EXAMPLE PROBLEM : HEAT EXCHANGER BUNDLE RBI

Given a crude preheat exchanger, Tag# 191-X-25A-T3, 42 x 240 TEMA type AES, with SA-214 carbon steel tubes. There are 650 tubes - 1 inch OD by 12 BWG (0.12) inches).

INSPECTION HISTORY FOR T3 BUNDLE

Installation Date: Current T3 bundle installed on 1990-01-01

- June 1998 – Bundle had minor general corrosion throughout on OD, 10% of the tubes were sample using Elliot gages/calipers and found to have an average wall thickness of 0.10 inches (15% wall loss). Bundle was hydrotested without leaks. Inspection effectiveness grade as "C"
- September 2001 – Bundle showed significant wall loss to 0.09 inches average thickness (25% wall loss). Bundle was hydrotested without leaks. Inspection effectiveness grade as "C".

OTHER DATA

RBI Date: Today – September 2006 (16.7 years after installation)
T/A Date 1: March 2007 (17.2 years after installation)
T/A Date 2: March 2011 (21.2 years after installation)
Unit Production Costs: $100,000/day
Production Impact: Bypass with Rate Reduction of 25% if bundle failure
Shutdown Days to Repair: 2 days
Cost of Shutdown, including bundle replacement costs: $50,000
Economic Impact: $0.00/day
Risk Tolerance: $70,000

SOLUTION

Consequence of Failure

The consequence is determined using the following equation:

$$COF = Cost_{prod} \times \frac{Rate_{red}}{100} \times Sddays + Cost_{env} + Cost_{sd} \tag{1}$$

For our example problem, the consequence of failure is:

$$COF = 100,000 \times \frac{25}{100} \times 2 + 0 + 50,000 = \$100,000 \tag{2}$$

Risk Tolerance and Calculation of Acceptable POF

The acceptable failure rate (POF) for the bundle can be determined using the risk tolerance specified above:

$$POF_{max} = \frac{Risk_{tol}}{COF} = \frac{70,000}{100,000} = 0.70 \text{ or } 70\% \tag{3}$$

Probability of Failure

Critical to the ability to perform failure analysis on bundles, the User needs to have a bundle failure database. The software utilizes a local database as well as a seed database. The local failure database is populated directly from the exchanger bundles (both active and inactive bundles) that are currently in the API RBI database (on the J-tree). The seed database sits in the background and also supplies failure data from bundles that the User has accumulated. Examples of this might be a corporation's database that includes bundles at other facilities, a User Group failure database, or the CCPS database.

For our example problem, the seed and local databases were searched to find bundles matching the following criteria:

- Tubeside fluid category – Crude
- Controlling Damage Mechanism – General Corrosion
- Shellside temperature range between 350 and 500 ^{o}F
- TEMA Type AES
- Exchanger type – Liquid/Liquid process exchanger
- Sulfur content greater than 1%

Nine bundles in the databases were retrieved. Five failures and four suspensions (bundles in-service without failure reported) were found. The data is represented in Table 1.

The first three records, noted by the exchanger tag number 191-X-25A are data accumulated from the local failure database for the specific bundle that we are evaluating. The remaining data was obtained from other similar bundles in the seed database.

The calculation of probability of failure as a function of in-service duration can be performed either of four ways:

1) User Input Weibull Parameters – This involves the User providing the Weibull Beta and Eta parameters. If input, these will be used.
2) User Input MTTF – This involves the User providing the Mean Time to Failure (MTTF) for the specific bundle being evaluated. If input, this will be used. The method will convert the MTTF to a Weibull curve using a Beta value of 2.5 (needs to be verified)
3) Seed Database – When a User supplied value of the MTTF has not been input, a Weibull distribution is assumed and a Weibayes' analysis is performed on the matching bundles in the local and seed databases.
4) Specific Bundle Inspection History – Once enough inspection history is accumulated, the statistics could be determined specifically for the bundle being evaluated.

