MANITOBA HYDRO
ASSET DEGRADATION CURVE DEVELOPMENT

Kinectrics Report: K-814015-RA-0001-R02

July 20, 2017

Kinectrics Inc.
800 Kipling Avenue
Toronto, ON M8Z 5G5
Canada

www.kinectrics.com

DISCLAIMER

MANITOBA HYDRO
ASSET DEGRADATION CURVE DEVELOPMENT

Kinectrics Report: K-814015-RA-0001-R02

July 20, 2017

Prepared by:

Fan Wang Ph.D. P. Eng.
Senior Engineer/Scientist

Reviewed by:

Katrina Lotho B. ESc. B. Sc. P. Eng.
Senior Engineer/Scientist

Approved by:

Yury Tsimberg M. Eng. P. Eng.
Director – Asset Management

Dated: 2017-07-20

To: Manitoba Hydro
360 Portage Avenue
Winnipeg, MB R3C 0G8

Revision History

Revision Number	Date	Comments	Approved
R00	2017-03-28	Draft	
R01	2017-04-30	Draft	
R02	2017-05-28	Draft	
R02	2017-06-29	Draft	
R02	2017-07-20	Final	

EXECUTIVE SUMMARY

A study was conducted aiming at developing asset degradation curves for the major asset groups at Manitoba Hydro (MH), namely Transmission/Distribution/Generation Transformers, Transmission Oil/Air/SF6 Circuit Breakers, Generation Air/Oil Circuit Breakers, Conductors, Wood Poles, Electromechanical/Solid State/Digital Relays, Steel Structures, Steel Structure Footings PIPE/PIFA/Stubs Legs.

Given the data availability at MH at this stage, asset removal based degradation curves were developed for most of the asset groups except for Transmission SF6 Circuit Breakers, Conductors and Structures, in which cases the industry curves were adopted.

Asset condition based degradation curves were developed for some selected asset group that had their Asset Health Index (AHI) information ready, namely Transmission Transformers, Transmission Oil Circuit Breakers, Wood Poles, and Electromechanical/Solid State/Digital Relays.

For the selected asset groups with AHI data, AHI vs Annual Failure Rate curves were also developed based on some assumptions validated by MH.

For most of the assets groups, MH's removal curves indicate that MH's assets tend to stay in service longer than in other jurisdictions. Since the "removal based" curves are rather conservative due to replacement of assets for reasons other than condition, i.e. resulting in shorter useful lives, the expectation is that the "condition based" curves will demonstrate even longer service lives.

It is also worth noting, however, that this conclusion is based on the removal data available for only the last 10 to 15 years depending on the asset category. Earlier removals were not included, and it is not known which way they would have affected the removal based degradation curves.

MH is recommended to differentiate between condition based and non-condition based removals in the future collection of asset removal information.

This page is intentionally left blank.

DEFINITIONS

Terminology	Acronym	Definition
Annual Failure Rate		The rate of removal of an asset group at a given year.
Asset Health Index	AHI	A quantified index that indicates the overall condition status of an asset unit, based on condition data such as nameplate information, test results, asset inspection records, corrective maintenance records, operational experience, etc.
Degradation		The act or process of decline in strength and/or value of an asset unit, due to physical wear-out, degraded technical characteristics, incompliance with updated operation needs, or other economic considerations by utilities.
Effective Age		The age corresponding to the probability of failure based on actual condition status of an asset unit
Failure		The status that makes an asset to be removed out of service permanently.
Probability of Failure	POF	The percentage of a group of assets that will fail at or before a specific age.
Removal		The action of taking an asset unit out of service due to degradation.
Scale / Shape	α / β	Weibull distribution parameters indicating the distribution range and variation steepness respectively

Terminology	Acronym	Definition
Survival Percentage		The percentage of a group of assets that will survive at or before a specific age.
Trend Line		A linear approximation of correlation between 2 parameters.
Weibull Distribution		A continuous probability distribution expressed in exponential function, with known versatility of adapting to different types of hazard scenarios.

TABLE OF CONTENTS

This page is intentionally left blank.

TABLE OF FIGURES

This page is intentionally left blank.

TABLE OF TABLES

This page is intentionally left blank.

INTRODUCTION

Manitoba Hydro (MH) engaged Kinectrics Inc (Kinectrics) as a successful bidder in the response to the MH's RFP 039928 "Provision of Asset degradation curves for Long Term Asset Planning".

As requested in the RFP, the development of the degradation curves is to be based on MH's historic maintenance and replacement records, i.e. these curves represent the practice at MH and therefore are MH specific.

Theoretically speaking, an asset degradation curve should be based on the removals that were due to asset condition degradation. In this study, the following information was available:

a. Historic removal records, including both the condition based and non-condition based scenario. This applies to all the asset groups

b. Existing demography. This applies to most of the asset groups

c. Asset Health Index (AHI) results for existing demography. This applies to a few selected asset groups

With the data availability mentioned above, this report presents findings that included development of the following 3 types of curves for the asset groups specified in the RFP, based on MH's removal statistics and comparison of some of these curves with available utility industry curves:

- Asset removal based degradation curves (all asset groups), i.e. Probability of Removal vs Chronological Age
- Asset condition based degradation curves (selected asset groups with AHI information), i.e. Probability of Failure vs Chronological Age
- Asset health index (AHI) vs Annual Failure Rate curves (selected asset groups with AHI information)

These curves for individual asset groups are presented in the Appendix to this report for each of the asset categories. Additionally, the report includes the following information:

- Summary of the Weibull parameters for each of the asset groups and degree of the fitting based on the provided information
- Description of different approaches based on the availability and quantity of the removal data provided by MH
- Curve fitting methodology
- Explanation of the difference between "removal based" and "condition based" degradation curves and approaches for deriving them depending on the availability and quantity of the removal data
- Methodology for relating AHI with Probability of Failure

ASSET GROUPS STUDIED IN THIS PROJECT

The following MH asset groups are addressed in this study:

- Transmission transformers
- Distribution transformers
- Generation transformers
- Transmission Oil Circuit Breakers (OCB)
- Transmission Air Circuit Breakers (ACB)
- Transmission SF6 Circuit Breakers (SCB)
- Generation Air Circuit Breakers (ACB)
- Generation Oil Circuit Breakers (OCB)
- Conductors
- Wood Poles
- Relays – Electromechanical
- Relays – Solid State
- Relays – Digital
- Steel structure
- Steel structure Footing -PIPE
- Steel structure Footing -PIFA
- Steel structure Footing -Stubs Legs

DATA PROCESSING APPROACHES

Among all the asset groups, there are 3 typical scenarios with respect to the data sources for degradation curve development:

Scenario 1. An MH asset group has sufficient historic removal records: in such cases, the removal curves were developed using the historical removal data and were in fact “removal” curves rather than failure curves.

Scenario 2. An MH asset group has small size of historical removal records: in such cases, the removal curves were developed based on both the removal data and existing demographic data.

Scenario 3. An MH asset group has very little or no historic removal records: in such cases, the MH-specific removal curve could not be developed and typical industry curves were adopted.

REMOVAL BASED CURVES VS CONDITION BASED CURVES

In this project, the available data from MH were the asset removal records and asset demographics. The removal data could include the records of units that were removed due to both condition based and non-condition based considerations, namely:

1) System or capacity upgrades making a unit unable to operate as design
2) Obsolescence resulting in a lack of spare parts for routine maintenance
3) Economic end of life when replacement is less expensive than continued repairs
4) Actual Failures

A unit can be removed for any combination of the above factors, with removal drivers 1) and 2) usually non-condition based, removal driver 4) usually condition based (with exception being major storms or external causes, e.g. drivers or animals), and removal driver 3) could be either condition or non-condition based. In most cases, however, even in the presence of the main driver for replacement, all other factors listed above are usually taken into consideration. "Replacement" therefore refers to a removal due to either condition or non-condition based decision. This means that for any given chronological age, a unit's corresponding probability of removal and annual removal rate values do not necessarily tell how likely the unit will fail, but rather how likely the unit might get removed. This makes curves developed in this study more conservative as compared with removal curves based on condition alone.

Both removal based and condition based degradation curves have their own applications.

Removal based curves can be used as the basis for predicting the total number of units to be removed in the future, assuming the existing maintenance and replacement strategy and loading will remain unchanged. This provides useful information for capital planning and budgetary considerations usually done at the fleet level.

Condition based curves should be used as the basis for predicting the replacement trend of specific units, assuming the existing inspection and maintenance strategy will remain unchanged. This provides useful information for maintenance staff for making a decision on timing for either switching from time based maintenance to condition based maintenance protocol or and on deciding when it makes sense to actually replace the unit for economic reasons.

In this study, the only available data were MH Asset Health Index (AHI) results and removal based curves. In the later section, details are presented to indicate the way to convert removal based curves to condition based curves.

