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ISSUES AND APPROACHES IN RISK-BASED AGING ANALYSES OF PASSIVE COMPONENTS[1]

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INTRODUCTION

In previous NRC-sponsored work a general methodology was developed to quantify the risk contributions from aging components at nuclear plants (Vesely, et al. 1990; Vesely, 1992). The methodology allowed Probabilistic Risk Analyses (PRAs) to be modified to incorporate the age-dependent component failure rates and also aging maintenance models to evaluate and prioritize the aging contributions from active components using the linear aging failure rate model and empirical components aging rates. In the present paper, this methodology is extended to passive components (for example, the pipes, heat exchangers, and the vessel).

The analyses of passive components bring in issues different from active components. Here, we specifically focus on three aspects that need to be addressed in risk-based aging prioritization of passive components:

- Aging effects on passive components based on qualitative, semi-quantitative engineering information on degrading passive components,
- Alternate approaches to include passive components in PRAs, and
- Prioritization of passive contributions according to their aging contribution.

We present a method and approach for prioritizing the risk effects of aging of passive components.

Aging effects are defined as changes in failure rates of the component. Although there are general approaches for modelling of age-dependent failure rates, there is a lack of actual age-dependent failure rates for passive components. No data bases generally are available, nor are there standard techniques to estimate plant specific, age-dependent failure rates from histories of component failures. Various techniques for estimating age-dependent passive component failure rates have been identified; however, there are no consensus procedures comparable to those for active components in PRA data analyses. Since there is a gap between engineering and risk evaluations, in present risk evaluations failure rates used in PRAs are based largely on expert judgment, which has large associated uncertainties.

However, there is an extensive engineering information on the aging of passive components. This information cannot be used directly to determine the associated reliability and risk implications of aging because of the

[1]Work performed under the auspices of the US Nuclear Regulatory Commission.

qualitative or semi-quantitative nature of the information. Also, much of the information involves mechanistic relations which do not directly involve reliability or risk implications. For the most part, the engineering evaluations of the aging effects are descriptive, discussing the failure mechanisms, changes in physical properties, and failure modes which have been observed for aged components or structures. The engineering evaluations do not explicitly determine the reliability characteristics of passive components, such as failure rates or changes in failure rates. This deterministic and mechanistic engineering information needs to be translated into estimates of age-dependent failure rates for passive components, which would not only facilitate risk evaluations of aging of passive components, but also could be used to identify the important root causes of aging.

A process is described in this paper for translating qualitative and semi-quantitative engineering information into reliability and risk implications. The process is a general one and can be applied to any information not only to aging. Fuzzy Set Theory is used to formally handle the information and determine the reliability implications. The process is demonstrated with passive components to evaluate the reliability implications of aging data assembled in NRC's Nuclear Plant Aging Research (NPAR) Program. The demonstration shows the age-dependent reliability behavior of passive components due to particular aging contributors.

A general approach to include aging passive components in PRA analysis also is described. Three ways to incorporate passive components into PRAs are described. The straightforward way, which is difficult to implement, is to add the component to the model and treat it with standard PRA approaches. In some cases, new initiating events may have to be added and new sequences of events considered. A second way, which is much simpler to implement, is to identify active components which are included in the current PRA analysis to serve as surrogates for the corresponding passive components. The failure probabilities of these active components are increased to account for the contributions from the corresponding passive components. The third way involves a system-level approach which calculates the risk contributions for a particular component as a product of the risk significance of the system and the failure probability of the component. This approach can be implemented relatively easily but (1) it does not directly account for interactions of multiple aging components; (2) it is over-conservative because of its main assumption that the failure of a passive component in a system fails this system; (3) it calculates approximately the same risk significances for the components within the system, while they can be considerably different.

Finally, an approach to prioritization of passive components is described. Components are prioritized according to their aging risk contributions, which are calculated as the products of changes in failure probabilities due to aging and the risk importances of the components. This approach has the following specific features which differentiate it from traditionally used techniques:

- changes in the failure probabilities are used, instead of the base-line failure probabilities;
- risk importances are calculated with the unavailabilities of the aged component to account for possible changes in importances because of aging;
- total aging risk of passive components is estimated;
- a list of top contributors covering the major part of the total aging risk in considered (the list covers single and interaction aging terms).

