends, in Figure 2 we have plotted the Abramson weighted, approximately unbiased average CDF estimates for PWRs and BWRs for the years 1990-1993. Note the decreasing trend in the industry-wide total CDF estimate from approximately $5.3E-4$ in 1990 to approximately $2.3E-4$ per operating year in 1993.

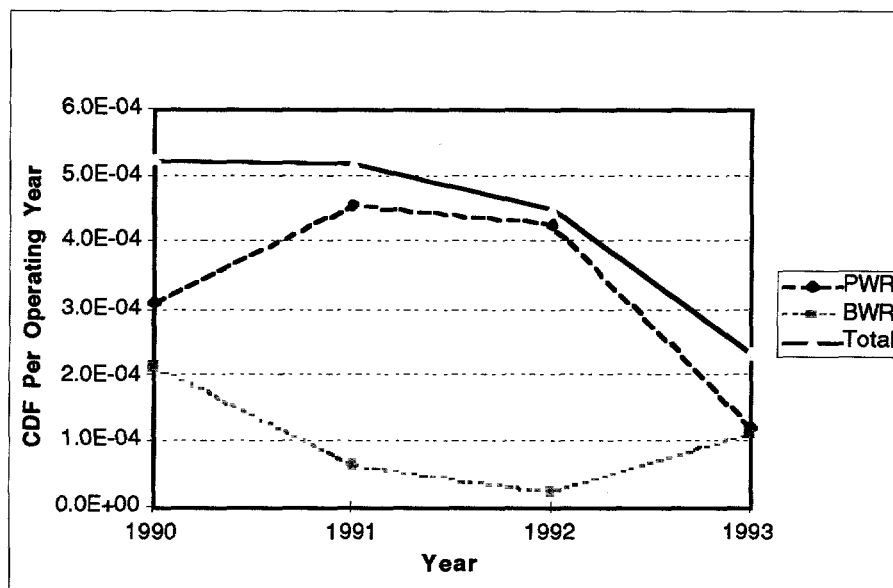


Figure 2. ASP-Produced Estimates of Total CDF from 1990-1993

4 Conclusions

Although we observed slightly smaller CDF estimates for BWR Class C plants in three of the four individual years when using the approximately unbiased estimator, a one-year calendar time period provides insufficient operating time for the approximately unbiased estimator to provide significantly different estimates than those provided by the biased estimators. All five estimators provided essentially the same CDF estimates both for the separate classes of PWRs and BWRs as well as industry-wide. The same is true for the combined four-year period. A greater expected reduction in bias, and thus correspondingly smaller CDF estimates on average, will occur for significantly longer operating times.

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