Risk-Based Inspection Methodology
Part 5—Special Equipment
Annex 5.A Contents

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Risk-Based Inspection Methodology
Annex 5.A—Bundle Weibull Approach

5.A.1 General

One method of an exchanger bundle Weibull analysis is performed using an exchanger reliability library to calculate β and η parameters. This Annex provides an example and additional information for conducting a Weibull analysis using the reliability library described in Part 5.

5.A.2 References

API Recommended Practice 581, *Risk-Based Inspection Methodology*, *Part 1—Introduction to Risk-Based Analysis Methodology*, American Petroleum Institute, Washington, DC.

API Recommended Practice 581, *Risk-Based Inspection Methodology*, *Part 2—Probability of Failure Methodology*, American Petroleum Institute, Washington, DC.

API Recommended Practice 581, *Risk-Based Inspection Methodology*, *Part 4—Inspection Planning Methodology*, American Petroleum Institute, Washington, DC.

API Recommended Practice 581, *Risk-Based Inspection Methodology*, *Part 5—Special Equipment Methodology*, American Petroleum Institute, Washington, DC.

5.A.3 Determining Weibull Parameters

Weibull parameters (eta, η, and beta, β) are required to determine the POF of a heat exchanger bundle unless an MTTF is specified. Part 5 references the process of statistically determining Weibull parameters of a set of previous bundles of a given heat exchanger or a set of similar bundles from an exchanger bundle reliability library. The Weibull parameters are used to calculate POF as a function of time for a bundle. This Annex provides an example of calculating the Weibull parameters from a bundle failure library.

The advantage of using Weibull analysis to calculate POF is engineering decisions can be made with fewer failure data points than needed with other statistical distributions [11]. Weibull analysis is performed with less data, which is an advantage when little or no specific bundle failure data is available to provide a POF determination.

Two Weibull analyses to consider are provided in Part 5:

1. An exchanger has experienced multiple tube bundle failures. A Weibull analysis is performed using the failure data from that specific exchanger. For example, if there is an exchanger with a 6^{th} bundle in service, a Weibull analysis is performed using the 5 previous bundles failure data for that exchanger. This is a 2-parameter (η and β) Weibull analysis.

2. An exchanger has no prior tube bundle failure data. In this case a slightly different Weibull analysis (Weibayes) is used. The Weibayes approach combines the methods of Weibull with the principles of Bayes theorem to develop statistical inferences using a combination of prior knowledge and current observations. The principle assumption of the Weibayes approach is that the shape parameter, β, which represents the slope of the Weibull plot for the group of similar bundles, will be identical to the bundle under evaluation. This assumption is valid for similarly designed bundles in similar service with the same failure mechanisms. The Weibayes approach provides a statistical failure analysis without large amounts of failure data for the specific bundle under evaluation.

Both Weibull analyses use a median rank regression analysis procedure to determine the Weibull parameters.

5.A.4 Required and Recommended Data to Perform a Weibull Analysis

The minimum required data to perform an RBI analysis of an exchanger bundle is given in Table 8.1. Additional information is recommended to determine η and β from a Weibull statistical analysis using a reliability library. This information is used to match criteria from the reliability library and filter the library to a subset of bundles with similar physical design and service. More data provided from the recommended data improves the subset of bundles that will represent the bundle under evaluation. The list of recommended additional data to perform a Weibull analysis is listed in Table 5.A.1.

5.A.5 General Steps to Determine Weibull Parameters from an Exchanger Bundle Reliability Library

The following steps outline the procedure to determine Weibull parameters from a matching cut-set chosen from an exchanger bundle reliability library. If there are sufficient bundle failures of the specific exchanger, a Weibull analysis using only those bundles should be performed.

a) STEP 1: Provide the required and recommended bundle failure data or use a reliability library.

   A reliability library is required for evaluation of risk associated with bundle failure. Specific exchanger data are required for each bundle in the reliability library. Minimum basic data required are indicated in Table 8.1. Recommended additional data needed for matching/filtering capability using a bundle reliability library are shown in Table 5.A.1.

b) STEP 2: Determine the specific bundle failures or matching criteria cut-set[1].

A group of bundles with similar characteristics is selected to create the data set for the Weibull analysis using the bundle reliability library and filtered using the data defined in Part 5, Section 3.11, Table 8.1 and Table 5.A.1. The bundle reliability library if filtered to isolate one specific damage mechanism and to create an acceptable Weibull plot. It is important to note that exchanger bundles experience several damage mechanisms including corrosion, pitting, cracking, erosion/corrosion, vibration damage, mechanical failure, and tube end thinning. Failure data as well as “no-failure” data (suspensions) are used in the plotting of the Weibull curve.