DEFINITIONS IN CURVE FITTING

As the removal data included both condition based and non-condition based events, in this study the term "Failure" addresses all the removals (refer to Definition section).

The following example diagram illustrates the definitions in curve development in this project, for both the asset removal based curves and AHI vs condition based curves.

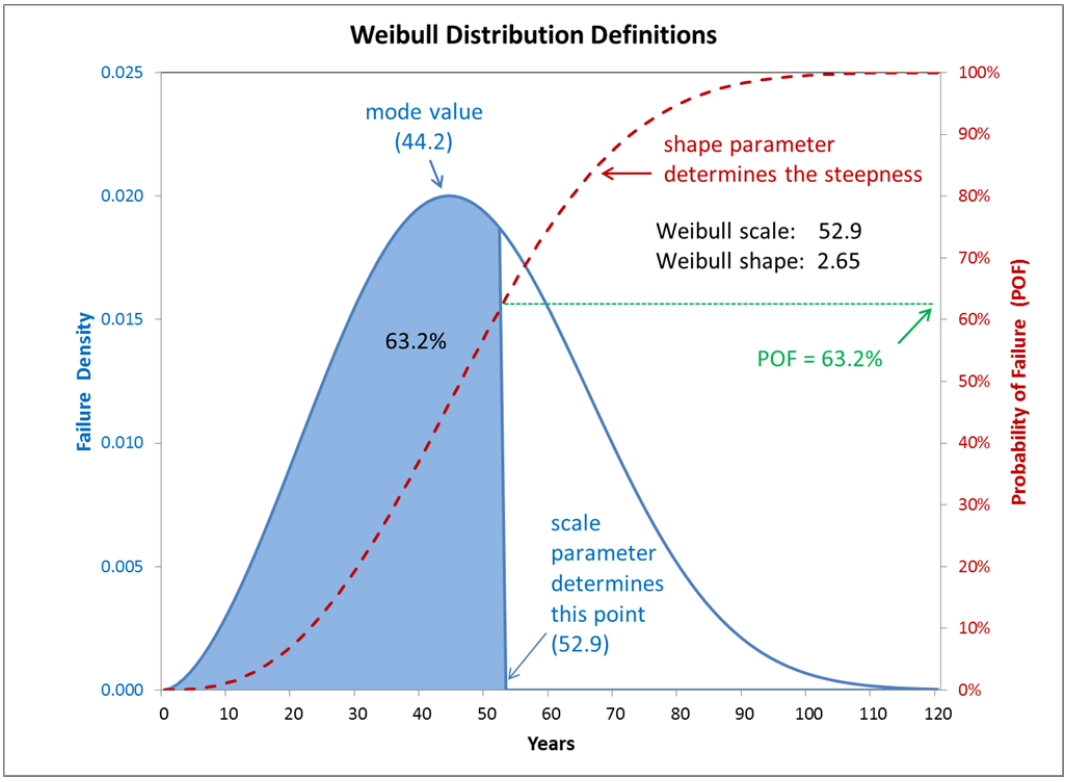

Figure 1 Example of Weibull Distribution Curve

In the Figure 1,

- The **Weibull scale** value represents the age when $1-e^{-1}$ =63.2% of the entire fleet would get removed
- The **Weibull shape** value represents the steepness of removal acceleration, the higher the shape value the quicker the removal rate changes.
- The mode age represents the most likely age at removal

Furthermore, in Table 1 below, curve fitting correlation coefficient represents the accuracy of the assumed Weibull distribution model so that the closer it is to 1, the more accurate the model is to Weibull distribution.

CURVE FITTING METHODOLOGY

In this study, linear regression approach was adopted to handle the removal data that were assumed to follow Weibull distribution.

By definition, linear regression models the relationship of groups of points scattered on x-y coordinates, so as to find the best-fitting straight line through them, yielding the minimum standard deviation.

Since Weibull distribution function is not linear, it is necessary to transform it into the form of a linear expression so as to adopt linear regression.

For a standard expression of Weibull cumulative probability of event

$$\boldsymbol{F(t) = 1 - e^{-(\frac{t}{\alpha})^{\beta}}} \qquad \textbf{Equation 1}$$

Where
- α Weibull scale as defined in previous section
- β Weibull shape as defined in previous section
- t time, i.e. the chronological age in this study

For a given sample with a population of *n* units, the expected number of events by time *t* is:

$$\boldsymbol{N(t) = \left(1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}}\right) n} \qquad \textbf{Equation 2}$$

Rewrite the above expression into the following format:

$$\boldsymbol{\ln\left(ln\left(\frac{1}{1-\frac{N(t)}{n}}\right)\right) = \beta \ln(t) - \beta \ln(\alpha)} \qquad \textbf{Equation 3}$$

This converts the previous exponential expression into a linear expression. For any historic removal data from MH in this study, they can be sorted by their removal ages in ascending order as shown in the following example:

Rank (i)	Removal Age (t)
1	9
2	12
3	12
4	15
…	…
17	26

The term N(t)/n is the expected rank for a failure occurring at time t. In statistics, it can be approximated using the following formula:

$$\frac{\boldsymbol{N(t)}}{\boldsymbol{n}} \approx \frac{\boldsymbol{i-0.3}}{\boldsymbol{n+0.4}} \qquad \textbf{Equation 4}$$

Where n population size of removal sample
i rank of the unit failing at time t

Let $Y(t) = ln\left(ln\left(\frac{1}{1-\frac{i-0.3}{n+0.4}}\right)\right)$ and X(t) = ln(t), Equation 3 can be rewritten as:

$$\boldsymbol{Y(t) = \beta\, X(t) + \beta \ln(\alpha)} \qquad \textbf{Equation 5}$$

This allows linear regression to calculate the α and β that minimize the standard deviation of such a straight line.

When the sample size of removal data is small, the accuracy of the above method might get compromised. In such a case, the ages of the units that are still in service (the right censored data in statistics) should also be taken into account by adjusting the median rank calculation shown in Equation 4.

The accuracy of the developed curves (i.e. their correlation to a true Weibull distribution curve) can be assessed by checking the regression statistics results. Among all the indices that indicate such a correlation, in this study the correlation coefficient was examined. The closer it is to 1, the closer the curve is to Weibull distribution.

LINKING ASSET HEALTH INDEX TO FAILURE RATE

When an asset is in service, it is exposed to external stresses. An event will happen when external stress exceeds its internal strength or condition. Replacement is the result of combined effects from both the strength (condition) and stress.

Asset Health Index is a mathematical quantification of an asset unit's internal strength (condition) and is based on available technical information, such as inspection and testing results, historical loading, nameplate data and input from maintenance staff.

However, in practice it is almost impossible to know the exact external stress, as it is a combined impact of various factors, e.g. continuous loading, fault magnitude and duration, switching and lightning surges, etc. so there is no precise way to quantify these factors. As a result it is challenge to interpret meaning of Health Index value, specifically how likely an asset unit could resist the external stress or how likely it would fail under the external stress.

One possible approach to relate Health Index with the probability of failure is to start from the result: although the stresses inputs are unknown, the consequence of stresses can be tracked in the degradation curves.

The following approach is proposed to link Asset Health Index to probability of failure (POF).

1) Initially assign 2 sets of mapping points:

	AHI	POF
Point 1	100%	0%*
Point 2	25% *	99% *

* Could be of different value for different assets

2) Assume the combined external stress is of normal distribution and then move AHI at a constant rate between the above assigned 2 values and calculate the corresponding POF value each time. This allows an initial AHI vs POF curve to be produced.

3) Develop removal based curves (POF vs Age, Annual Failure Rate vs Age) based on MH's historic removal statistics.

4) With the information in 2) and 3), the AHI vs Annual Failure Rate curve is obtained.

5) Starting from the AHI vs Annual Failure Rate curve, MH could calculate the number of units that require action each year.

6) The calculated number of units to be addressed each year is reviewed by MH subject matter experts, and the gap is used for iteration of adjusting point 2 in step 2)

7) The iteration is terminated when the number of flagged for action units complies with MH experience. The final HI vs POF curve is thus established.

However the above approach requires historic Asset Health Index analysis results as well as historic removal records following the AHI analysis. It is applicable if a utility has relatively stable maintenance and replacement strategy. When there is change in such strategy or Health Index formulation, the data needs to be re-set and new iteration analysis is needed.

In this study, a simplified approach was proposed to convert the removal based curves to condition Based Curves. In this methodology, both the removal based curves and MH's HI vs Age information are used.

To establish link between a removal based and a condition based degradation curve, both curves are to be approximated by straight lines. In the former case, it is the line that links the point at age zero and the point at end of life. In the latter case, it is the trend line of MH's HI vs Age correlation chart. By assuming these straight lines sharing the same HI value at their characteristic ages (corresponding to survival percentage of 36.8% for Weibull distribution), one could build up the condition based degradation curve. The following diagram shows the methodology. Steps from removal based curve to condition based curve are marked by sequential numbers.

