BNL-NUREG--36056

TI85 010230

RELIABILITY ALLOCATION IN NUCLEAR POWER PLANTS

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Abstract

The technical feasibility of allocating reliability and risk to reactor systems, subsystems, components, operations, and structures is investigated. A methodology is discussed which identifies top level risk indices as objective functions and plant-specific performance variables as decision variables. These are related by a risk model which includes cost as a top level risk index. A multiobjective optimization procedure is used to find non-inferior solutions in terms of the objective functions and the decision variables. The approach is illustrated for a boiling water reactor plant. The use of the methodology for both operating reactors and for advanced designs is briefly discussed.

1. Introduction

Quantitative performance criteria and guidelines related to the safety of nuclear power plants has been a subject of wide interest for many years. Early activities included the papers by Farmer [1] and by Starr [2]. More recent activities include efforts [3,4] in the U.S.A. to formulate safety goals for nuclear power plants as well as considerations of safety goals by other countries [5].

Before quantitative values for safety performance can be put forth or developed, one must decide on and select the performance variables or risk indices to be quantified. Typically, some measures of public health impact are adopted as risk indices. These include early fatalities due to radiation exposure and latent cancer fatalities. In addition, some measures of the engineering design, such as reactor core integrity or containment building integrity, have been considered as performance variables. In some studies, criteria or guidelines have been promulgated [6,7] at even more specific levels of detail of the engineering design. In Reference 6, criteria were developed for the decay heat removal function in light water reactors and in Reference 7 "target reliabilities" for safety systems in CANDU heavy water reactors were discussed.

Thus there are various options for selection of performance variables and/or risk indices. The selection process involves (or should involve) a consideration of how and by whom the criteria and guidelines are going to be used. For example, a plant designer may want to select systems or components according to some algorithm related to the unavailability of the systems or components. On the other hand, a decision maker who is considering alternative means of generating electricity may want to focus on public health risk indices.

Two questions arise with regard to the establishment of guidelines or criteria: 1) How are guidelines or criteria verified against actual plant performance? 2) If more than one performance variable or risk index is specified, are the guidelines or criteria collectively consistent? Clearly, for probabilistic criteria with very long mean times to failure, direct verification is not practical. For example, criteria for loss of core integrity are usually specified such that they could not be verified within the lifetime of a given plant. On the other hand, criteria for subsystem and component failures are likely to be in a range that makes verification more meaningful. The second question applies to situations in which the selected risk indices or performance variables are on equal footing (e.g., early fatalities and latent fatalities) and depend on subordinate performance variables in different ways and to situations in which one performance variable is clearly subordinate to another (e.g., core integrity and emergency coolant system reliability). In both situations, plant systems models (perhaps probabilistic risk assessment (PRA) models) could be used to develop the logical and physical connections between performance variables or risk indices.

The concept of cost effectiveness has been used in the consideration [3,5] of safety goals by various authors. The cost associated with various alternatives is an implicit or explicit element of most rational decision making processes involving risk.

This paper presents the results of a study on the technical feasibility of allocating reliability and risk in a self consistent manner to various levels of plant performance. Specifically, the study addressed the allocation of reliability and risk to reactor systems, subsystems, components, operations, and structures.

2. Technical Approach

Several approaches [8-12] to the allocation of reliability and risk were reviewed and considered. While some of these contain features of direct relevance to this study, it was, however, necessary to seek a broader framework to address the allocation problem.

The fundamental elements of the present approach are threefold: 1) a global set of measures of plant performance (top level risk indices or "objective functions") which would be subject to a preference assessment by a decision maker; 2) a model or prescription for relating the global set of measures of plant performance to the specific set of measures of plant performance (system and component unavailabilities, etc. or "decision variables"); 3) a method for deriving a finite, manageable set of self-consistent relations between the global and specific sets of measures.

In this study the first element was chosen to be the following global set: core damage frequency (C_d), expected acute (or early) fatalities (A), expected latent fatalities (L), and the cost (G) of achieving a particular set of values for the first three members of the global set. There were several reasons for choosing the global set at this level of plant performance. First, this set is not plant-specific. Second, this global set is likely to be understandable by the policy-level decision makers. Third, this global set is commensurate with the level of safety criteria that have been promulgated by various parties [1-5] who have an interest in nuclear power plant operation. We note, however, that our global set of measures are not regarded as prescribed safety criteria or safety goals. Rather, they are a set of attributes which can be studied, compared and traded-off by the decision makers. Furthermore, the overall methodology can also be formulated with other sets of global risk indices.

Central to our approach is the identification and use of the fourth member of the global set, cost. It was recognized early in this study that the cost of achieving a particular set of values for the first three members of the global set represented a necessary dimension from the point of view of those who must make practical, real world decisions and from the point of view of those who must obtain feasible engineering solutions from the methodology presented in this study.

The second fundamental element, namely, a model which relates the global set to the specific set was identified to be the probabilistic risk assessments (PRAs) which derive top level risk values from plant-specific failures and vulnerabilities. The PRA model is the natural choice for this element because of the abundance of existing PRAs for various nuclear power plants, the level of detail contained in PRAs in the areas of interest to this study, and the potential for enhancing the insights already gained from PRAs by performing the type of study presented in this paper.

The third element was identified to be a multiobjective optimization procedure [13,14] performed on the PRA model with the global set regarded as objective functions. The optimization approach was selected, in part, to reduce the multiplicity of possible solutions to the problem defined by the relation between the global and plant-specific set to a manageable handful and, in part, to obtain the best and most rationally acceptable subset from the multiplicity of solutions. Therefore, the concept of selection of noninferior solutions was introduced; with this concept, solutions which did not yield a relatively favorable value for at least one of the four members of the global set were rejected from further consideration.