AGING EFFECTS ON PASSIVE COMPONENTS

Aging effects on passive components usually are couched in engineering language, including descriptions of stressors, failure mechanisms, and possible failure sites. For example, for a pipe, it can be specified that some weld leaked and that the probable cause of the failure was the intergranular stress corrosion. This descriptive information is very valuable but can not be directly used in PRAs. Since failures of passive components are rare, this type of descriptive information must be converted into reliability parameters to analyze reliability implications of aging effects. Further, we discuss an approach which can be used to translate qualitative and descriptive information into reliability parameters.

One basic reliability parameter describing the reliability of a component is the failure rate; other reliability parameters then can be calculated knowing the failure rate. We defined the aging effect on a passive component as an increase in its failure rate. The failure rate of a passive component is a function of the piecepart and the material, the age of the component or piecepart, the environment, including any abnormal conditions, aging mechanisms, or stressors, and the maintenance/inspection strategies.

TRANSLATING ENGINEERING INFORMATION INTO RELIABILITY AND RISK IMPLICATIONS WITH FUZZY SET THEORY

In this section, we develop a process to transform engineering information on aging into implications on component reliabilities. These reliability implications are determined as a function of the component's age, and can be used in aging management programs. The reliability implications also can be translated to aging rate, and failure rate implications to input into a Probabilistic Risk Analysis (PRA) to determine their effects on risk, that, in turn, can focus aging management and engineering applications on the most risk-important areas.

To develop this interface, an approach is needed to transform engineering information into data useable in PRAs and reliability models. Thus, the engineering information needs first to be transformed into qualitative implications on component reliability which then are translated into semi-quantitative information for the PRAs. Semi-quantitative information means characterizing the aging effects on reliability in terms of categories of impacts, such as "small," "medium," and "large."

The Role of Semi-Quantitative Approaches

Generally, information on passive components is not in the form of their failure times which can be directly translated into estimated failure rates and aging rates. Instead, relations are generally identified among aging effects and the conditions and stressors causing those effects. Often, these relations are descriptive, or qualitative; sometimes, the sizes of the aging effects are categorized. If the engineering relations are quantitative, then they generally do not involve implications on reliabilities or failure rates but instead, involve mechanistic relationships, such as those describing the characteristics of materials as a function of age.

Often, the engineering information on the aging of passive component is not expressed in terms of the implications on component reliability, even qualitatively. Hence, the first step in translating engineering information to semi-quantitative reliability implications is to transform it into qualitative descriptions of the implications of aging on a component's reliability. These descriptions involve discussions of what stressors and environments most affect the reliability of a component, at what general age reliability is affected, and what maintenance practices are most instrumental in controlling aging. They also require descriptions of the components or pieceparts whose reliabilities are most affected by aging in given environments. Discussions can be included of the general behavior of the reliability effects, such as whether the aging effects are gradual or cause rapid deterioration after some initial stable period. We note that these reliability implications are qualitative, involving general descriptions and behaviors.

The next step is to translate the qualitative information into semi-quantitative information. To do this, the reliability impact of an aging effect needs to be characterized according to its general size, such as "small," "medium," and "large" which classifies the relative size of an impact. The categories differentiate the aging effects on performance and reliability of the component. For more detailed information, the size of the aging effect on a given component or piecepart can be categorized for different stressors and for different operating conditions.

Fuzzy Set Theory as a Formal Technique for Handling Semi-Quantitative Information

Fuzzy Set Theory is a formal technique for using semi-quantitative information, such as categories of impacts, in models and calculations (Dubois, et al. 1981; Pedrycz, 1993; Zimmerman, 1991). In the methodology, each category is converted into possible values which can be in that category. These possible values are input to standard reliability models or PRA models, and the resulting increase in unavailability or increases then are translated back into impact categories. Thus, the possible values are used only as a mechanism for translating the aging effect categories into unavailability-impact categories or risk-impact categories.

No probabilities are assigned to the values in a category to distinguish which ones are more likely. Also, there do not have to be clear boundaries between categories; there can be (and often are) significant overlaps in the categories. Thus, the category definitions do not have to be precise but can be fuzzy (one of the reasons for the name "Fuzzy Set Theory"). Moreover, since the results also in the form of categories, they are not sensitive to the precise definitions of the categories.