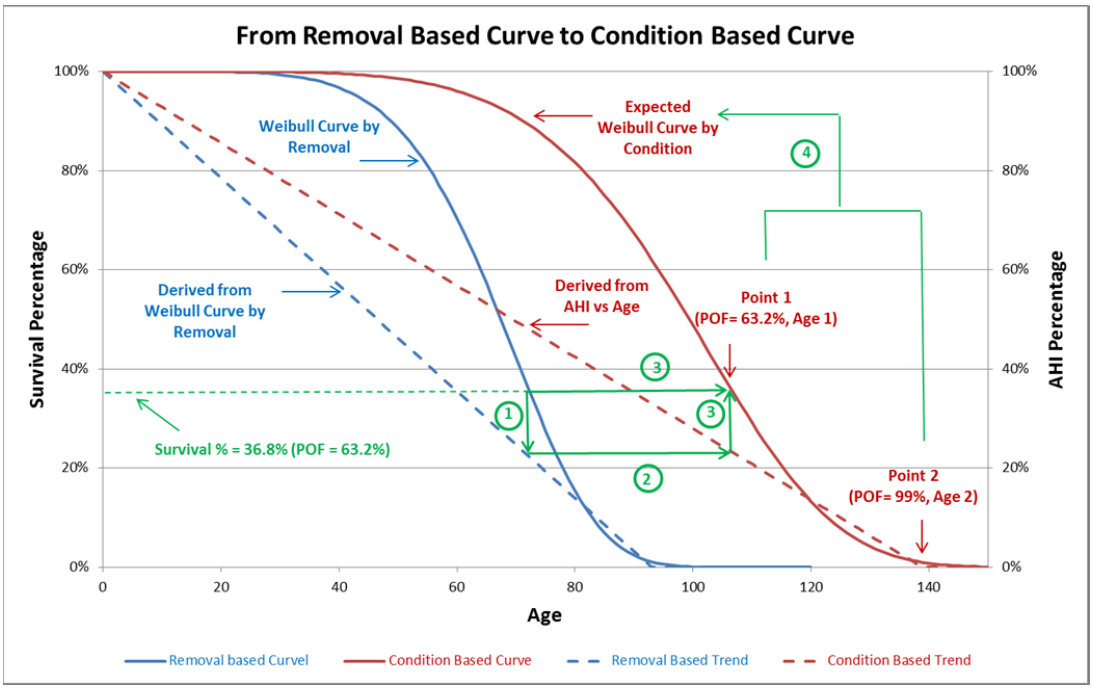

Figure 2 From removal based curve to condition based curve

With the condition based curve developed, the relationship between AHI and failure rate is known.

SUMMARY OF REMOVAL BASED DEGRADATION CURVE RESULTS

Table 1 shows a summary of the removal based asset degradation curve results. Bear in mind the results for all types of relays were at relay family level, not at relay unit level.

Table 1 Summary of removal based asset degradation curves

Asset	MH Data Size		Weibull Curve Parameters (Removal Based)		Mode Age at Removal	Curve Fitting Correlation Coefficient
	Removal	Existing Population	Scale	Shape		
Transmission transformers	19	265	83.69	5.15	80	0.978
Distribution transformers	39	193	93.26	2.84	80	0.975
Generation transformers	41		69.79	2.52	57	0.948
Transmission OCB	34	195	71.84	5.82	70	0.985
Transmission ACB	8	23	50.31	17.55	50	0.945
Transmission SCB			45.52	8.54	45	Sample too small
Generation ACB	30	24	53.85	6.87	53	0.791
Generation OCB	22	33	65.38	9.27	65	0.924
Conductors			59.28	4.36	56	No sample available
Wood Poles	560		56.42	5.77	55	0.975
Relays – Electromechanical	2345		47.27	5.64	46	0.966
Relays – Solid State	391		31.44	1.91	21	0.953
Relays – Digital	60	3686	37.54	2.99	33	0.950
Steel structure			70.23	3.30	63	No sample available
Steel structure Footing -PIPE Mat	41		25.32	8.37	25	0.918
Steel structure Footing -Quadruped	45		39.02	8.91	39	0.816

No data adopted 12 Industry data

Following are observation regarding the developed degradation curves:

- Transformers and circuit breakers had relatively small removal sizes. As they have good inventory records on the in-service units, their removal based degradation curves were developed with reasonable accuracy, based on the combination of both removal and age profile information (Scenario 2).

  The only exceptions were transmission SF6 breakers and generation air breakers. In the former's case, the removal size is too small for any curve fitting so CIGRE curves were used (Scenario 3). In the latter's case, all the removals happened at 2 specific ages, making curve fitting correlation coefficient low.

- Wood poles and relays (including all the sub-categories) have relatively sufficient removal size for curve fitting with reasonable accuracy (Scenario 1).

  The only exception is digital relays, which has relatively small removal size. For this asset category removal based degradation curve is developed by combining the removal and age profile information (Scenario 2).

- All the steel structure footing categories has relatively small sizes and their inventory information is not available for this project. The removal based degradation curves are developed based on removal records only. Their accuracy remains to be validated by MH.

- There is little or no data for overhead conductors and steel structures. Industry experience curves (mainly CIGRE statistics) are adopted (Scenario 3).

The comparison is not available for some of the asset groups, due to lack of industry or MH data.

Details of the results of each asset category are presented in the Appendix of this report, which includes for each asset group the following information:

- Cumulative probability of event vs age curve
- Annual event rate vs age curve
- Event density vs age and removal/age profile curve
- Comparison of MH developed curve with industry experience curves (wherever available)

SUMMARY OF CONDITION BASED ASSET CURVE RESULTS

Table 2 shows a summary of the condition based asset curve results. The results for all types of relays were at relay family level, not at relay unit level.

In this study, some of the asset categories were selected by MH to relate their Asset health Index (AHI) to probability of failure and annual failure rate. These case studies were sufficient to demonstrate the methodology proposed in this study. Other asset groups were not addressed either due to lack of data or due to data quality issue.

Table 2 Summary of condition based asset degradation curves

Asset	MH Data Size		Weibull Curve Parameters (Condition Based)		Annual Failure Rate	
	Removal	Existing Population	Scale	Shape	AHI = 50%	AHI = 20%
Transmission Transformers	19	265	118.01	5.44	0.007	0.060
Transmission OCB	34	195	106.04	5.66	0.007	0.066
Wood Poles	560		90.01	5.89	0.044	0.441
Relays – Electromechanical	2345		90.34	5.83	0.003	0.032
Relays – Solid State	391		68.58	1.87	0.019	0.028
Relays – Digital	60	3686	76.45	2.75	0.014	0.033

No data adopted

Details of the results for each of the above asset categories are presented in the Appendix of this report, which includes the following information:

- AHI vs annual event rate curve
- AHI vs cumulative probability of event curve
- Comparison of removal based curve and condition based curve

CONCLUSIONS AND RECOMMENDATIONS

In this study, asset degradation curves were developed for multiple transmission asset groups at MH. For selected these asset groups, the AHI vs failure rate curves were developed.

The principle in this study was to develop asset event curves based on MH historic removal records. Industrial practice curves were presented for the asset groups whose removal records were unavailable at this time.

For some shortlisted asset groups, the AHI vs event rate curves were developed for the purpose of linking MH's existing AHI results to condition based degradation failure rate.

Among all the asset groups in this study, all but 3 asset groups had available historic removal records for development of asset curves. Transmission SF6 Breakers had removal record that was of too small sample size to conduct curve fitting. Overhead Conductors and Steel structures did not have removal records for curve fitting.

In all the groups with available removal records, the sample size itself was sufficient for curve fitting for wood poles, electromechanical relays and solid state relays. For the other asset groups, current demography information was incorporated together with removal records for better curve fitting accuracy.

In general, the developed MH asset curves (removal based) seem to indicate that most of the MH asset groups considered in this project have longer service lives relative to the other utilities. This could be attributed to MH's very effective and thorough inspection and maintenance practices combined with colder climate which allows equipment to operate at lower temperatures thus reducing overheating stresses.

As the historic removal records included the ones that were removed due to non-condition factors, the actual asset degradation curve based on condition would indicate a longer degradation lifespan of an asset group. Efforts have been taken to work out the condition based asset degradation curves by tracking the condition based removals in data collection at MH.

Due to data availability and data quality, in this study only 6 asset groups were shortlisted for linking AHI to condition based failure rate. These are Transmission Transformers, Transmission Oil Breakers, Wood Poles and all 3 types of relays (Electromechanical, Solid State, Digital).