<u>POF using the User Supplied MTTF</u>

When the User has enough inspection information for a specific bundle, such that an MTTF can be determined, the user can specify the bundle MTTF. A Weibull distribution will still be used. The beta slope parameter will be assumed to be 2.5 (needs verification) and the eta characteristic life will be calculated from equation(4):

$$MTTF = \eta\Gamma\left(1+\frac{1}{\beta}\right) \tag{4}$$

POF calculated using Weibayes' with the Seed Database

The data supplied in Table 1 for the matching bundles has been plotted as a Weibull distribution on Figure 1. The calculated Weibull parameters for the matching bundle set is:

$$\begin{aligned}\beta &= 2.568 \ \text{ Slope parameter} \\ \eta &= 20.45 \ \text{ Characteristic Life, years}\end{aligned} \tag{5}$$

The goodness of fit parameter, pve, is shown on Figure 1 to be 99.9 which implies that the data fits the Weibull distribution extremely well. For small samples (i.e. failure less than 20) a calculated pve greater than 20% is considered adequate.

Most statisticians will utilize confidence bounds on data of this nature to account for the statistical distribution in the data. For API RBI a 90% lower bound confidence interval has been selected using Fisher Matrix Bounds [Nelson 1982]. The 90% LBC provides a 90% confidence that the data point will fall to the right of the line.

POF calculated using Specific Bundle History

Once the bundle being evaluated has accumulated at least two life cycles with inspection data, a Weibayes' analysis can be performed keeping the Beta (slope parameter) the same as determined from the matching bundle criteria. The Eta parameter (characteristic life) can be recalculated using equation (6):

$$\eta = \left[\sum_{i=1}^{N} \frac{t_i^{\beta}}{r} \right]^{1/\beta} \tag{6}$$

where:
N is the number of past bundles
t_i is the time in service for each bundle (years)
r is the number of failed bundles
β is the Weibull slope parameter

For the 191-X-25A exchanger in our example, there were failures recorded after 18 and 20 years. The current bundle (T3) has been in-service for 16 years without failure (suspension).

The modified characteristic life can be recalculated using equation (7) as follows:

$$\eta = \left[\frac{(22)^{2.568} + (18)^{2.568} + (16)^{2.568}}{2} \right]^{1/2.568} = 22.16 \text{ years} \tag{7}$$

Note that this is slightly higher than the 20.45 year characteristic life calculated using the matching bundles from the local and seed database [see equation (5)].

The User should be cautioned that this method assumes that the bundle has not been redesigned over it life time. Changes in metallurgy, changes in process, or bundle design need to be considered before assuming that all of the failures are representative of the current bundle being evaluated.

Inspection Planning without Inspection History (First Inspection Date)

To plan inspections, the risk at any point in time must be calculated. Figure 1 provides the results for our example problem using the matching heat exchanger bundles from the local and seed databases. However, without a large sampling of inspection data for the bundle, there is an amount of uncertainty associated with whether or not the matching set of exchanger bundles from the failure databases actually represents the bundle we are evaluating.

To further account for inaccuracies and bias that is inherent in the failure databases, additional uncertainty is introduced into the statistics. For RBI, a default value for additional uncertainty of 50% has been chosen to apply. Figure 2 shows the curve shifted to the right as a result of the addition of the 50% uncertainty.

If the bundle has no inspection records and no knowledge exists as to the condition of the bundle, the 50% uncertainty curve is used to predict the probability of failure as a function of time for the bundle. For our example bundle, without any inspection, the recommended length of service for the bundle as a function of time can be determined using the 50% AU curve on Figure 2 or can be read off of Table 2.

At an allowable probability of failure [based on the risk tolerance per equation (3)] of 70%, the recommended first inspection is 8.8 years. The first inspection would have been predicted to be in late 1998 or early 1999.

Inspection Planning with Inspection History

Since our bundle was inspected twice since installation in 1990, we can use the information gained to evaluate the actual condition of the bundle and to make adjustments to the failure rate curves as necessary.