Using Fuzzy Set Theory, semi-quantitative categorical aging information can be input to any reliability or risk model, such as the standard models used in a PRA. The results then are transformed to unavailability or risk value categories using the rules of Fuzzy Set Theory. When the input information is precise, then each category becomes one number and the Fuzzy Set results reduce to the usual numerical results calculated in a PRA. Thus, fuzzy set theory generalizes the calculations carried out in a PRA when specific data on failure rates are not available, but instead, only semi-quantitative, categorized data. However, even though the unavailability and risk impacts are fuzzy, in terms of categories, they are meaningful because they are based on engineering information of the size of the aging effects and their causes. The methodology for using fuzzy set theory in reliability calculations and in PRAs has been described in a variety of papers (Singer, 1990; Misra, et al. 1990, Sharma, et al. 1993).

Demonstration of the Process. This section demonstrates the application of Fuzzy Set Theory to translate engineering information on aging into data for reliability evaluations or PRAs. Specifically, for a given component or set of components, the steps in translating the information:

1. Assemble the engineering information on the component.

2. Translate it to qualitative implications on the performance and reliability of the component.

3. Translate the qualitative implications into semi-quantitative information by categorizing the general sizes of the impacts of the aging effects.

4. Define the possible values of impacts in each category which describe the possible aging impacts.

5. Use Fuzzy Set Theory to determine the resulting unavailability and risk impacts of the aging effects.

These steps can be applied not only to aging information, but to any engineering information to obtain the associated reliability and risk implications. These steps are demonstrated here for cables where such engineering information is translated to age-dependent reliability implications that provide important information in themselves, and also can be used in risk analysis (PRAs). This information is valuable because cables play an important role in assessing risk in a nuclear power plant and aging can cause multiple cables to degrade.

Assemble Engineering Aging Information on Component. The first step is to identify aging information on cables which can have reliability implications. As an example of the available information, use NUREG/CR-4731, Vol. 2. More information would be assembled in a broader application, but the summary in NUREG/CR-4731 will serve here to illustrate the basic steps of the process. Table 1 is a reproduction of Table 13.1 in NUREG/CR-4731, and summarizes the engineering information on aging of metallic components in cable systems.

NUREG/CR-4731 also describes the major stressors which can affect the longevity and performance of cables. This information can be used to increase the aging rates for particular high stressors which can exist in harsh environments. NUREG/CR-4731 furthermore describes particular degradation sites on cable-system components, and so can be used to increase the aging rates for those particular sites of high stress. However, we shall not use this additional information, but only the basic aging information in Table 1.

Translation of Aging Information to Implications on Reliability and Performance. Focusing on Table 1, the column labeled "Aging Concern" is in assessment of whether aging can affect cable performance and is based on the engineering assessment which has been carried out in NUREG/CR-4731. In Table 1, the column labeled "Level" denotes the assessed level or degree of aging which can be expected to occur in the metallic component based on the engineering assessment carried out in NUREG/CR-4731. The rankings in this column are a qualitative assessment of the sizes of the aging effects. Thus, Table 1 already contains the qualitative implications on reliability and performance which are summarized under the column "Aging Concern." The more detailed discussions in NUREG/CR-4731 give the bases for these assessments. As indicated, these discussions also describe the stressors and conditions which can further aggravate aging.

Define the General Range of Possible Values in Each Category. The next step is to translate each category into a range of possible values, which do not have to be precisely defined, but can be fuzzy. Furthermore, no probability distribution is assigned to identify most likely values. The identification of possible values for each category does not need to be accurate since their range is propagated in the reliability model or PRA model, and the results are translated back to categories.

For the aging effects in Table 1, we need to define possible values for the categories "Small," "Moderate," and "Large," the values for each category will represent the possible values the aging effects can be when they are described by the category.