[1] Cut-sets are the unique combinations of component failures that can cause system failure. Cut-sets are user defined partial data sub-sets of a heat exchanger bundle reliability library that share common attributes such as tube material, exchanger type, process unit, and shellsideor tubside fluids.

c) STEP 3: Perform the Goodness of Fit Test

The bundle data will not plot properly if the Weibull plot is created from a broad cut-set of the bundle reliability failure library. This is often caused by including multiple failure mechanisms in the plot and requires further filtering of the matching criteria to isolate the failures for one mechanism. A goodness of fit test is required to determine whether the subset of data accurately represents the bundle.

The two approaches for Goodness of Fit Test for the data are $pve\%$ and r^2 methods, outlined in the New Weibull Handbook [14]. In general, a $pve\%$ of > 20% is adequate for small failure sample sizes (< 20) and $pve\%$ fit improves at it approaches 100.

d) STEP 4: Determine Weibull Parameters from the Matching Cut-Set

The Weibull parameters β and η are obtained after the Goodness of Fit Test has been applied in accordance with the Weibull Handbook methodology [14]. The standard method and best practice for estimating the Weibull parameters β and η for small to moderate-sized data sets is a median rank regression curve fitting using the time-to-failure as the dependent variable (X onto Y). Commercial software is available for performing a Weibull statistical analysis.

NOTE most statisticians use confidence bounds on data to account for statistical distribution of the data. A 90% Lower Bound Confidence (LBC) interval is recommended using Fisher Matrix Bounds [19]. A 90% LBC interval provides a 90% confidence that the data point will fall to the right of the line on a Weibull plot.

5.A.6 Example Determination of Weibull Parameters using Weibayes Analysis with a Reliability Library

Exchanger bundle 191-X-25A was evaluated using a bundle reliability failure library to match the following criteria:

a) Tubeside fluid category – Crude
b) Controlling damage mechanism – General corrosion
c) Tubeside operating temperature range between 350ºF and 500ºF
d) TEMA type AES
e) Exchanger type – liquid/liquid process exchanger
f) Sulfur content greater than 1%

Of the nine bundles matching the criteria in the library in Table 5.A.2, five were failures and four were suspensions (bundles in-service without failure reported). Three records were inspection records for the specific bundle under evaluation (191-X-25A). The remaining data was obtained for similar service bundles in the reliability library.

The data from Table 5.A.2 was plotted as a Weibull distribution in Figure 5.A.1 and calculated Weibull parameters for this matching bundle set were:

$$\beta = 2.568 \qquad \textit{slope parameter}$$

$$\eta = 20.45 \qquad \textit{characteristic life in years}$$

The Goodness of Fit Test parameter, $pve\%$, is shown in Figure 5.A.1 to be 99.9 which implies that the data properly fits a Weibull distribution.

POF as a function of time is determined for the cut-set data using Part 5, Equation (5.56).

$$P_{f,adj}^{tube} = 1 - \exp\left[-\left(\frac{t}{\eta_{mod}}\right)^{\beta}\right]$$

$$P_{f,adj}^{tube} = 1 - \exp\left[-\left(\frac{t}{20.45}\right)^{2.568}\right] \tag{5.A.1}$$

NOTE: the difference in η if only the previous bundles are used in the Weibull analysis.

Table 5.A.2 shows 191-X-25A bundle failures experienced after 18 and 22 years. The third bundle (T3) was in-service for 16 years without failure (suspension). The modified characteristic life may be recalculated using Part 5, Equation (5.51) as demonstrated below:

$$\eta_{mod} = \left(\frac{1}{r}\sum_{i=1}^{N} t_{i,dur}^{\beta}\right)^{\frac{1}{\beta}}$$

$$\eta_{mod} = \left[\frac{(22)^{2.568} + (18)^{2.568} + (16)^{2.568}}{2}\right]^{\frac{1}{2.568}} = 22.16 \text{ years} \tag{5.A.4}$$

The characteristic life for the specific bundle experience is higher than the 20.45 year characteristic life calculated using the matching bundles from the reliability library (Figure 5.A.1).

It should be noted that this method assumes that the operating conditions for the bundle have not changed for the time period being evaluated and has not been redesigned. Changes in metallurgy, process conditions, or bundle design should be considered to determine if all of the past bundle history is representative of the current bundle under evaluation.

5.A.7 Nomenclature

The following lists the nomenclature used in Section 5.A.1.