An inspection provides us two things:

1) Reduction in uncertainty resulting in the use of a different failure rate curve, e.g. moving from a 50% AU curve (no inspection history) to a curve 20% AU curve (Usually Effective Inspection)
2) Knowledge of the actual condition of the bundle, this may result in a shift of the failure rate curve to the right or to the left. The current condition of the bundle could either be quantified by remaining wall thickness data or by an estimate of the remaining life.

Reduction in Uncertainty

If the bundle has been inspected, the uncertainty is reduced (POF curve moves to the right) and the probability of failure at any time goes down. In this way, the RBI methodology allows inspection knowledge to reduce probability of failure and the resultant calculated risk.

At this point the concept of Inspection Effectiveness is introduced, similar to the methodology used in other modules of API RBI. Table 3 provides the current defaults used in the software as a function of inspection effectiveness for heat exchanger bundles.

As better and better inspection techniques are used, the amount of uncertainty goes down and the weibull plot will shift to the right. Using this concept will also result in more rigorous inspection techniques being implemented as the bundle reaches end of life.

Knowledge of Actual Conditions

Not only does an inspection reduce the uncertainty in the data, it also provides us with knowledge of the current condition of the bundle. We may find out that the bundle is in excellent condition and that the curve being used for the probability of failure is way too conservative. We also may find out that the bundle is in worse condition than what would be predicted using data from bundles in similar service.

For general corrosion, the current condition of the bundle can usually be quantified or expressed as a percent remaining wall thickness. Different definitions for failure exist; for this example problem, failure is defined as the time at which the average remaining wall thickness reaches 50% of the original wall thickness.

The uncertainty involved in determining the percent remaining wall thickness is dependent on the type of inspection technique employed during the shutdown. For example, measuring ODs and IDs using mechanical means, such as calipers and/or Elliot gauges, provide a usually effective means for determining the remaining wall thickness. The use of eddy current testing will greatly reduce the uncertainty of the inspection.

Adjustments to the Failure Rate Curve Based on Inspection

For our example problem, the bundle was inspected in September 2001 after 11-3/4 years in service. The average measured wall thickness went from 0.12 inches down to 0.09 inches, a reduction of 0.002553 inches/year. At this rate, the average wall thickness would reach 50% of the original wall thickness (Failure Definition) in 23.5 years, or in June of 2013.

Plotting this as the failure point on the Weibull diagram, results in a shift to the right as shown in Figure 3. Note that the Beta parameter (Weibull slope parameter) was kept the same as the original curves from data obtained from similar bundles. This is the basis of Weibaye's analysis which assumes that similar failure mechanisms will produce similar slope values.

The new POF curve in Figure 3 (second from left) shows the impact of the 2001 inspection. Two adjustments to the right were made. The uncertainty was reduced from 50% (no inspection) to 30% ("C" Inspection) as a result of the Elliot gauging/calipers measurements taken to estimate the remaining wall thickness. Additionally, the base curve containing the raw data was shifted to the right of the original raw data curve as a result of the condition of the bundle not being in as poor a condition as what was expected using the initial curve.

As a result, the recommended inspection interval at the 70% POF point for the bundle was increased from 8.8 years to 20.6 years.

Future Inspection Recommendation

With this information, a Level "C" inspection would need to be targeted in July of 2010. Since the next TA is scheduled for March 2007 and the next one after that is scheduled for March 2011 (after the target date), the software would recommend a "B" level inspection or better at the March 2007 inspection. Figure 4 provides an overall view of inspection plan.

A "B" level inspection is recommended since skipping the 2007 inspection would cause the bundle to exceed the acceptable risk 8 months ahead of the 2011 inspection.

Summary

- With this proposed method, the recommended inspection technique will become more rigorous as the bundle starts to near its predicted end of life.
- Knowledge gained during inspection reduces uncertainty and considers the actual bundle condition, which may be significantly different than what the initial failure rate curve would have predicted.
- Seed database filter used to target specific exchanger design, fluid service and damage mechanism expected for a particular bundle.

