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# DESIGN OPTIMIZATION OF A PROTOTYPE LARGE BREEDER REACTOR SAFETY SYSTEM

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ABSTRACT

This paper presents a procedure that can be used in the conceptualization of, evaluation of, and selection among several conceptual liquid metal fast breeder reactor (LMFBR) designs. The method can be effectively used to: (a) allocate optimal component redundancy, (b) evaluate design trade-offs, and (c) help in design finalization. The procedure is applied to three diverse design options for a shutdown heat removal system. The selected configuration is analyzed for potential common cause failures.

## 1. INTRODUCTION

In the nuclear industry as a whole, and in the LMFBR project in particular, each hardware component is being fabricated in essentially the best manner now known. Within the technology available, the reliability of individual components cannot now be significantly improved. As further research indicates better ways to design components, designers will incorporate those indicated changes. However, more reliable components cannot now be specified for use in proposed advanced reactor systems since the technology for producing such components is not available.

In view of the foregoing, the only means to achieve design improvement in plant safety and productivity is by intelligent choice of both the types of systems and subsystems to be used in the designs and configurations of these systems. In order to make such intelligent choices, those responsible for the decisions must have some way of assessing what functional reliability is realistically achievable from the various systems they must choose among. Moreover, if several systems can be made to achieve equal levels of availability through (a) use of different numbers and sizes of components in series and/or parallel (i.e. redundancy allocation) or (b) use of alternate means to accomplish a given purpose (i.e. diversity choices), it is necessary to determine which system can be made to do so at the least cost. Clearly, the ability to make such determinations would be most valuable if applied during the earliest possible stage of the design process. If such determinations could be made, and made well, for the designs of prototypical nuclear power plants, the design effort would be substantially reduced on subsequent plants of that same type.

There is no intention to imply that design decisions are not now being made intelligently. However, given a task to be performed by some system, there are a number of types of systems that will perform that task. There also are a large number of possible, workable, reliable configurations for each type. Granted, common sense and good engineering judgement can be used to eliminate a great many candidates from the field, but there will still remain a large number of possibilities to choose from.

The design decision making process can be improved by new applications of probabilistic methods and system optimization techniques [1]. The methods described in Reference 1 require basic system designs as starting points. A basic design is meant to describe a system that is devoid of redundant and diverse components, loops, and modules. Unavailability logic models are to be constructed from the basic designs. Mathematical expressions, containing integer variables indicating diversity and redundancy choices, are then derived from the logic models. Cost functions are constructed in terms of the integer variables.

These mathematical expressions for cost and unavailability can be used to generate functions which provide estimates of the best cost obtainable for a given level of system availability. Reference 1 contains discussions of several possible uses of these functions as well as extensions, wherein it was assumed that some numerical level of acceptable societal risk for plant operation has been defined. The cost functions were used to develop a method for performing cost and availability trade-offs among various safety systems. Reference 2 contains extensions to the methodology and suggests additional applications.

This paper presents a technique to the above method to approximate the minimum cost unavailability relationship. The technique is then applied to the selection of the "best" prototype large breeder reactor (PLBR) shutdown heat removal system (SHRS).

Section 2 presents a summary of the technique which is illustrated via a simplified example in Section 3. The results of the PLBR SHRS application are presented in Section 4.

## 2. SUMMARY OF SOLUTION TECHNIQUE

The general method was briefly outlined in the Introduction. The solution technique steps used in the PLBR SHRS study are summarized here and illustrated in the next section. The steps are:

(1) The basic system design is generated, and assumptions are made. The design is devoid of all redundancies and diversities.

(2) Logic models are constructed for the basic system unavailability.

(3) Cost and failure rate data are collected for each basic event.

(4) Components are identified for which redundancy and/or diversity will be evaluated. Each is represented by an optimization variable.

(5) Mathematical expressions for cost and unavailability are constructed (components identified in Step 3 above, enter as integer variables).

(6) Constraints for the optimization variables and other considerations are formulated.

(7) An approximation to the minimum cost/unavailability functional relationship is determined by identifying the optimization variables that reduce unavailability the greatest with minimum increase in cost.

(8) The adequacy of this relationship is checked using techniques to be discussed in Section 3.

(9) The optimal configuration is selected from candidate configurations using engineering judgement, cost effectiveness considerations, etc.

A common cause failure analysis can then be performed on the selected design.

## 3. ILLUSTRATIVE EXAMPLE

The steps of the solution technique summarized in the previous section will now be illustrated using the basic LMFBR system of Fig. 1 which contains a simplified SHRS.

