NUCLEAR POWER PLANT COSTS AS A FUNCTION OF NDE RELIABILITY

Michael J. Avioli, Jr.

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Soung-Nan Liu

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

INTRODUCTION

The economic efficiency and safety of any power plant depends on the proper functioning of its component systems. The functioning of such systems (e.g., piping) is evaluated through performance of periodic nondestructive examinations (NDE). The results of these examinations determine actions the power plant owner must take regarding inspected components. If a component is found malfunctioning or containing a defect, the owner may decide to repair or replace the component. If the results of NDE indicates that the component is functioning as it should or is defect-free, he would most certainly take no action but to record such a finding for future reference. Any action the owner takes, though, depends on NDE results and involves risks associated with either not identifying defective components or mislabeling components defective when they are not. Nuclear power plants, because of their unique circumstances, must pay costs for these types of errors that far exceed those in other industries. This paper depicts the framework for relating inspection capability to the economics of power plant operation.

COMPONENT RELIABILITY

Reliability is typically treated as a function of the probability of failure as a function of time [1]. As time continues, the probability of failure may decrease, remain constant or increase, depending on the nature of a component and environment and loadings to which the component is subjected. For many components this variation of probability of failure over time is described by a "bathtub" hazard function [2]. Such a function is shown in Fig. 1. The first portion of curve describes the time period when fabricated components are initially inspected to weed out defective ones before service and to replace components that fail early in their lives. This duration in a nuclear power plant context would be called the pre-service inspection period or PSI. The probability of failure decreases because of the elimination of a high percentage of defective components.

The central portion of the curve represents a span of time where the probability of failure is relatively constant and failures are considered to be chance failures attributed to events such as rapid change in component stress loading or variations in the environment of the component (e.g., higher temperatures than normal). During this period of time, power plants perform in-service inspections, called ISI's. The last portion of curve describes an increasing probability of failure due to aging, wear, and cycling effects. The results of the ISI inspections are typically coupled with findings from material characterization and fracture mechanics to ensure that a minimum of components are remaining during the final segment of the bathtub curve. Restricting ourselves to the middle portion of the bathtub curve, the probability of failure is essentially independent of time, and depends only on the quality of the components and the ability to correctly assess their integrity.

TIME INDEPENDENT RELIABILITY

One very informative formulation of time independent reliability is given in [3]. This formulation considers reliability as a function of component quality and inspection capability. Reliability is defined as the probability that a condition that can cause malfunctioning or failure does not exist given that, after inspection, no such condition is indicated. In terms of conditional probability,

$$R = P(\,nf \mid ni\,)$$

nf - no failure, (e.g., no flaw that can cause failure)

ni - no indication of such a flaw

Using Bayes theorem, an explicit expression for reliability, R, can be developed that is a function of component quality and inspection capability. The following mimics the development found in [3].

$$P(\,nf \mid ni\,) * P(ni) = P(\,ni \mid nf\,) * P(nf)$$

P(ni) - Probability of no indication

P(nf) - Probability of no failure (flaw)

or
$$R = \frac{P(\,ni \mid nf\,) * P(nf)}{P(ni)} \tag{1}$$

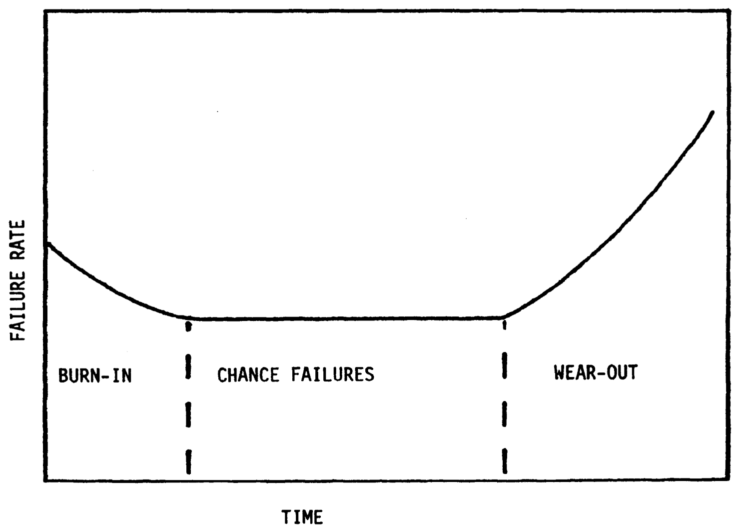

Figure 1. "Bathtub" curve showing variation of failure rate over time

The probability of no indication, P(ni) is a combination of the probabilities that no indication will occur when one should and when one shouldn't:

$$P(ni) = P(ni \mid f) * P(f) + P(ni \mid nf) * P(nf)$$

Substituting into (1).