Table 1: Matching Bundles from Local and Seed Database

Bundle Tag #	In-Service Duration (years)	Failure Reported
191-X-25A-T1	18	Yes
191-X-25A-T2	22	Yes
191-X-25A-T3	16	No
E101-A-T1	10	Yes
E322-A-T1	12	No
E322-A-T2	13	No
HE-115-T1	14	Yes
HE-115-T2	25	No
PR6419-T1	8	Yes

Table 2: Time In-Service as a Function of POF and Uncertainty

Method	Time in Service (years)						
	POF= 1%	2%	5%	10%	20%	50%	90%
Weibull, Raw Data	3.48	4.47	6.43	8.51	11.4	17.7	28.3
90% LBC	1.51	2.24	3.76	5.57	8.31	14.3	21.3
90%LBC with 5% AU	1.44	2.13	3.57	5.29	7.89	13.54	20.2
90%LBC with 10% AU	1.36	2.01	3.38	5.01	7.48	12.8	19.2
90%LBC with 20% AU	1.21	1.79	3.00	4.46	6.65	11.4	17.0
90%LBC with 30% AU	1.06	1.57	2.63	3.9	5.82	9.98	14.9
90%LBC with 50% AU	0.76	1.12	1.88	2.79	4.15	7.13	10.6

Table 3: Inspection Effectiveness and Uncertainty

Inspection Effectiveness	General Corrosion		Other Damage Mechanisms	
	Description	**Uncertainty (%)**	**Description**	**Uncertainty (%)**
E - Ineffective	Visual or thickness sampling without documentation of wall thickness	50		
D – Usually Not Effective	0-10 % Elliot Gage/Caliper Readings with Hydrotest	30		
C –Moderately Effective	10-20% Elliot Gage/Caliper Readings with Hydrotest	20		
B - Usually Effective	10-20% Eddy Current	10		
A - Highly Effective	100% Eddy Current	5		