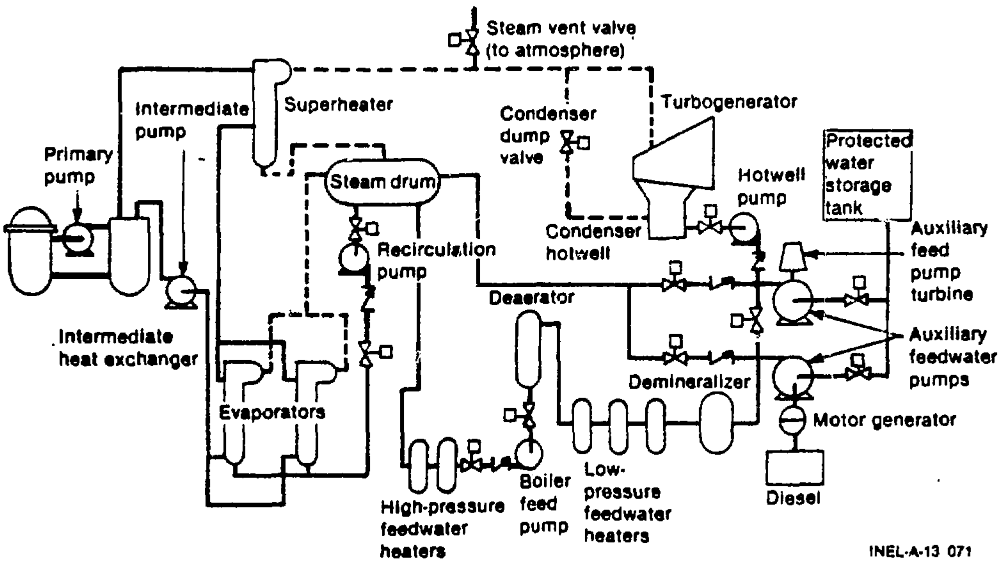


Fig. 1 Basic LMFBR system.

The SHRS consisted of two subsystems: (a) a condenser dump valve in conjunction with the normal return path to the steam drum; and (b) a steam vent valve, a protected water storage tank, and a line to the steam drum through either a steam or a motor generator driven pump. (Assume that pump diversity here was a requirement imposed on the design by regulation.) For simplicity, the SHRS was the only safety system included.

Several additional simplifying assumptions were made in the development of the logic models for this example. These assumptions and the logic models are contained in Reference 1.

Cost and failure rate data were gathered and tabulated. These data are not presented here due to space limitations.

Eight optimization variables are identified for this problem. From the logic model for SHRS unavailability, Eq. (1) was obtained of the following form:

$$\bar{A} = \Big[\bar{A}_1 + U_1 S_1^{(RP - 1)} + U_2 * P$$

$$+ U_2 S_2^{(P - 1)} + U_3 * I + U_3 S_3^{(I - 1)}\Big]^L \qquad (1)$$

$$+ (U_4 * DV + U_5 S_5^{(FP - 1)} + U_6 S_6^{(HP - 1)} + \bar{A}_2)$$

$$(\bar{A}_3 + U_7 * VV) + \bar{A}_3 U_7 * VV$$

where

$\bar{A}_i$ = unavailability of fixed portions of the plant

$U_i$ = unavailability of active components

$S_i$ = unavailability of components on standby

L = number of loops

P = number of primary sodium pumps per loop

I = number of intermediate sodium pumps per loop

RP = number of recirculation pump modules per loop

VV = number of steam vent values

DV = number of condenser dump values

FP = number of boiler feed pump modules

HP = number of hotwell pump modules.

The cost expression has the following form:

$$COST = C_1 + C_2 * VV + C_3 * DV + C_4 * FP \qquad (2)$$

$$+ C_5 * HP + L * (C_6 * P + C_1 * RP + C_7 * I + C_8)$$

where the $C_i$ are unit costs of the appropriate components. $C_1$ and $C_8$ are costs of the fixed portions of the plant.

All eight optimization variables are integer variables. The following constraints were considered:

$$L = 3,4 \tag{3}$$

$$P,\ I,\ RP,\ VV,\ DV,\ FP,\ HP = 1,\ 2,\ 3.$$

This completes the first six steps.