The aging effects described in NUREG/CR-4731 are relative effects on reliability and, equivalently, can be interpreted as relative effects on failure probability. Because failure probability is proportional to the failure rate to first order, the relative effect on the failure probability also is the same as the relative effect on the component's failure rate. For each of the three categories, we shall describe the following possible relative effects:

TABLE 1. MATERIALS FOR METALLIC COMPONENTS IN CABLE SYSTEMS[a]

Material	Use	Aging Concern	Level	Degradation Mechanism
Stranded copper (bare or tinned)	Cable conductors	Yes	Moderate	Corrosion
Solid copper (bare or tinned)	Cable conductors	Yes	Small	Corrosion
Nickel-plated copper	Cable and connector conductors, terminals	Yes	Moderate	Corrosion, wear
Silver-plated copper	Connector pins	Yes	Moderate	Corrosion, wear
Nickel-rhodium-plated copper	Connector pins	Yes	Moderate	Corrosion, wear
Gold-plated copper	Connector pins	Yes	Small	Wear, gold-solder interaction
Copper connector (bare or tinned)	Splices and terminals	Yes	Small	Corrosion, splice loosening with age
Braided copper (bare or tinned)	Shield	Yes	Moderate	Corrosion
Tinned copper tape	Shield	Yes	Small	Corrosion
Aluminum foil	Shield	Yes	Moderate	Corrosion
Metallized Mylar Tape	Shield	Yes	High	Corrosion
Stainless steel	Cable sheath, (mineral insulated cable), conductor, connector parts	No	–	–
Inconel	Cable jacket, conductor	No	–	–
Zirconium	Cable conductors	No	–	–
Chromel	Cable conductors, connector pins	No	–	–
Alumel	Cable conductors, connector pins	No	–	–

[a]The aging concerns are based upon observations reported in LERs and NPRDs and upon field observations. The relative levels are subjective judgments, based on experience in the general cable industry and considerations of exposed surface area-to-volume ratios.

Category	Description of the Possible Relative Aging Effects
Small	Yearly increase in the failure rate is small compared to the basic failure rate
Large	Yearly increase in the failure rate is comparable to or larger than the basic failure rate
Moderate	Yearly increase in the failure rate is between "Small" and "Large" behaviors

The relative aging effects, as defined above, are still fuzzy but they will be adequate in obtaining the associated unavailability and risk impact which also will be fuzzy but will give useful information. Because the aging effects are defined relatively, the resulting unavailability and risk impacts also will be relative. Thus, all the evaluations will be relative.

The aging effects as described in the previous table now can be translated to the corresponding possible relative increase values:

Category	Approximate Relative Increases in Failure Rates
Small	Relative increases which are small, e.g. increases which are about 10% or less.
Large	Relative increases which are significant, e.g. increases which are about 100% or larger.
Moderate	Relative increases between small and large, i.e. between approximately 10% and 100%.

In the above table, the precise values are not important, only the general range is. Characterizing the "Small" category as consisting of relative increases less than approximately 100% also would be adequate. For the "Large" category, relative increases of 30%, or 50%, or other similar values, also are possible as are values much higher. Since the "Moderate" category consists of values between "Small" and "Large", the relative values can fall between approximately 10% and roughly 100%.

The above descriptions illustrate the types of fuzzy descriptions that only are needed in characterizing the possible range of values associated with a given category. More information or more detailed categorizations of aging effects would allow less fuzzy ranges of values to be defined for the categories. The description of the range of values for a category is based on the knowledge available, and more detailed.

Use Fuzzy Set Approaches to Determine the Unavailability and Risk Impacts. Having characterized the possible values in each aging category, Fuzzy Set Theory then can be used to determine the unavailability and risk impacts. We do not give details of the fuzzy set calculations; rather we focus on illustrations and interpretations of the results. Figure 1 illustrates the increase in relative unavailability versus age which results when the metallic component of the cable has a small aging rate. From Table 1, solid copper cable connectors and gold-plated copper connector pins are those cable components having small aging effects. For these types of cables, Figure 1 would apply.

The first point we note in Figure 1 is that the increases in unavailability are in the form of categories, similar to the input aging rates. Such categories also would be obtained if a risk model (a PRA) were used to calculate the associated relative increase in core-damage frequency caused by cable aging. Here, we used the unavailability model in NUREG/CR-5510 (see, Vesely, et al. 1990) which assumes a linear aging rate. Instead of using precise values for the aging rates, we are using categories of aging effects determined from engineering information.