$$R = \frac{P(ni \mid nf) * P(nf)}{P(ni \mid nf) * P(nf) + P(ni \mid f) * P(f)}$$

and, after identifying like terms,

$$R = \frac{1}{1 + \frac{P(ni \mid f) * P(f)}{P(ni \mid nf) * P(nf)}} \qquad (2)$$

In (2) it should be noted that the terms P(f), P(nf) are a function of the component's state alone and do not depend on inspection capability. The remaining two terms depend on inspection capability and component quality. Equation (2) can be simplified by defining two parameters—Quality Index, and Success Probability Ratio.

Quality Index

As noted, the terms P(f) and P(nf) are independent of inspection capability. These terms are related by

$$P(nf) = 1 - P(f), \text{ since } P(nf) + P(f) = 1$$

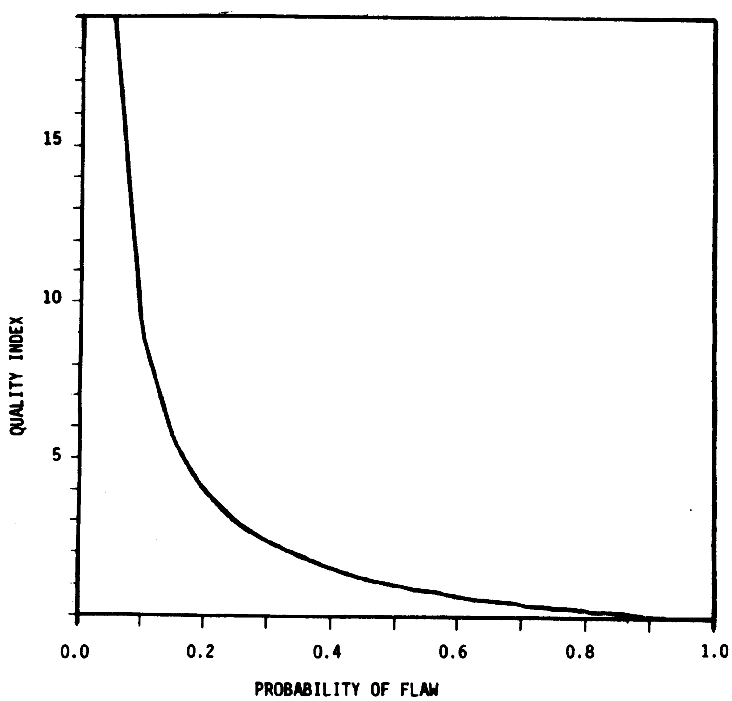

Fig. 2. Variation of Quality Index (QI) as a function of Probability of Flaw

An intuitive sense of quality suggests that quality is inversely related to the probability of failure or of a flaw: The greater this probability, the less quality one would attribute to a component. Also, if the probability of a flaw were 1, then one would expect no quality or "0" quality. These feelings can be represented by the following expression:

$$QI = \frac{1 - P(f)}{P(f)} \tag{3}$$

Fig. 2 shows the variation of QI as a function of P(f). We can substitute (3) into (2) getting,

$$R = \frac{1}{1 + \frac{P(ni \mid f)}{P(ni \mid nf) * QI}}$$

Success Probability Ratio

The two remaining probabilistic terms are related to inspection capability through the chance of getting no indication of a failure or flaw after an inspection. The following relationships hold:

$$P(ni \mid f) = 1 - P(i \mid f)$$

$$P(ni \mid nf) = 1 - P(i \mid nf)$$

The expression $P(i \mid f)$ is the probability of an indication of a flaw given that a flaw exists (of a failure, given a failure is possible). The more common term for this probability is "Probability of Detection" or POD. Likewise, the expression $P(i \mid nf)$ is the probability of an indication flaw given there is no flaw. This probability is commonly called the "False Alarm Rate," FAR. Using the acronyms POD and FAR and substituting into (2):