To begin Step 7, each of the optimization variables is set equal to its minimum value. For this sample problem we have

$$RP = 1,\ VV = 1,\ DV = 1,\ FP = 1,\ HP = 1,\ P = 1,\ I = 1, \text{ and } L = 3.$$

Putting these values into Eq. (1) and (2), we get $\bar{A} = 1.129 \times 10^{-6}$, and COST = \$82.644 x $10^6$. These values can be plotted in the cost unavailability plane as shown by the point O in Fig. 2.

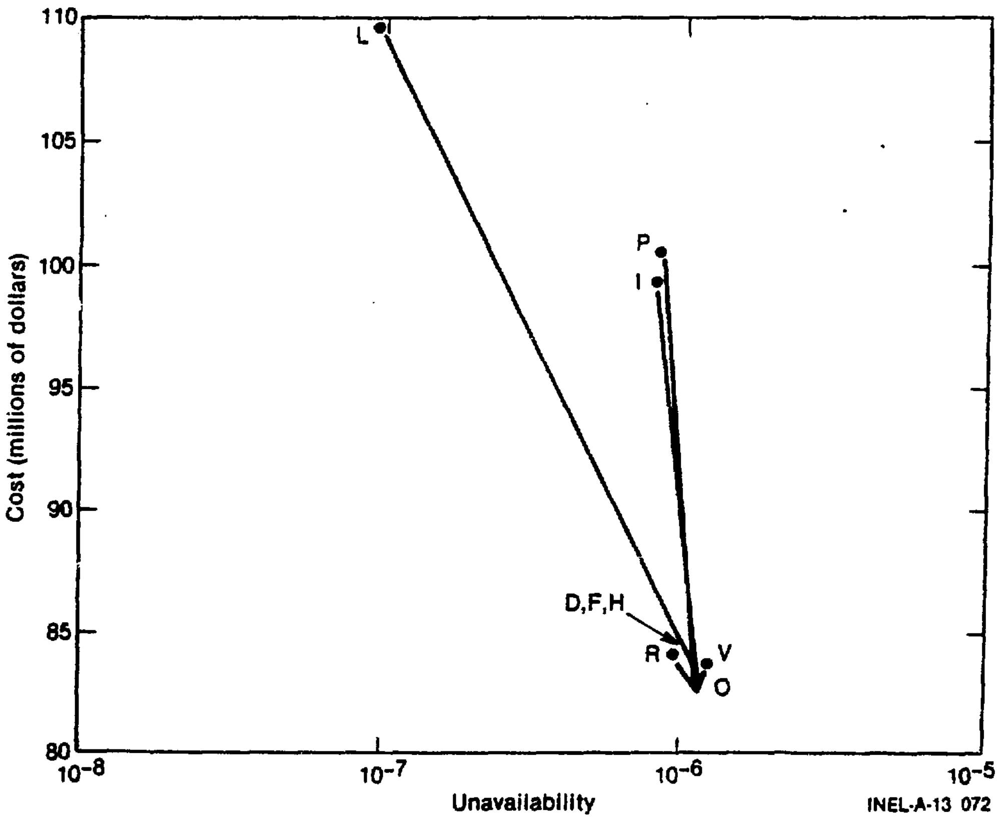


Fig. 2 First iteration of the optimization for the sample problem.

Next we increment one of the optimization variables by one and repeat the process. For example, selecting the recirculation pump we get

RP = 2, VV = 1, DV = 1, FP = 1, HP = 1, P = 1, I = 1, and L = 3.

Substituting these values into Eq. (1) and (2), we obtain $\bar{A} = 0.9491 \times 10^{-6}$, and COST = \$84.144 x $10^6$. The point corresponding to these values is labeled R in Fig. 2.

The next step is to set RP = 1 and VV = 2 and keep the remaining variables at their present values, i.e.,

RP = 1, VV = 2, DV = 1, FP = 1, HP = 1, P = 1, I = 1, and L = 3.

Putting these values into the cost and unavailability expressions we get $\bar{A} = 1.1451 \times 10^{-6}$, and COST = \$82.668 x $10^6$. This point is indicated by V in Fig. 2.

The process is repeated until all of the optimization variables have been done. The results of this iteration are summarized in Table I and plotted in Fig. 2.