The unavailability increase categories in Figure 2 are defined as follows:

Unavailability Increase Category	Description
Small	Unavailability increases comparable to or less than the original unavailability.
Moderate	Unavailability increases larger than the original unavailability, but generally less than an order of magnitude.
Large	Unavailability increases about an order of magnitude, but generally less than two orders of magnitude.
Very Large	Unavailability increases greater than or equal to about two orders of magnitude.

Thus, the unavailability categories are fuzzy but still differentiate order of magnitude sizes of impacts. Figure 1 shows that for small aging effects on metallic components, the relative increase in unavailability of the cable remains small for the first 20 years, then becomes moderate for ages 20 to 60 years, and then becomes large after 60 years of age. These relative unavailability increases can be input into PRAs to obtain the corresponding risk increases, but also can provide important information in themselves. Since a moderate unavailability increase does not represent significant degradation in an individual cable's performance and reliability, Figure 1 indicates that when aging effects are small, then their impact on the reliability and performance of an individual cable will be moderate throughout the lifetime of the plant.

The impacts of aging on multiple cable components still would need to be evaluated to determine the resulting impact on the system's unavailability. However, the unavailability performance of the individual cable component in Figure 1 is useful since it translates the assessed aging effects in engineering information into the corresponding time-dependent unavailability implications.

Figure 2 illustrates the relative unavailability impact for those metallic cable components having a moderate aging rate. From Table 1, cable components having this type of aging include nickel-plated copper conductors and terminals and stranded copper conductors. As Figure 2 shows, for moderate aging effects, the relative unavailability impact is small for approximately the first 10 years, then becomes moderate as the age advances to 20 years. The impact becomes large between 20 and 30 years of age and remains large through the remaining life of the plant. Even though the impact on the individual cable is large, the resulting risk impact may still be small to moderate because of redundancy in the cable system. The evaluation of the impact of individual cable unavailability is useful since it identifies the age at which the impact becomes large.

Finally, Figure 3 illustrates the relative unavailability impact versus cable age for a large aging effect or aging rate. From Table 1, cable components exhibiting large aging effects are restricted to metallized mylar tape shields. If no maintenance or refurbishment is carried out on them, then the increase in unavailability is small for approximately the first 10 years, then becomes large within the next 10 years and remains large until approximately 40 years. Between 10 and 20 years, the increase in relative unavailability appears to jump from small to large; however, this is due to the fuzzy descriptions of the categories. After approximately 40 years, the increase in relative unavailability becomes very large.

EVALUATION AND PRIORITIZATION OF RISK CONTRIBUTION FROM AGING PASSIVE COMPONENTS

Passive components and passive pieceparts of active components are very reliable. Since the failure probabilities of these components usually are few orders of magnitude lower than then those of active components, most passive components are not included in PRA analysis. Moreover, even if they are included, associated cutsets have very small probabilities, and, in most cases, do not satisfy cutoff criteria. These initial very small failure rates may rise with the age of the components. Nevertheless, this rise might not be reflected in the PRA model since the appropriate components and cutsets are not included in the analysis.

Incorporation of Passive Components in Probabilistic Risk Analysis

A general approach to include aging passive components in PRA analysis is described in Phillips et al., 1991. The total number of passive components in the plant is very large, and different components belong to systems having quite different risk significance. Preliminary screening can considerably reduce the list of possible candidates to be included in the model. It is reasonable to include only those components which can cause risk-significant systems to fail. Standard PRA techniques can be used to identify such systems. First, passive components which belong to risk-significant systems can be included in the analysis. Then, passive components that could destroy or disrupt the operation of other risk-significant passive or active components in their vicinity also can be included; these passive components may not belong to the risk-significant systems. We describe three ways to incorporate passive components into PRAs.

Direct Modeling to Incorporate Passive Components into PRAs. Direct modeling, which is difficult to implement, is to add the component to the model and treat it with standard PRA approaches. In most cases, this means just adding a new event to fault tree. In some cases, it is necessary to add new initiating events and consider sequences of events that were previously unconsidered.

Using the Surrogate Active Components to Incorporate Passive Components into PRAs. A second way, which is much simpler to implement, is to identify active components which are included in the current PRA analysis to serve as surrogates for the corresponding passive components. The failure probabilities of these active components are increased to account for the contributions from the corresponding passive components.