Figure 1: Weibull Plot of Similar Bundle Data

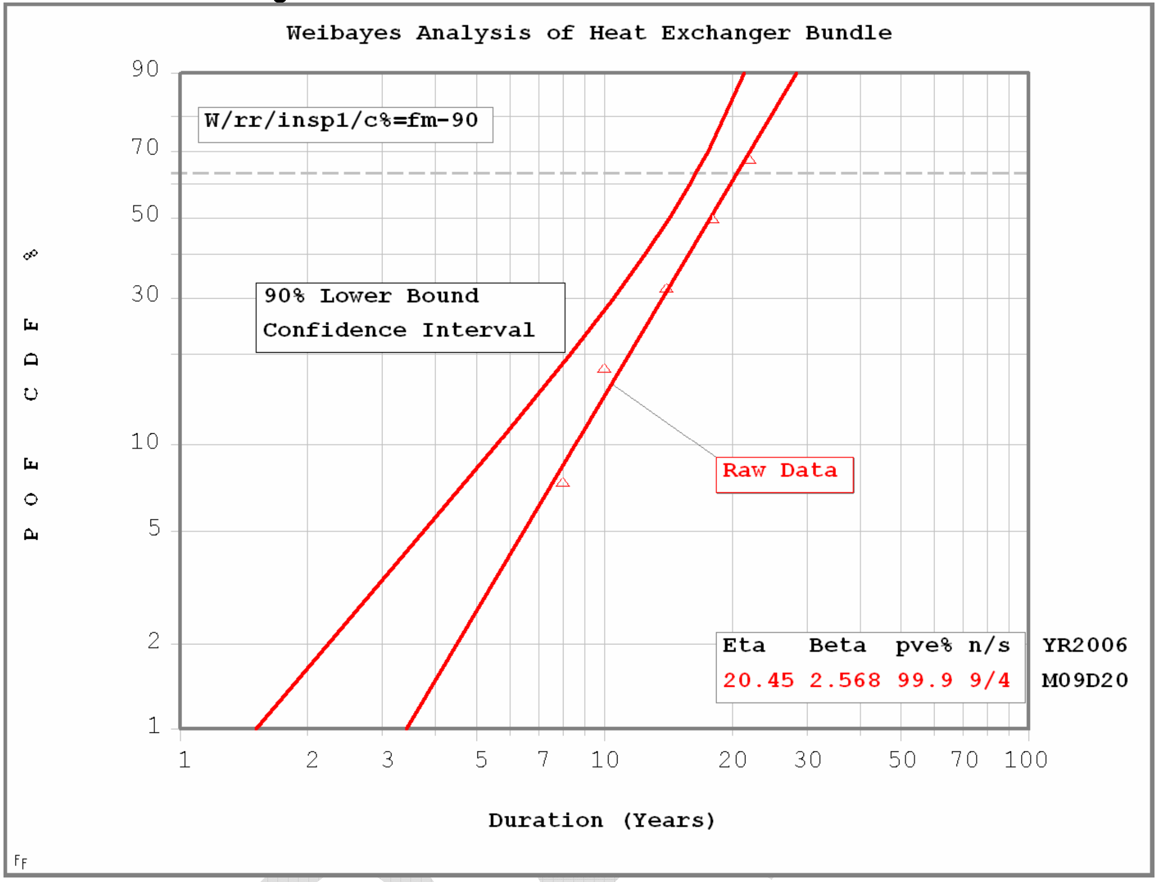

Figure 2: Weibull Plot of Similar Bundle Data with 50% Additional Uncertainty