$$R = \frac{1}{1 + \frac{1 - POD}{(1 - FAR) * QI}}$$

We can define "Success Probability Ratio" as

$$SPR = \frac{1 - FAR}{1 - POD} \tag{4}$$

Again, this is intuitive in that as POD increases toward 1, SPR or successful detection increases; and as FAR increases toward 1, successful detections decrease. Fig. 3 shows the variation of SPR for different PODs with P(f); FAR fixed at 0.02. Expression (4) can be substituted in (2) to give the following form for reliability:

$$R = \frac{1}{1 + \frac{1}{SPR * QI}} \tag{5}$$

RELIABILITY AS FUNCTION OF INSPECTION CAPABILITY

The reliability of a component cannot be changed by inspecting it, but the reliability of a collection of components can be improved by repairing or replacing defective components. Inspection helps to identify which components to replace or repair. Expression (5) can be used to show the effects of inspection on reliability. First note that with no inspection POD = FAR = 0, or SPR = 1. This leads to

$$Rb = \frac{1}{1 + \frac{1}{QI}} = \frac{QI}{QI + 1} = 1 - P(f). \tag{6}$$

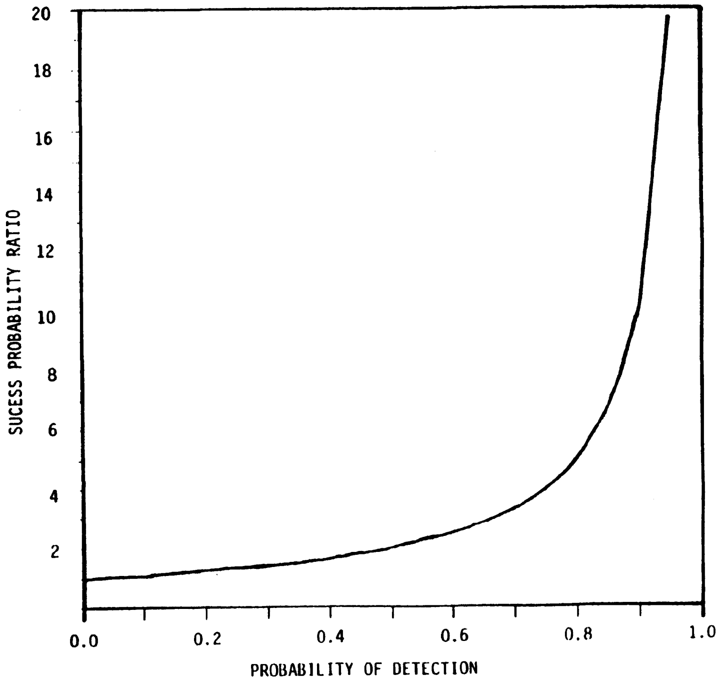

Fig. 3. Success Probability Ratio (SPR) variation with Probability of Detection

Rb = Reliability before inspection

Refer to Fig. 4. The x-axis of Fig. 4 is 1 - P(f) and represents reliability before inspection. Using the y-axis to represent reliability after inspection, the line labeled "No Inspection" shows that no change in reliability takes place. Now note that from (6),

$$P(f) = 1 - Rb$$

$$QI = \frac{1 - P(f)}{P(f)} = \frac{Rb}{1 - Rb}$$

$$R = \frac{1}{1 + \frac{1 - Rb}{Rb}} = Rb$$

When inspection is used POD $\neq$ 0, and FAR $\neq$ 0; SPR $\neq$ 1.