As for the future, MH is recommended to start collecting removal information for Overhead Conductors and Steel structures, while keeping on the existing process of removal data entries for the other asset groups. For Overhead Conductors, the information of both the age and length at removal is to be recorded.

Further refining the AHI for relays is recommended so as to address the relays at asset unit level rather than model/family level.

APPENDIX A: LINKING AHI TO CONDITION BASED DEGRADATION

This page is intentionally left blank.

From AHI to Condition Based Degradation

The following example shows the detailed steps for linking MH's AHI to condition based degradation.

Step A. Find the removal based trend line

Starting from the removal based degradation curve, an imaginary line can be drawn based on 2 age points corresponding to POF 0% (Survival percentage 100%) and POF 99% (Survival percentage 1%), as shown in the following diagram. These 2 points are assumed to correspond to AHI = 100% and AHI = 0% respectively.

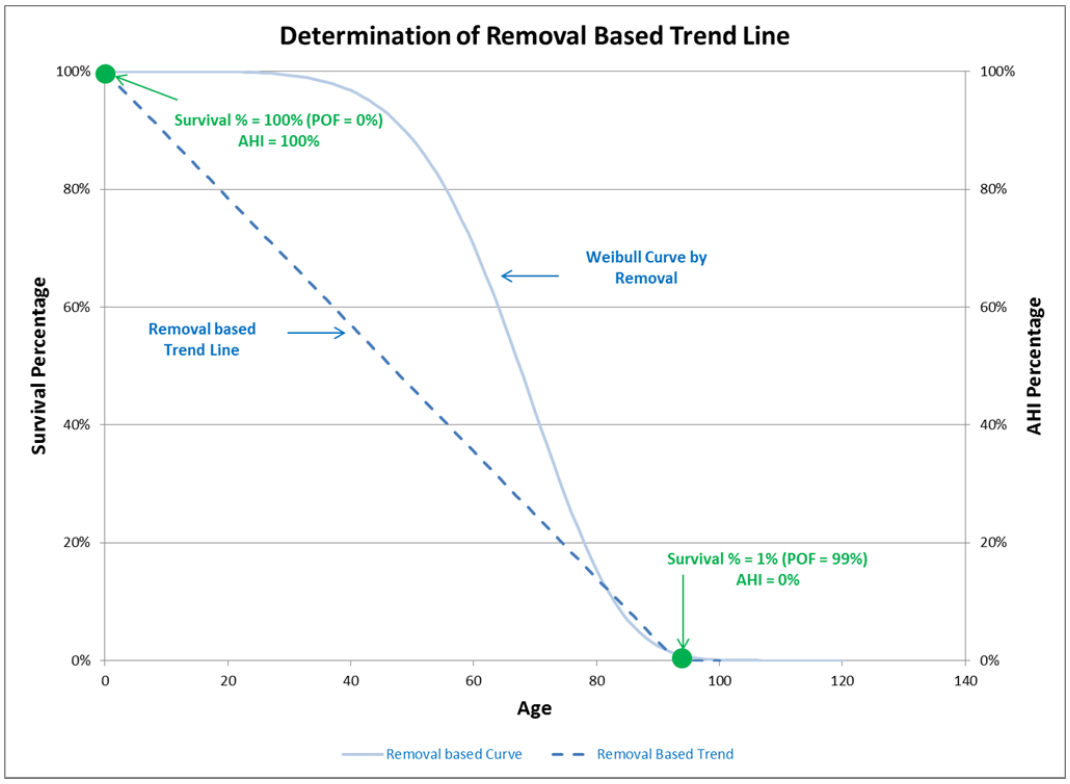

Figure 3 Determination of removal based trend line

Step B. Find the characteristic age and corresponding AHI

The characteristic age of a Weibull distribution corresponds to the one at which the POF = 63.2% (Survival percentage = 36.8%), as shown in the following diagram.

The AHI corresponding to this characteristic age can then be determined on the removal based trend line.

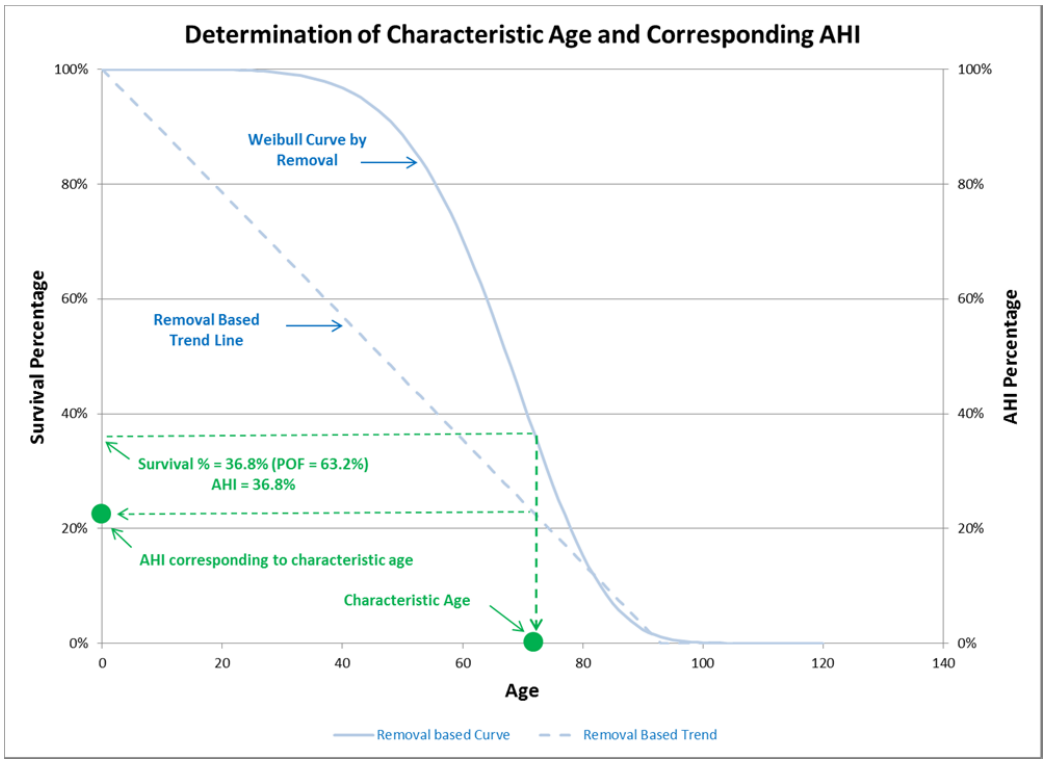

Figure 4 Determination of characteristic age

This completes step 1 as shown in Figure 2.

Step C. Find the condition based trend line

The following diagram shows AHI vs Age correlation. From the diagram it can be observed that the slope of this linear correlation is -0.0072.

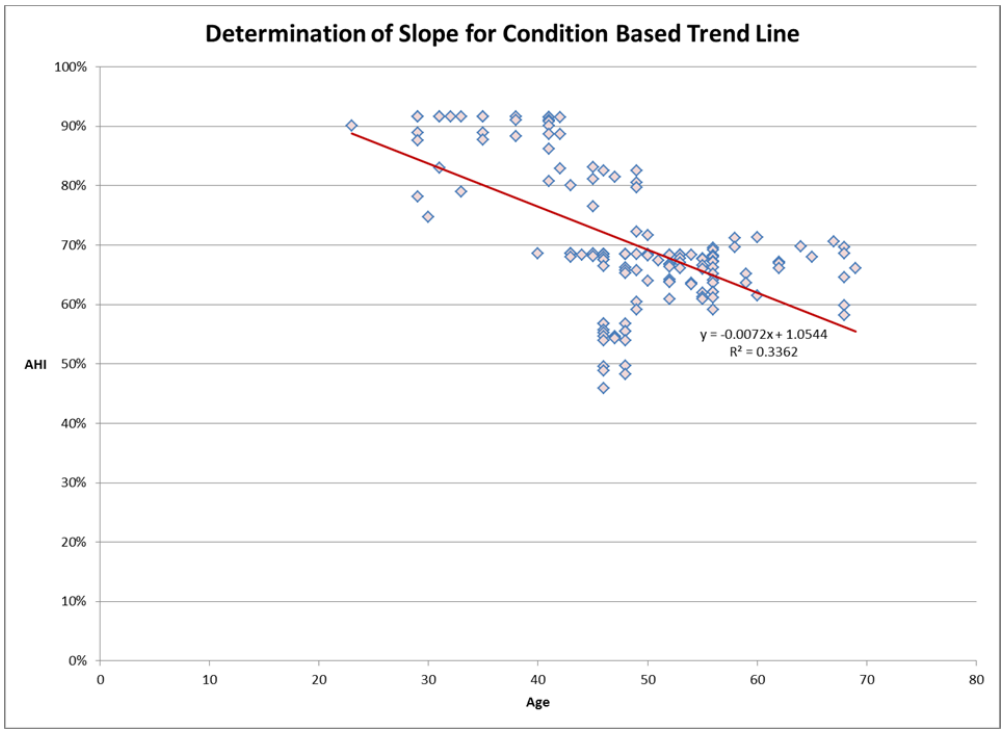

Figure 5 Determination of slope for condition based trend line

With such slope data, a condition based trend line is established by assigning a crossing point at (AHI = 100%, age =0).