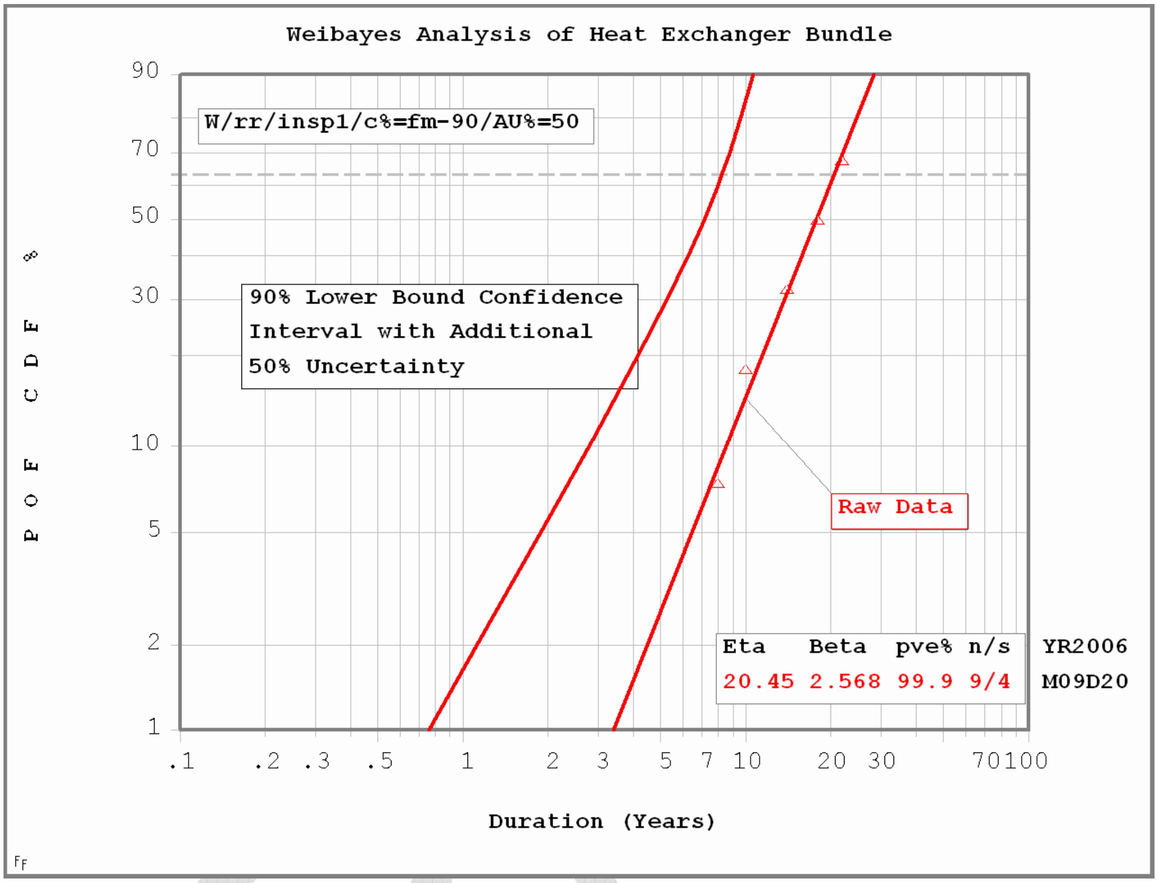

Figure 3: Weibull Plot Shifted for Inspection

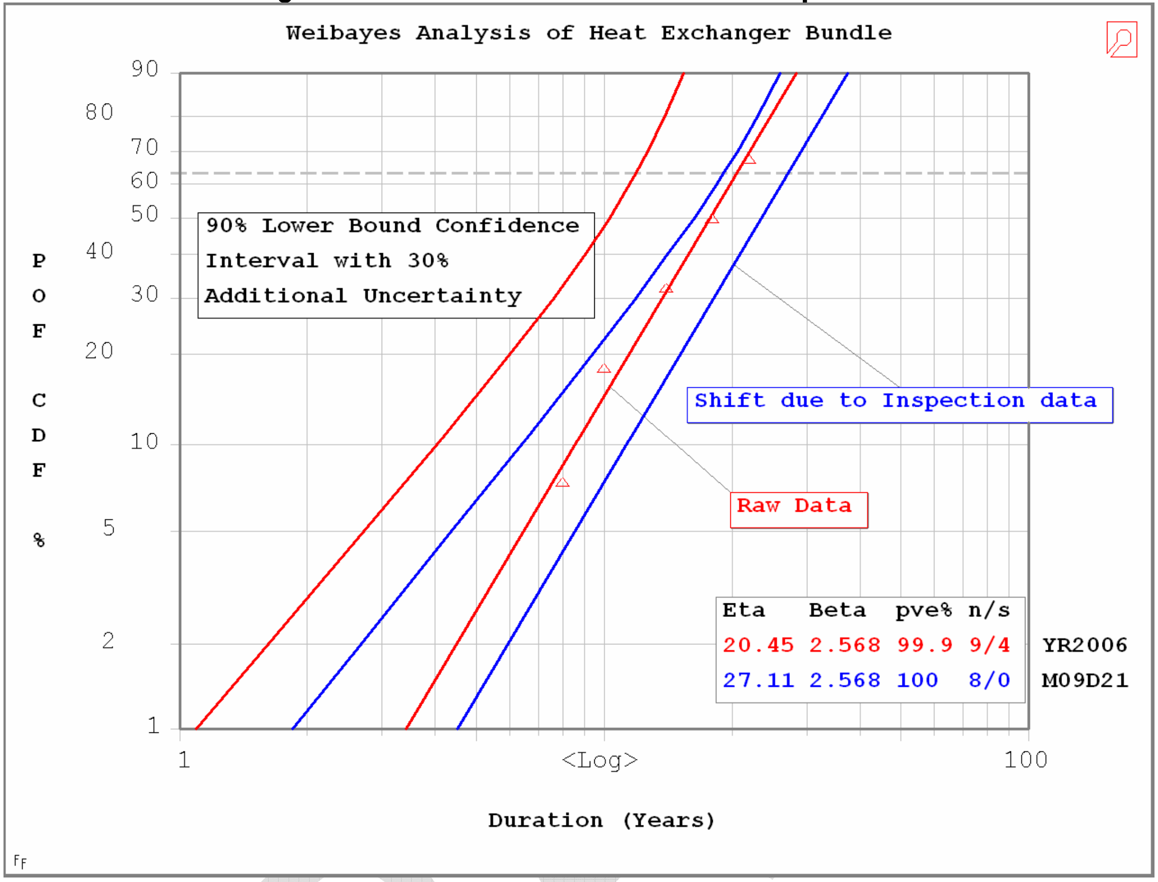