Three types of active surrogate components are considered:

- an active contributor which fails as a result of the passive failure; this contributor is called a resultant active surrogate;
- an active contributor which fails, if, and only if, the passive contributor fails; this contributor is called an equivalent active surrogate;
- an active contributor which causes passive components to fail; this contributor is called a casual active surrogate.

Associating the passive components with resultant, equivalent, or casual active surrogates can lead to different estimates of the CDF. Using the resultant active surrogate, one can underestimate CDF. With the equivalent surrogate, the same CDF is obtained as if the passive component is directly included in the PRA. With the casual active surrogate component, the CDF may be overestimated.

System-Level Approach to Include Passive Components in PRA. The third way involves a system-level approach, whose basic assumption is:

> failure of a passive component in a system fails this system.

Evidently, it is a conservative assumption because a system can have redundant trains. If a component failed in this train, it can be isolated and system still will perform the mission. The system-level approach was developed by Vo, et al. 1989, and Vo, et al. 1993 to rank nuclear power plant systems and components on the basis of the risk importance of failures caused by ruptures in pipes. This methodology was used to determine the allocation of resources for piping inservice inspections (among systems, within these systems, and among their major piping segments). This approach can be implemented relatively easily but it does not account for interactions of multiple aging components. With this approach, the risk contributions for a particular component are calculated as a product of risk significance of the system and the failure probability of the component. The approach calculates approximately the same risk significances for the components within the system. Actually, failures of some particular components can fail the whole system, while failures of components in redundant trains do not fail the whole system. Therefore, the risk significance for passive components within the system may differ by a few orders of magnitude.

EVALUATION OF RISK CONTRIBUTION FROM AGING PASSIVE COMPONENTS: SINGLE CONTRIBUTOR APPROACH

This section describes single contributor approach to evaluate aging risks. The single passive aging-risk contribution is estimated as a product of the risk importance of the passive contributor, and aging effects on its failure probability. This approach does not take into account interactions between components, and can be implemented relatively easy.

The single contributor approach can be considered as a part of general methodology (Vesely 1987, Vesely et al. 1990, Vesely 1992) to determine the aging effects of active and passive components. This approach corresponds to evaluation of linear terms in the Taylor expansion series (see, Vesely et al., 1990). When aging effects are small enough, linear terms dominate the other terms of the Taylor series expression; this might be not the case with large aging effects. Nevertheless, even then, it is possible to prove that if a large enough list of contributors is generated based only on single contributions, this list also will cover components which are