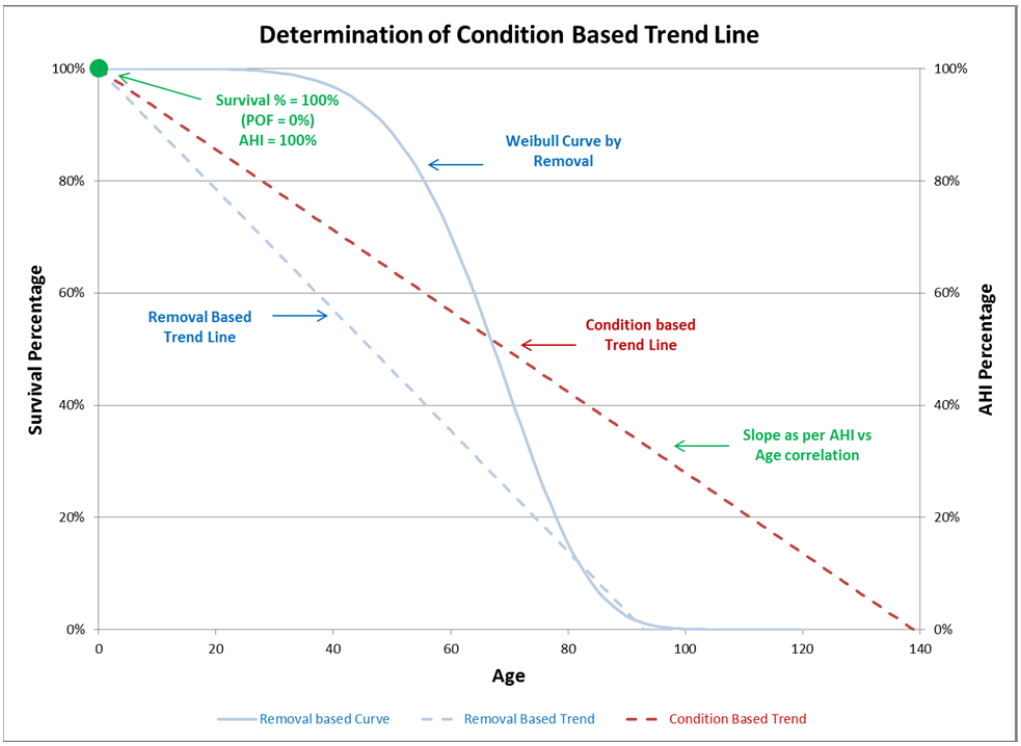

Figure 6 Determination of condition based trend line

This completes step 2 as shown in Figure 2.

Step D. Find the characteristic age of condition based curve

With the assumption that the 2 trend lines have the same AHI at their characteristic ages, the characteristic age of the condition based curve can be determined.

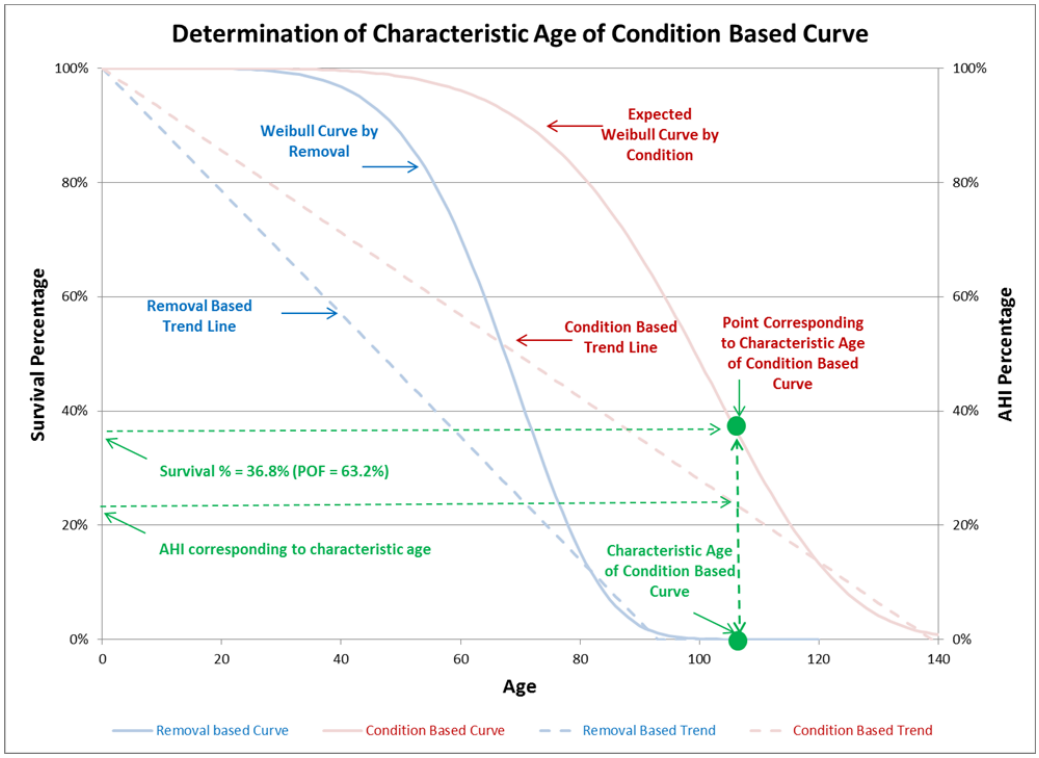

Figure 7 Determination of characteristic age of condition based curve

This completes step 3 as shown in Figure 2.

Step E. Build up condition based degradation curve

The condition based degradation curve can be built up based on the following 2 points:

- Point 1: POF = 63.2%, Age = (characteristic age)
- Point 2: POF = 99%, Age = (the crossing point of the condition based trend line on age axis)

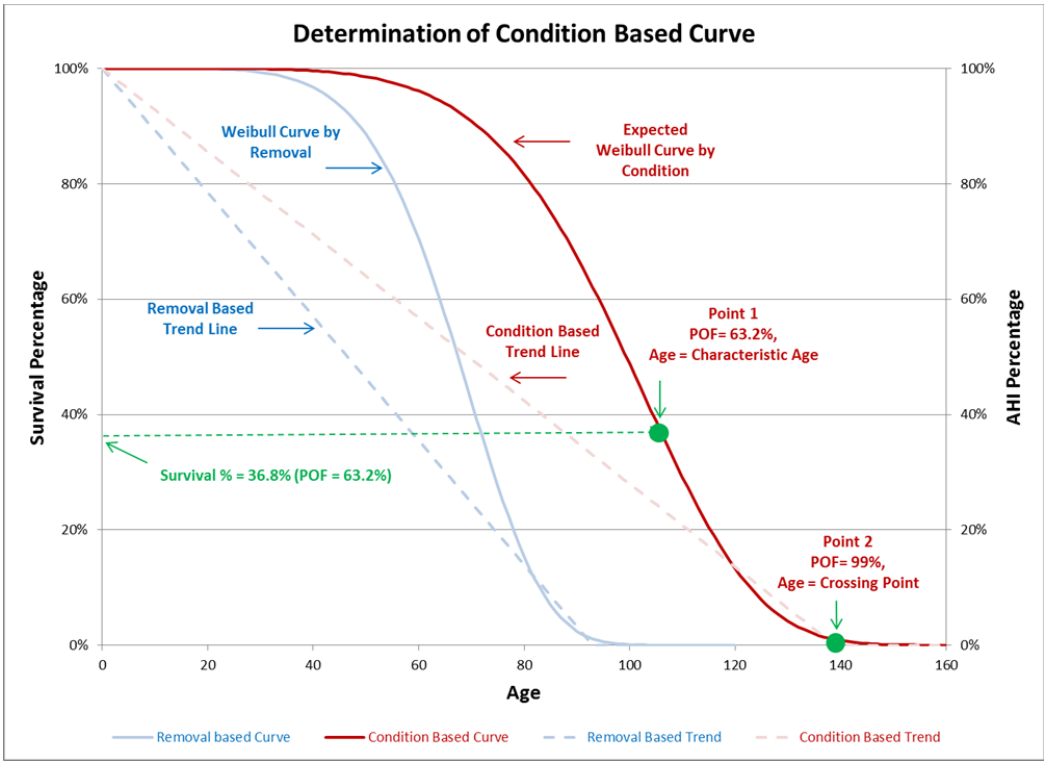

Figure 8 Determination of condition based curve

This completes step 4 as shown in Figure 2.