For example, if POD = 0.5 and FAR = 0.02, then

$$SPR = \frac{1 - 0.02}{1 - .5} = 1.96$$

and

$$R = \frac{1}{1 + \frac{1 - Rb}{1.96 * Rb}} = \frac{1.96 * Rb}{1 + 0.96 * Rb}$$

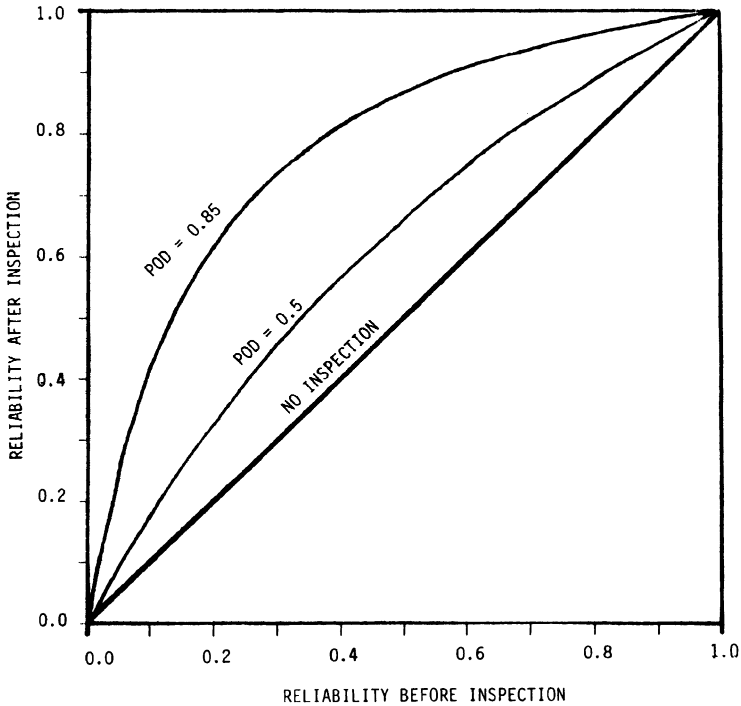

Fig. 4. Reliability as a function of Probability of Detection; False Alarm Rate = .02

if POD = .85, FAR = 0.02,

$$SPR = \frac{1 - 0.02}{1 - 0.85} = 6.53,$$

$$R = \frac{6.53 * Rb}{1 + 5.53 * Rb}$$

These two examples are shown in Fig. 4.

FALSE CALL RATE

It is often confusing to hear the terms False Alarm Rate and False Call Rate. They are not synonymous. False Alarm Rate is the probability of an indication of a flaw given no flaw exists. It is P(i I nf). On the other hand, False Call Rate is the probability of no flaw being present given there is an indication of a flaw. It is P(nf I i). The False Call Rate is of great concern when considering the economics of plant operation. This will be shown later. Essentially, the FCR indicates how often unnecessary repairs or replacements take place.

The FCR and FAR can be related to each other via Bayes theorem.

$$FCR = P(nf \mid i)$$

$$FCR * P(i) = P(nf \mid i) * P(i) = P(i \mid nf) * P(nf)$$

$$FCR = \frac{P(i \mid nf) * P(nf)}{P(i)}$$

$$= \frac{P(i \mid nf) * P(nf)}{P(i \mid nf) * P(nf) + P(i \mid f) * P(f)}$$

$$= \frac{1}{1 + \frac{P(i \mid f) * P(f)}{P(i \mid nf) * P(nf)}}$$

$$FCR = \frac{1}{1 + \frac{POD}{FAR * QI}}$$

If a component as a P(f) = .05, then QI = 19. With a POD = .85,

$$FCR = \frac{1}{1 + \frac{0.85}{FAR * 19}} = \frac{19 * FAR}{19 * FAR + 0.85}$$

For example, if FAR = 0.02, FCR = .301

Fig. 5 shows how FCR varies with FAR.