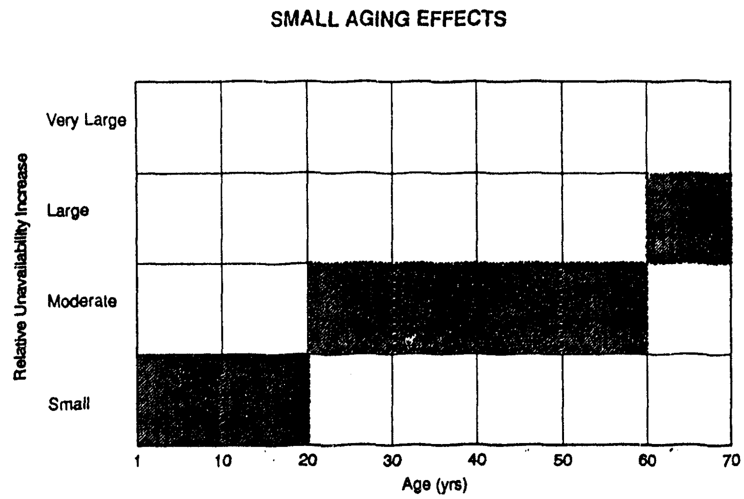

FIGURE 1. RELATIVE UNAVAILABILITY INCREASE VERSUS AGE

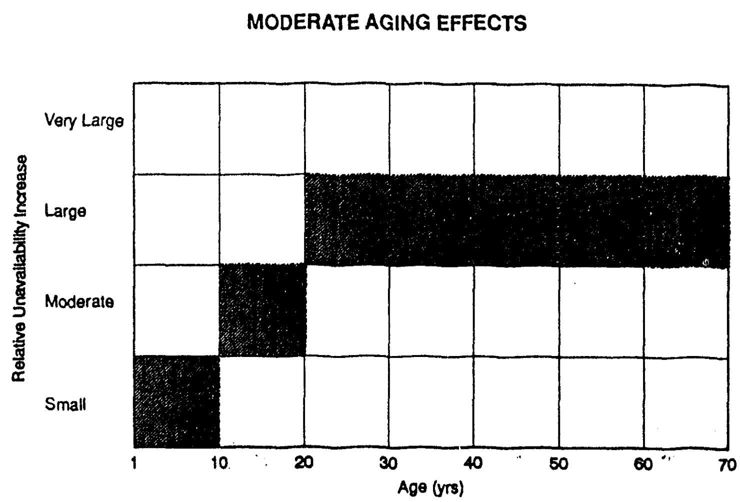

FIGURE 2. RELATIVE UNAVAILABILITY INCREASE VERSUS AGE

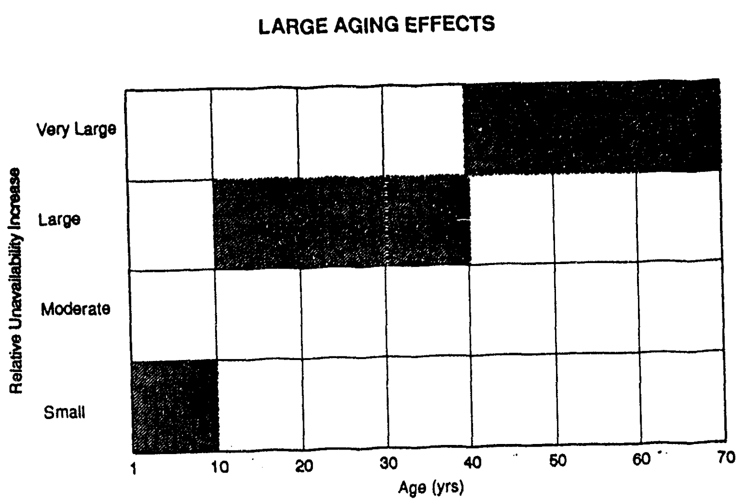

FIGURE 3. RELATIVE UNAVAILABILITY INCREASE VERSUS AGE

involved in important interactions. For example, for two NUREG-1150-based PRAs it was found that the list of components, which includes the top single contributors, also includes top second-order contributors (Hassan et al. 1993).

With single contributor approach, the passive aging-risk contribution for the group of components is evaluated as the sum of single contributions from each component in the group. For example, aging risk for the system of pipes is estimated as a sum of risks over the set of pipes in this system.

The methodology commonly used in PRAs estimates the risk importance of the passive component. Risk importance associated with the component can be calculated as the difference between the CDF calculated in the PRA when the component is always available, and the CDF when the component is defined as being unavailable. This measure of risk importance can be expressed as the derivative of CDF with respect to component failure probability. Generally, this definition should be broadened for passive components because many of them also contribute to initiating events frequencies. In this case, risk importance can be calculated as the derivative of the CDF with respect to the proper initiating event frequency. This derivative can be evaluated with finite difference formula, i.e., initiating event frequency can be increased, and the derivative is the ratio of the change of CDF and the change in the initiating event frequency. Then, the finite difference formula gives the exact value of the derivative because the value of CDF depends linearly upon the frequencies of initiating events.

The increase in failure probability of the passive contributor due to aging can be calculated knowing the changes of failure rate because of aging. In the general case, this estimate can be calculated as some integral over time. Assuming a linear increase in the failure rate as a function of time, the increase in failure probability can be estimated with formula:

$$a \times \frac{L^2}{2},$$

where,

a is an increase in the failure rate (from the rate used in the PRA) due to aging of the component, and is expressed as failures per unit time squared (also termed failure acceleration, Vesely, 1987);

L is an interval during which the component is aging (e.g., between overhauls).

THE DIFFERENT RISK CONTRIBUTIONS ASSOCIATED WITH THE AGING OF PASSIVE COMPONENTS

The risk contribution associated with the aging of passive components can be split into three parts:

- Individual passive components contributions;
- Passive-passive interactions;
- Active-passive interactions.