APPENDIX B: RESULTS FOR EACH ASSET CATEGORY

This page is intentionally left blank.

1. TRANSMISSION TRANSFORMERS

1.1. Removal Size and Population size

This asset group addresses the 110 kV and higher transformers at MH transmission substations.

For this asset category, there are 19 available removal records. They cover the units that were removed during the period of 2004 – 2014.

The root causes for the removals in additional to outright unit failures include one or more of the following factors:

- Capacity increase
- Age
- MH's own condition assessment
- Economic considerations of replacement cost vs increased maintenance cost

Since the removal size is relatively small, the existing age profile of 265 units is also incorporated in developing asset degradation curve.

There is no further sub-categorization by capacity, make, or location.

1.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

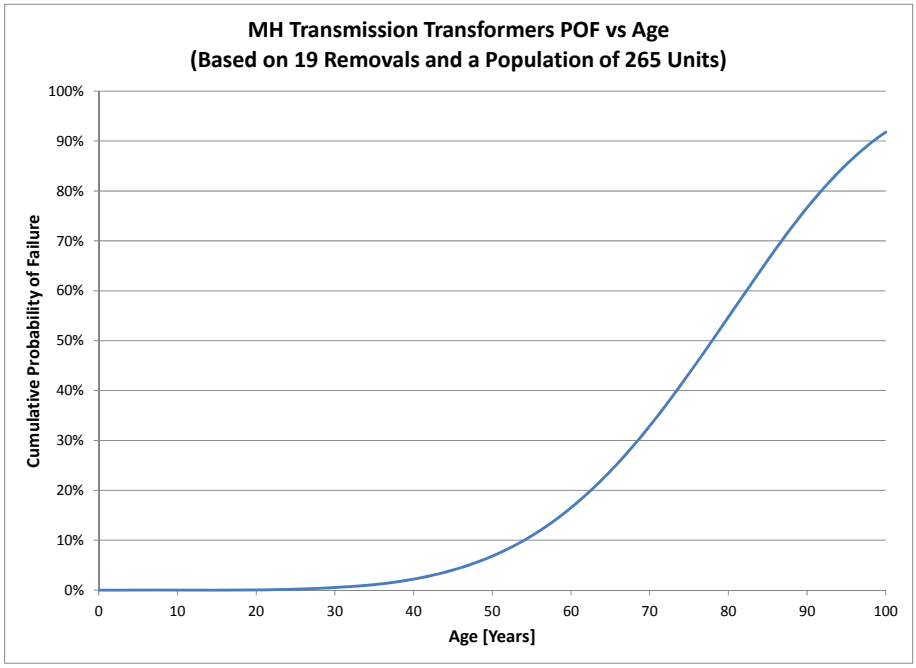

Figure 1-1 Cumulative Probability of Failure vs Age (Transmission Transformers)

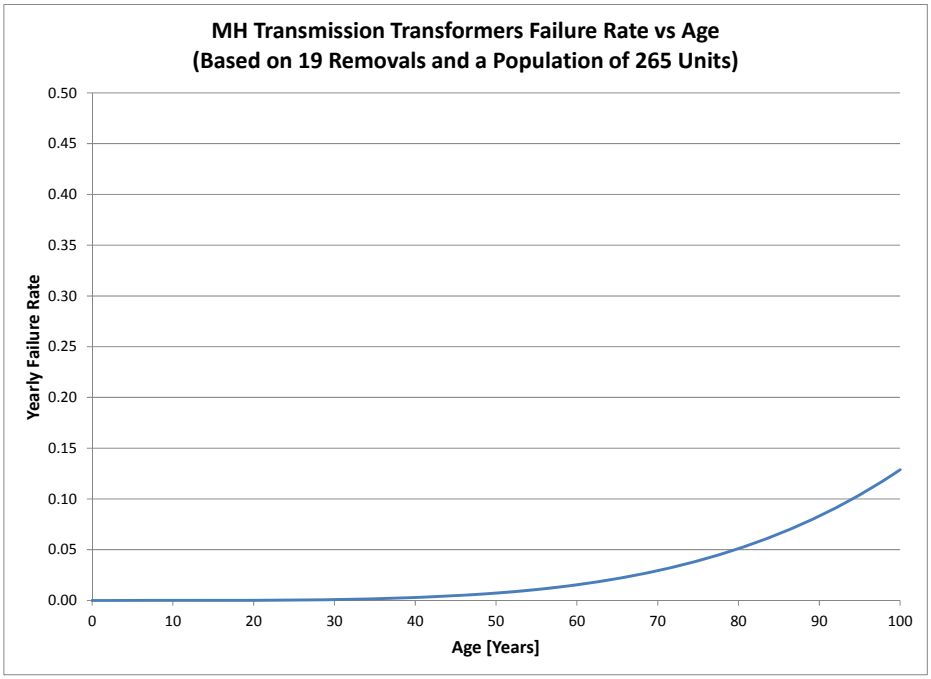

Figure 1-2 Annual Failure Rate vs Age (Transmission Transformers)

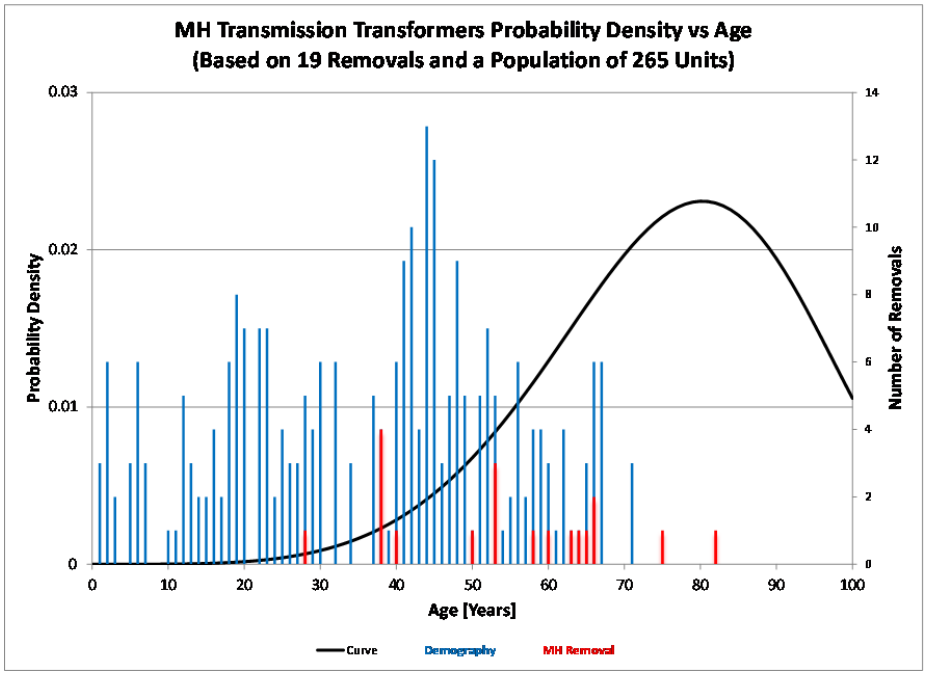

Figure 1-3 Failure Density Curve and Age Profile (Transmission Transformers)

1.3. Comparison of MH Curve with Industry Curves

The following diagram shows the comparison of MH curve with the ones from other utilities in industry.