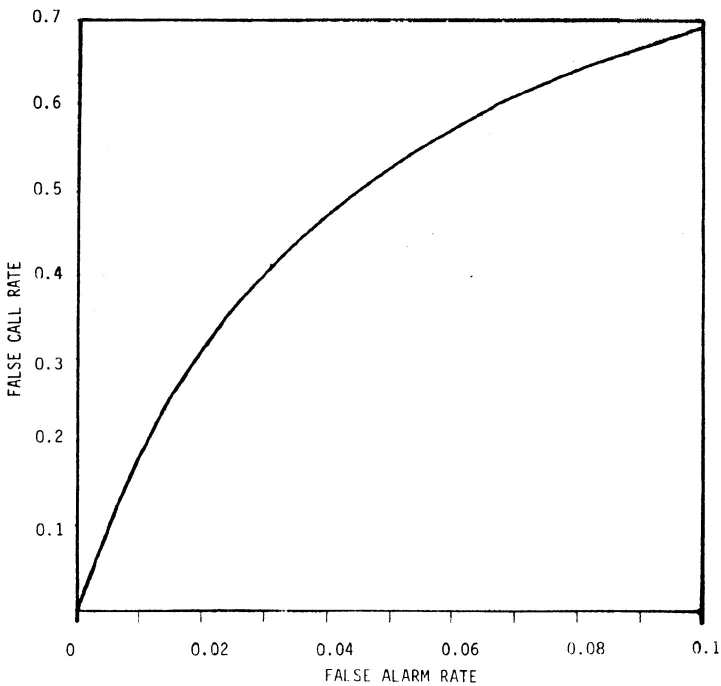

Fig. 5. Variation of False Call Rate (FCR) with False Alarm Rate (FAR); Probability of Detection = .85

COST CONSIDERATIONS

The risks [4] associated with inspection capability are based on the costs paid by power plant owners as a result of inspection-based decisions. There are two reasonable decisions that can be made. The component being inspected contains a critical flaw or it doesn't. These decisions correlate directly with inspection results, (no indication, no flaw—indication, flaw). Economic risk becomes apparent in that wrong decisions can lead to costly actions. Deciding that a flawless component has a flaw costs a power plant outage time (i.e., time to repair or replace the "bad" component) with the associated loss of revenue and costs paid to another utility for replacement power for their customers. There is also the loss of credibility regarding inspection capability, a situation that has direct effects on the implementation of their inspection programs, considering regulators such as the NRC. On the other hand, missing a flaw can lead to a very costly unscheduled outage. This happens when a critical flaw actually causes component failure.

Risk can be defined as the expected cost of making a particular decision or taking certain actions based on information. The risk, Rsk(nf I ni), deciding no flaw when there is no indication, can be written as:

$$Rsk(nf \mid ni) = C(nf, nf) * P(nf \mid ni) + C(nf, f) * P(f \mid ni)$$

where

C(nf, nf) =	Cost for actions associated with no flaw situations (inspection cost)
C(f, nf) =	Cost for actions associated with flaw situations where no corrective action is taken (forced outage, loss of credibility, etc.). Most of these costs can be avoided.

Noting that $P(f \mid ni) = 1 - P(nf \mid ni) = 1 - R$

(R = Reliability)

$$Rsk(nf \mid ni) = C(nf, nf) * R + C(f, nf) * (1 - R)$$

$$= C(f, nf) + R * [C(nf, nf) - C(f, nf)]$$

As R approaches 1, Rsk(nf I ni) approaches C(nf, nf), the cost of inspection. Reliability less than 1 will cause a fraction of the costs associated with a missed flaw to be included in the risk of saying "No flaw" when there is no indication of a flaw. Since these costs are quite large, the risk is severely affected.

The other risk case is calling a flaw when a flaw is indicated. This is written as:

$$Rsk(f \mid i) = C(f, f) * P(f \mid i) + C(nf, f) * P(nf \mid i)$$

C(f, f) -	The cost of actions associated with calling a flaw a flaw such as outage time, repair or replacement costs, and so on
C(nf, f) -	The cost of actions associated with calling a flaw when no flaw is present. These costs are the same as C(f, f) but are avoidable.

For this case, $P(f \mid i) = P(nf \mid i) = 1 - FCR$ (FCR = False Call Rate)

$$Rsk(f \mid i) = C(f, f) * (1 - FCR) + C(nf, f) * FCR$$

$$= C(f, f) + FCR * [C(nf, f) - C(f, f)]$$

Because [C(nf, f) - C(f, f)] > 0, Rsk(f | i) is reduced as FCR tends toward zero.

CONCLUSION

Component reliability depends on the initial quality of the component and how that varies over the life of the component. Quality is related to the probability of a critical flaw occurring within the component and can be quantified via the "Quality Index" for time independent assumptions. Component reliability also depends on inspection capability. This capability is quantified through the "Success Probability Ratio." Time independent reliability can be written as a function of QI and SPR.

Power plant costs associated with the actions pursued as a result of inspection results can be cast in a risk (expected cost) framework. Under this formulation, improving reliability and reducing the false call rate reduces the risk associated with power plant costs.

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