Figure 4: Example Problem Showing Effect of Inspection

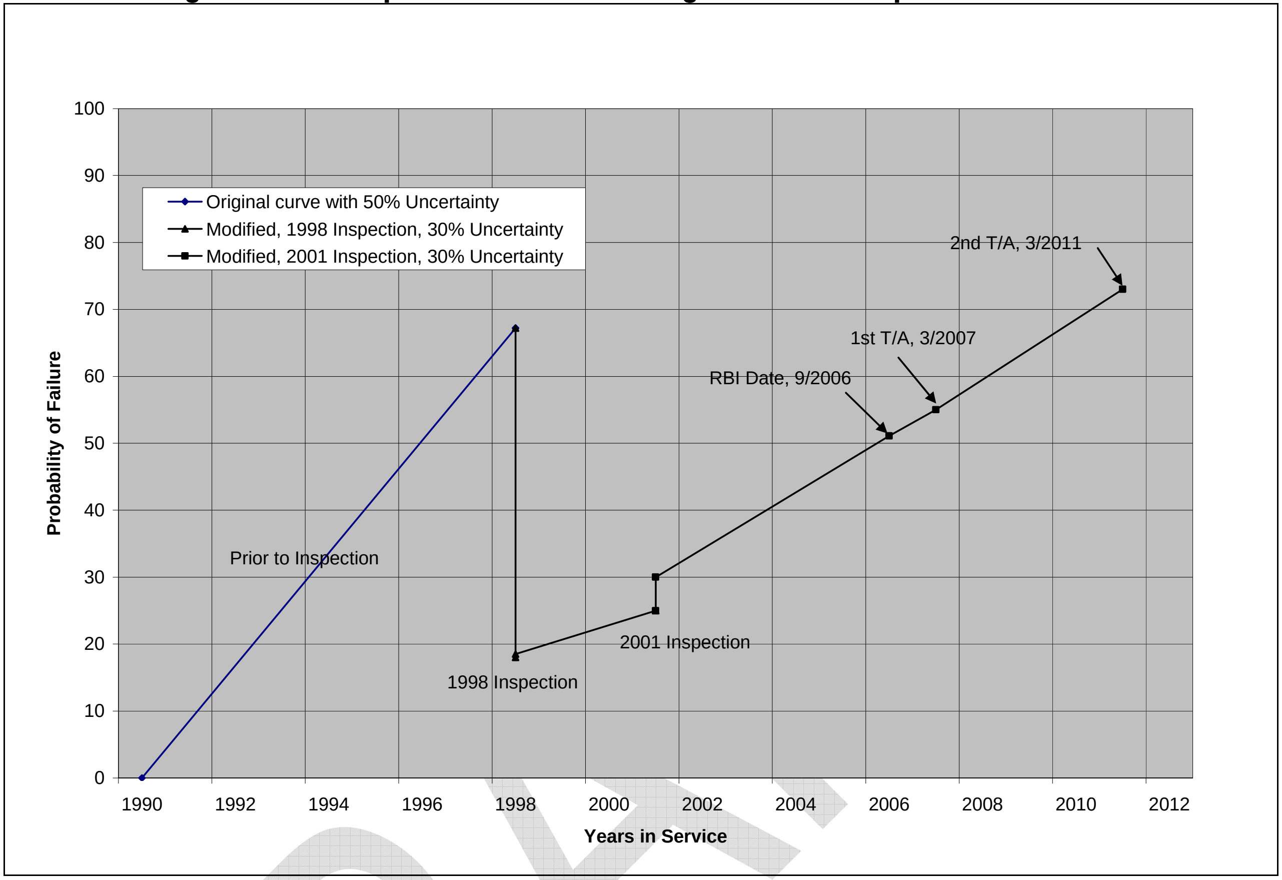

Figure 5: Example Problem Showing Effect of Future Inspection