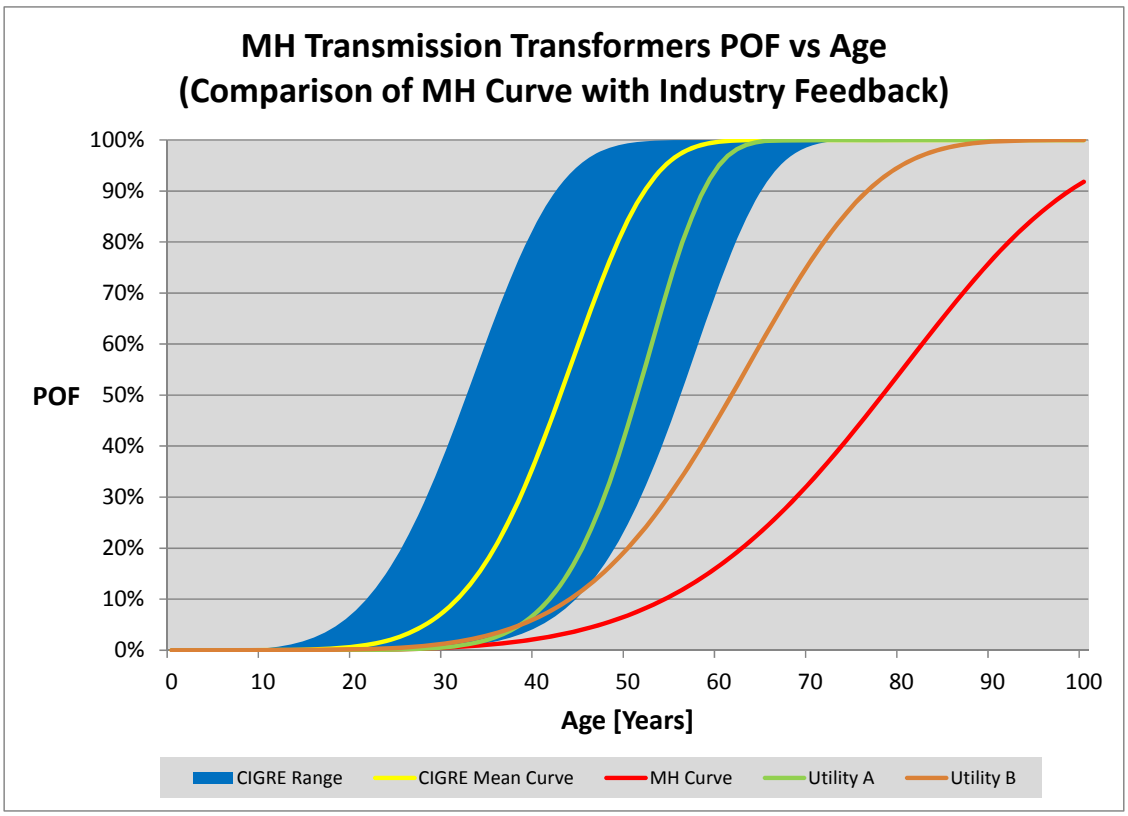

Figure 1-4 Comparison of MH Curve with Industry Experience (Transmission Transformers)

In the above diagram, MH curve is compared with CIGRE statistics and the curves from 2 utilities in North America.

As shown in the diagram, MH curve is an outlier when compared with CIGRE curve range. It also shows much longer service life than the other 2 utilities.

1.4. Link AHI to Condition Based Failure Rate

The following diagrams show the series of developed curves linking AHI to condition based degradation curves.

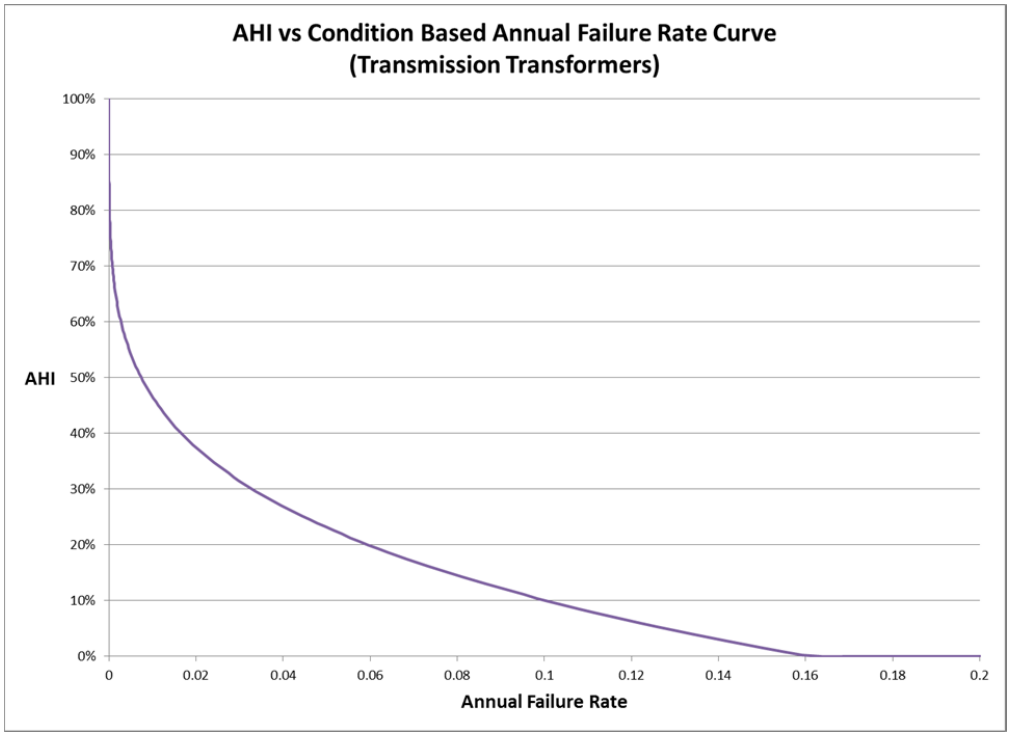

Figure 1-5 AHI vs Annual Failure Rate (Transmission Transformers)

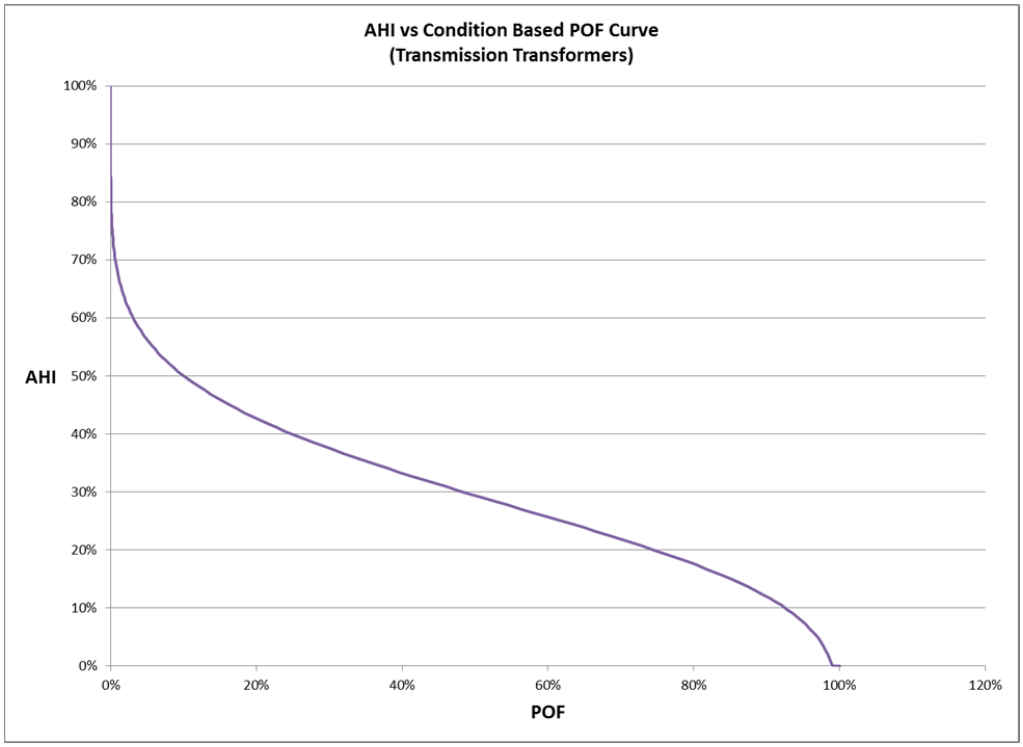

Figure 1-6 AHI vs Cumulative Probability of Failure (Transmission Transformers)

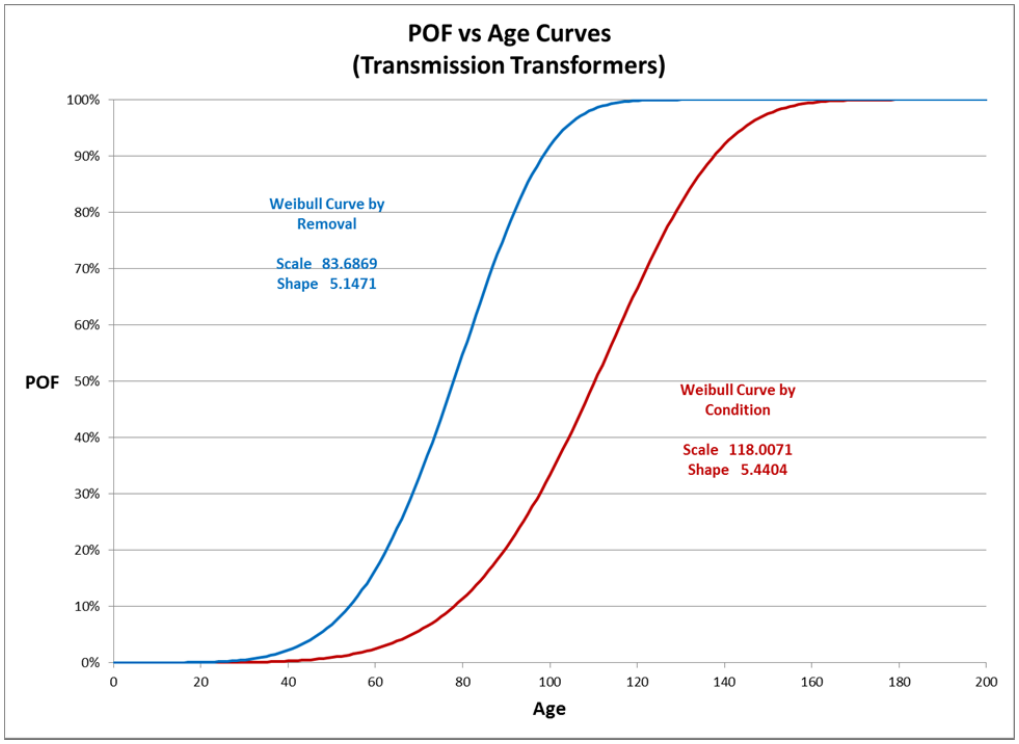

Figure 1-7 Removal Based vs Condition Based POF Curves (Transmission Transformers)