TABLE I

Results of First Iteration

| Configuration | | | | | | | | | | Point |
|---|---|---|---|---|---|---|---|---|---|---|
| RP | VV | DV | FP | HP | P | I | L | $\bar{A}$ ($10^{-6}$) | Cost (\$$10^6$) | in Figure 2 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 1.129 | 82.644 | O |
| 2 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 0.9491 | 84.144 | R |
| 1 | 2 | 1 | 1 | 1 | 1 | 1 | 3 | 1.1451 | 82.668 | V |
| 1 | 1 | 2 | 1 | 1 | 1 | 1 | 3 | 1.1289 | 82.664 | D |
| 1 | 1 | 1 | 2 | 1 | 1 | 1 | 3 | 1.1001 | 83.144 | F |
| 1 | 1 | 1 | 1 | 2 | 1 | 1 | 3 | 1.1001 | 83.144 | H |
| 1 | 1 | 1 | 1 | 1 | 2 | 1 | 3 | 0.8793 | 100.644 | P |
| 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 0.8793 | 99.744 | I |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 4 | 0.0874 | 109.844 | L |

The candidate variable to receive the redundancy for this iteration is the one that increases the cost the least while decreasing the unavailability the most. Geometrically, it is the variable that is identified with the line segment that has the smallest negative slope in Fig. 2. That is the line segment between R and O which corresponds to the recirculation pump. This configuration becomes the initial configuration for the next iteration.

The process is repeated until we reach our design goal or we wish to stop. For the sample problem the results of six iterations are shown by the line in Fig. 3. This line is an approximation to the minimum cost unavailability relationship.

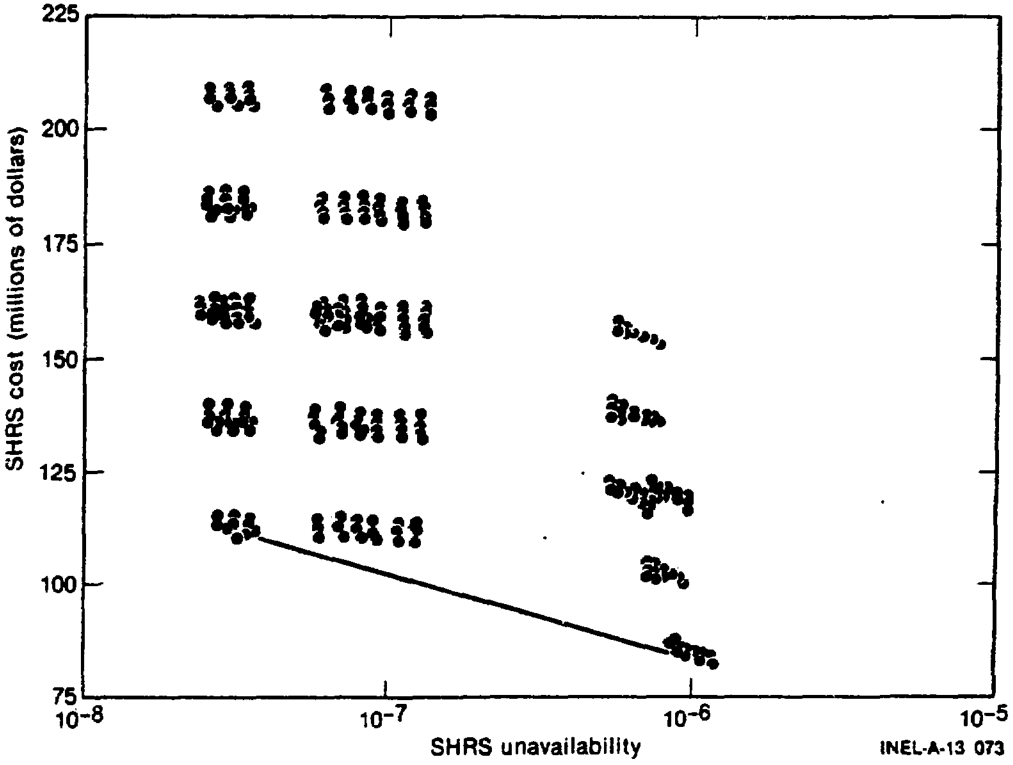


Fig. 3 Minimum cost/unavailability approximation.

There is no guarantee that this is the actual minimum cost unavailability relationship. Thus, ways of checking this minimality are needed. One way of doing this is to compare the curve with a Monte Carlo plot of cost versus unavailability of randomly selected configurations. Here, an integer value for each optimization variable is randomly selected from its set of feasible values. This selection for all optimization variables represents a configuration. These values are substituted into Eq. (1) and (2) to obtain the cost and the unavailability of the configuration. These data can then be plotted. This procedure can be repeated a given number of times, say 5000 or 10 000 times, and the resulting plot compared with the curve developed above.