Here, the individual passive aging contribution is the risk associated h the individual aging of a passive component. Passive-passive aging interactions include the risk contributions from the interactions of multiple passive components. Active-passive aging interactions include the risk contributions from the interactions of active and passive components. This splitting of contributions can be explained further, as follows. The CDF of a plant can be presented as a polynomial function of component unavailabilities, structure failure probabilities, and initiating event frequencies. Failures of active and passive components contribute to initiating event frequencies. Failures of passive components are included in the structure failure probabilities, and failures of active components are presented with the component's unavailabilities.

The Taylor expansion approach developed in NUREG/-CR-5510 (see, Vesely et al., 1990) gives a formal expression for the change of CDF due to aging. This approach separates the PRA models and the aging models, facilitating the use of available PRAs to calculate aging risk effects. The Taylor expansion approach calculates the increase in CDF due to aging as a sum of contributions from single components, and from successively higher order interactions among the aging components:

$$\Delta C = \Delta C^1 + \Delta C^2 + \ldots + \Delta C^N,$$

where,

$\Delta C^1 =$ contribution to CDF due to aging of single components,

$\Delta C^2 =$ contribution to CDF due to simultaneous aging of two components,

...

$\Delta C^N =$ contribution to CDF due to simultaneous aging of N components, and

N = maximal order of cut sets in CDF expression.

The linear terms in the increase of CDF due to aging of passive contributors are actually individual passive-aging contributions. Terms which include contributions from two or more passive components are associated with passive-passive aging interactions, and terms which include active and passive aging contributions are associated with active-passive aging interactions.

CDF nonlinearly depends upon the aging contributions. It can be proved that for sufficiently small aging contributions, the linear terms, i.e., individual passive aging terms, dominate the change in the CDF because of aging of the passive components. Generally, this is not true for large values of aging contributions, in this case, nonlinear terms, which we associate with interactions, may dominate the change of CDF. How large should these aging contributions be so that interactions dominate single contributions? The answer to this question very much depends upon the actual values of coefficients in the polynomial function. Single and interaction terms should be numerically compared for different ranges of aging contributions to ensure that the interaction terms can be neglected.

PRIORITIZATION OF PASSIVE CONTRIBUTORS ACCORDING TO AGING CONTRIBUTIONS

System and components usually are prioritized according to estimates of their risk contributions to CDF. For example, such approach was implemented on system level to rank nuclear power plant systems and components on the basis of the risk importance of failures caused by pipe ruptures (Vo, et al. 1989, Vo, et al. 1993). This approach does not account directly for the aging of the components. Although a component might be risk important, it can have insignificant changes in failure rate with age. So, this component cannot be considered as a risk important one from aging point of view. We defined aging risk contributions as product of the aging effects on the failure probability of the passive contributor and the risk importance of this component. Therefore, prioritization is performed according to aging risk contributions. We do not suppose that failure of a component in the system will fail the whole system, which separates this approach from the system-level approach. We consider that component failure probabilities can significantly change with time. Therefore, risk importances are calculated with aged component failure probabilities to account for possible changes in the importances because of aging. The basic steps of the prioritization procedure are as follows:

- Calculate total risk impact of the aging of passive contributors;
- Calculate Birnbaum importance vector $\boldsymbol{b}$ at point $\boldsymbol{q} + \Delta \boldsymbol{q}$, where $\boldsymbol{q}$ denotes the vector of failure probabilities, and $\Delta \boldsymbol{q}$ denotes changes in failure probabilities because of aging;
- Calculate aging risk importance $b_i \times \Delta q_i$ for each passive contributor i;
- Prioritize components according to their aging risk contributions;
- Create a list of top contributors which covers the major part of the total aging risk (for example, 95% of the aging risk).

With our prioritization approach, we directly evaluate the aging risks for the list of top contributors and show that this list covers the major part of the risks. This list covers also the interaction terms.

CONCLUSIONS

The paper describes an approach for aging risk based prioritization of passive components. It is based on calculating the aging risk impacts of the passive components. This methodology is an extension of the methodology previously used to prioritize aging risk contributions from active components. A process was described for translating engineering information into reliability implications using Fuzzy Set Theory as the formal calculational approach. When only semi-quantitative information is available, then meaningful reliability implications still can be obtained as a function of age, but in the form of categories of impacts. These reliability implications can be input into PRAs to obtain the risk implications. The demonstration of the effects of aging cables illustrates the feasibility of applying the process to existing information.

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