3. Application

The overall methodology has been demonstrated [15] with a nontrivial model. While the model does not represent a complete, particular, realistic power plant situation, it does contain many of the essential features that would be required of an analysis of such a situation. Thus the analysis was conducted for the purpose of technical feasibility and therefore particular features were purposely retained or built into the model in order to test and examine the successes and limitations of the overall methodology. The model is based on a full scope PRA for a BWR/4 MARK-II nuclear power plant. The significant classes of accident initiators and sequences are represented in the model. Dominant cutsets are retained and system dependences are included. In addition, containment performance variables and a seismic accident sequence are studied.

The cost models for the various systems and components are idealized parametric functions, but which nevertheless exhibit the correct intuitive trends for such models. Furthermore, sensitivity studies were performed on the parametric and functional forms of the cost functions in order to gain familiarity with the implied trends for the global set.

The results of the model analysis are displayed in terms of the set of noninferior solutions to the optimization problem. Thus, for each noninferior solution a set of global values (risk indices and cost) and a corresponding set of plant-specific values (system unavailabilities, etc.) are obtained and displayed. The set of noninferior solutions represents a hypersurface in the four-dimensional space (C_d, A, L, G). The intersection of this surface with a hyperplane corresponding to a constant value of C_d [i.e., (C_d = const, A, L, G)] is a curve in the three dimensional space (A, L, G). The "projection" of this curve on the (A, G) plane gives a trace which is depicted in Figure 1 for several values of C_d.

Figure 1 shows the general trends that lower early fatalities and/or core damage frequency occurs at higher costs. The existence of extreme points for a given C_d projection implies that it is not possible to vary the cost outside of the indicated range and simultaneously vary the early fatalities in a corresponding manner without also varying the core damage frequency.

Each point on each curve in Fig. 1 corresponds to a particular set of values for the plant-specific performance variables. In this example, these include the unavailabilities of the reactor protection systems, emergency coolant systems, DC power system, and several other safety and safety support systems that were modeled in the PRA [16]. The sensitivity of the resulting values for these performance variables can be studied as a function of the variations in the top level variables in order to gain familiarity with the interplay between these variables for the purpose of design alternative selection.

4. Discussion

At this point the technical analysis of reliability allocation is complete. It would then be the choice of the decision maker to choose among the noninferior solutions by performing a value tradeoff or preference assessment. While a performance of a preference assessment is not a trivial task, the more that is known about the decision problem, the easier it will be to understand and articulate preferences.

Finally, we comment on the application of this methodology to various types of reactors. For operating and constructed plants, a reallocation of reliability and risk would: 1) be done on a plant-by-plant basis; and 2) be limited by cost feasibility since there may be large capital and operating costs associated with a reallocation (retrofit). Alternatively, the methods may be useful in connection with seeking exemptions from existing requirements. One potentially fruitful area for reallocation concepts for operating plants is plant operational practices. For standard plants and for advanced designs, the methodology can be used and extended to optimize the safety and economics of such future plant designs.

Acknowledgments

This work was performed under the auspices of the U.S. Nuclear Regulatory Commission. Views expressed in this paper do not necessarily represent official NRC policy. We are grateful to members of a steering group for this project, who provided guidance and constructive criticism. They are: G. W. Cunningham, B. J. Garrick, E. P. Gyftopoulos, R. A. Howard, and F. S. Nowlan. In addition, we thank many of our colleagues at Brookhaven National Laboratory and at the U.S. Nuclear Regulatory Commission for their contributions to this project. In particular, we are indebted to A. El-Bassioni (NRC) for his support, comments, and encouragement.

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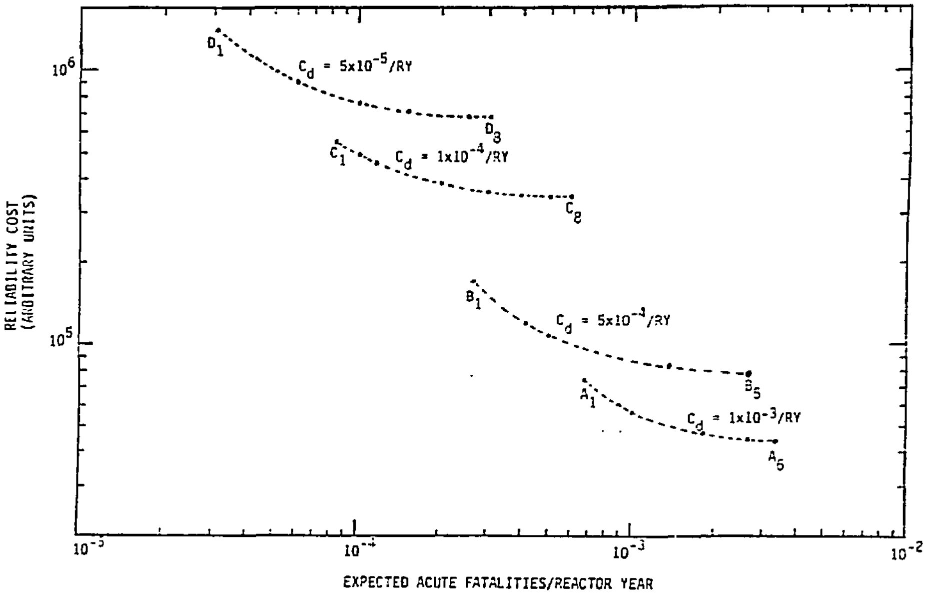

Figure 1 A Two-Dimensional Display of Noninferior Outcomes at Several Core Damage Frequencies.