For our example we see from Fig. 3 that the cost unavailability relationship is not minimal since configurations exist that have lower cost for a given unavailability. However, the configurations that generate the minimum cost unavailability relationship can be used as starting points and the region around those points explored using INTEROP [3] to find configurations with lower cost for the same unavailability.

Once the minimum cost unavailability relationship has been determined and minimality verified, the information can be used to select the configuration meeting the safety, economic, and engineering goals and constraints.

## 4. APPLICATION

The procedure illustrated in Section 3 was used to compare three diverse design options for the PLBR SHRS. The purpose of this application was not to select the best design option for consideration but to demonstrate the methodology which had been developed. Thus the results in this section should not be construed as an endorsement of a given design or vendor.

The design options correspond roughly to those submitted by the three vendors. We made certain assumptions for the designs without consultation with the vendors. Loss of offsite power was used as an initiating event. We also made the assumptions of having a dedicated diesel generator for each heat transport loop and not allowing credit for natural circulation in the main heat transport system.

Logic models were constructed for each design option using information from the Phase I and Phase II design reports. Cost data and failure rate data were gathered for the components and their corresponding failure modes. Obtaining these data, particularly the cost data, was the hardest task in the study.

From the logic models, mathematical expressions were formulated for the SHRS unavailability and cost. For each option the procedure illustrated in Section 3 was used to generate the minimim cost unavailability relationship. These relationships were checked for optimality by comparing them with Monte Carlo plots and also using INTEROP to assess the minimality of each. These relationships are shown in Fig. 4.

From Fig. 4 it is obvious that Option A is the "best." Also a goal of $\bar{A} = 10^{-6}$ was used. The configuration selected was the one with no redundancies since this meets the goal. Since common cause failures are not included in the optimization procedure, this configuration was analyzed for potential common cause failures using the generic cause approach and was implemented in COMCAN II [4]. Due to the early stage of the design no significant common cause failures were detected.

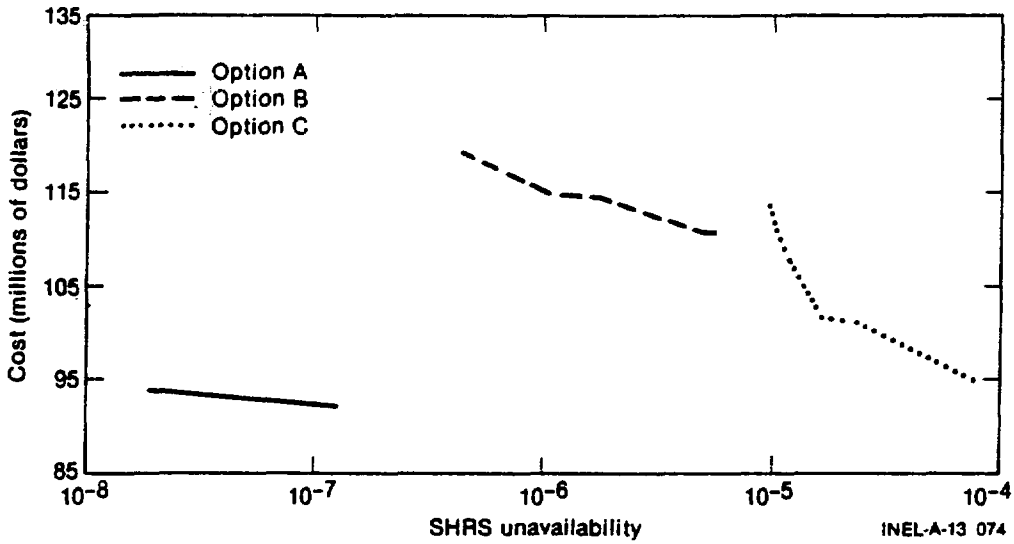


Fig. 4 PLBR SHRS minimum cost/unavailability approximations.

In this study, the assumptions, were found to be the strongest contributor in determining the optimal configuration. If the assumptions were changed, sometimes other design options yielded the optimal configuration. The cost data and failure rate data also contributed to determining the optimal configuration. The optimal configuration could also change if the unavailability goal was changed.

## 5. SUMMARY

A design optimization procedure has been presented which can be used to determine optimal component redundancy allocation, assess the sensitivity of assumptions, assist in design trade-off studies, and help in design selection and finalization while considering cost and safety considerations. The procedure discussed is a specialization of a more general method that can be used to allocate system cost and reliability goals. The procedure has been effectively shown to be feasible and workable.

## 6. ACKNOWLEDGMENTS

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