β	is the Weibull shape parameter that represents the slope of the line on a POF vs. time plot
η	is the Weibull characteristic life parameter that represents the time at which 62.3% of the bundles are expected to fail, years
P_f^{tube}	is the probability of the bundle failure, failures/year
$pve\%$	is a goodness of fit test method for the data
r^2	is a goodness of fit test method for the data
t	is time, years

3.A.8 Tables

Table 5.A.1 – Minimum Required Data to Determine Weibull Parameters

Bundle Attribute	Comments/Example Input
General Data	
Exchanger Type	Exchanger type or function e.g. steam generator, steam reboiler, vaporizer
Tube Type	Type of tube (e.g. plain, finned tube or twisted tube)
Tube Specification	Tube material specification and grade from TEMA datasheet and/or ASME manufacturer's form (e.g. SA-179, SA-213-TP304)
Tube Material	Tube material type (e.g. Carbon Steel, 2.25% Cr, 304L/321/347 SS, 2205 Duplex SS, 904L, Alloy 800, Nickel 200, Titanium Gr. 2, Aluminum Alloy)
Process Unit	Process unit type (e.g. Amine Treating, Crude Distillation Unit, Delayed Coker, Hydrogen Reforming, Sour Water Stripper, Tail Gas Treater, Ethylene, Polypropylene, Styrene)
Fluid Name	Fluid name or description (e.g., crude, effluent, heavy gas oil (HGO))
Fluid Category	Fluid category (e.g. heavy crude feed, medium distillate, rich amine, H_2S, hydrofluoric acid, well water, CO_2)

Table 5.A.2 – Example - Matching Bundles from Reliability Library

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

3.A.9 Figures

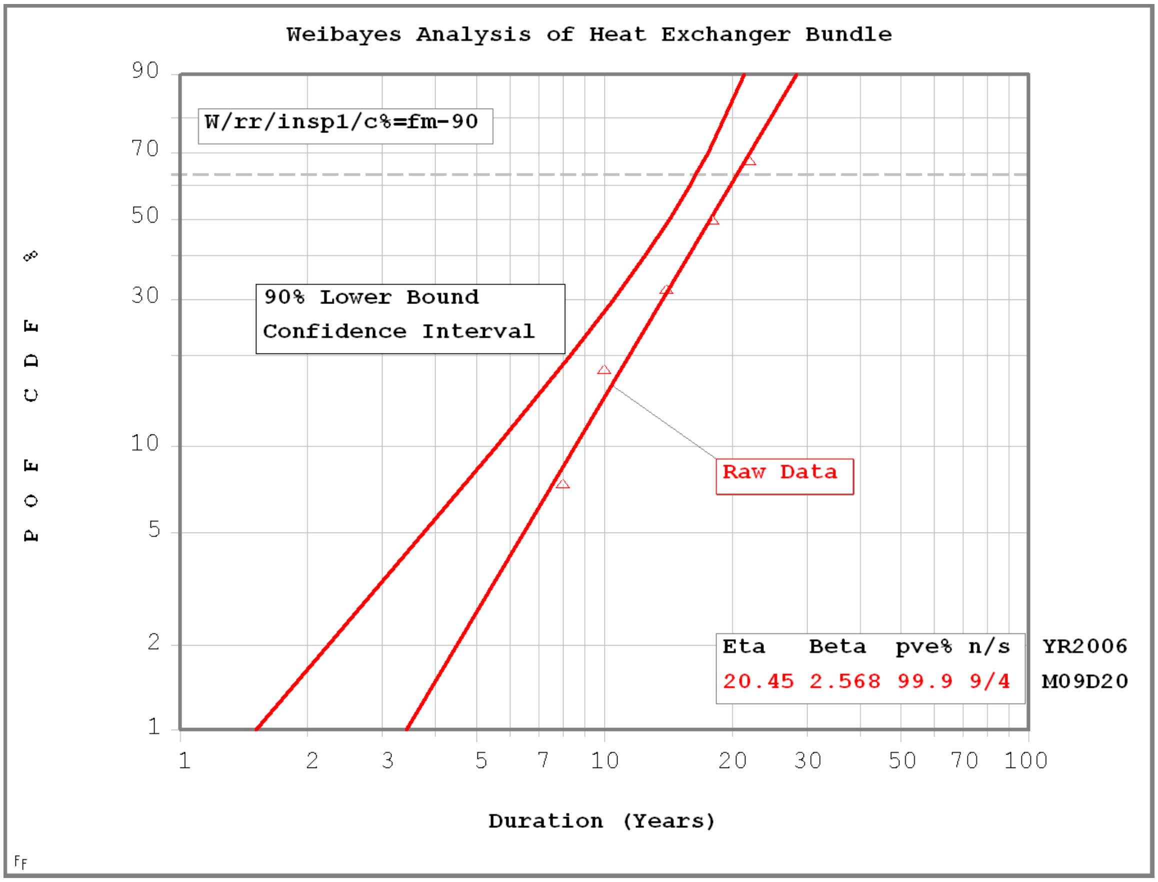

Figure 5.A.1 – Weibull Plot of Similar Bundle Data