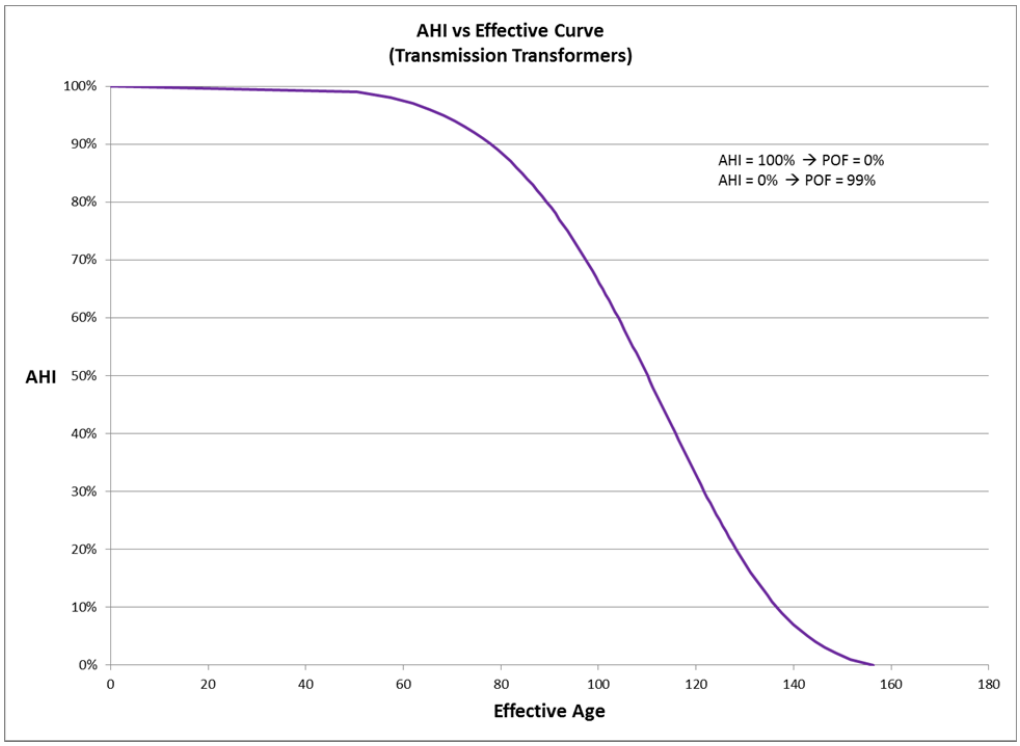

Figure 1-8 AHI vs Effective Age (Transmission Transformers)

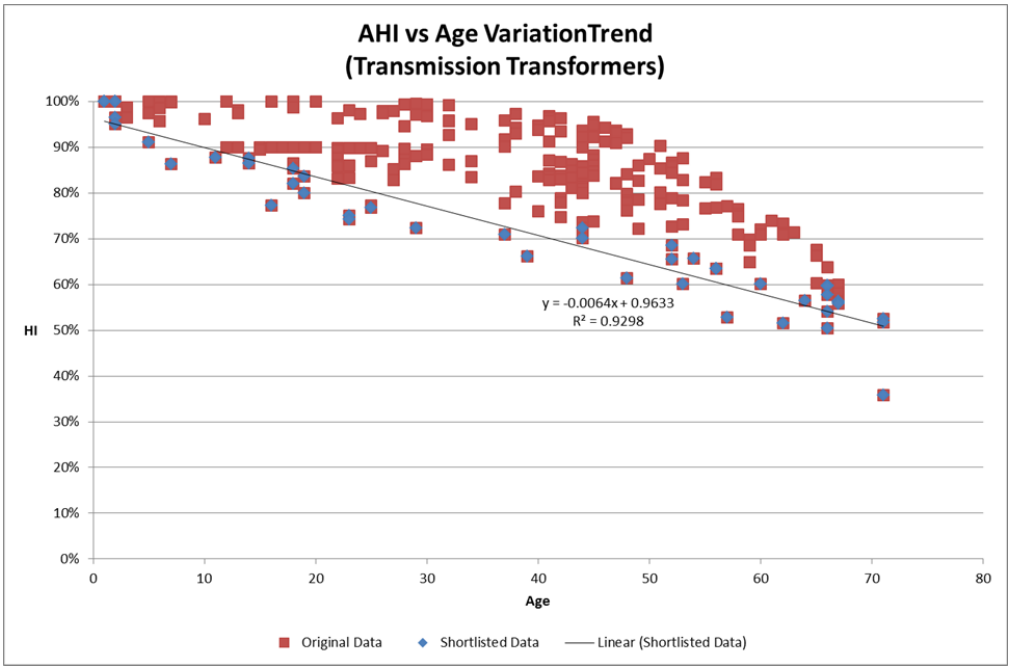

Figure 1-9 AHI vs Age Variation Trend (Transmission Transformers)

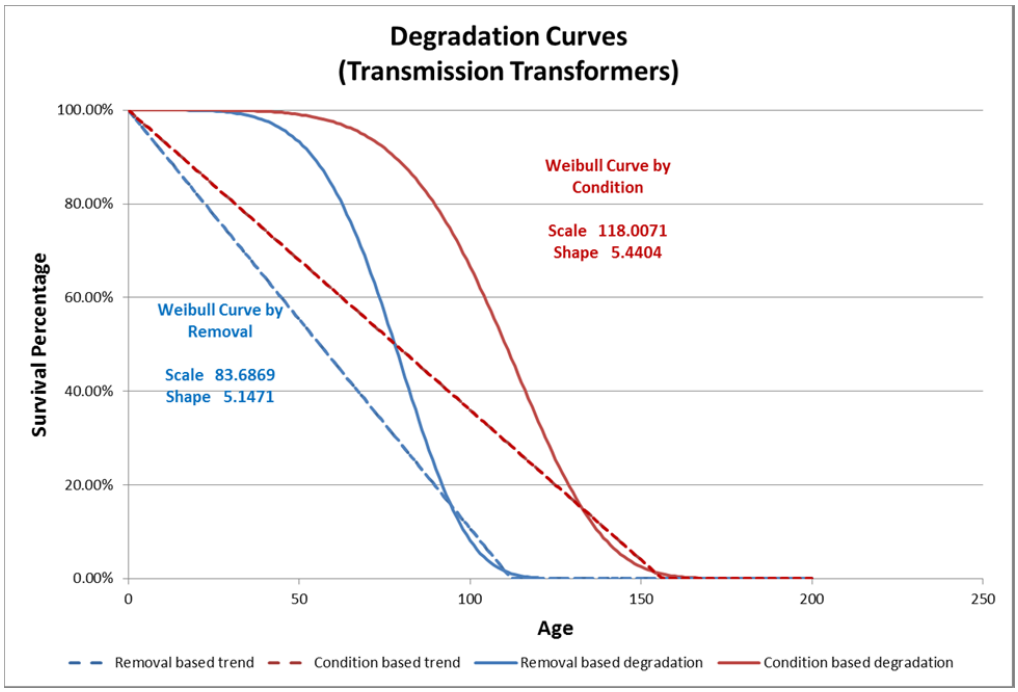

Figure 1-10 Removal Based vs Condition Based Degradation Curves (Transmission Transformers)

This page is intentionally left blank.

2. DISTRIBUTION TRANSFORMERS

2.1. Removal Size and Population size

This asset group addresses below 110 kV transformers at MH distribution substations.

For this asset category, there are 39 available removal records. They cover the units that were removed during the period of 2000 – 2015.

The root causes for the removals include:

- Unit failure
- Capacity increase
- Age and MH's own condition assessment

Since the removal size is relatively small, the existing age profile of 193 units is also incorporated in developing asset degradation curve.

There is no further sub-categorization by capacity, make, or location.

2.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

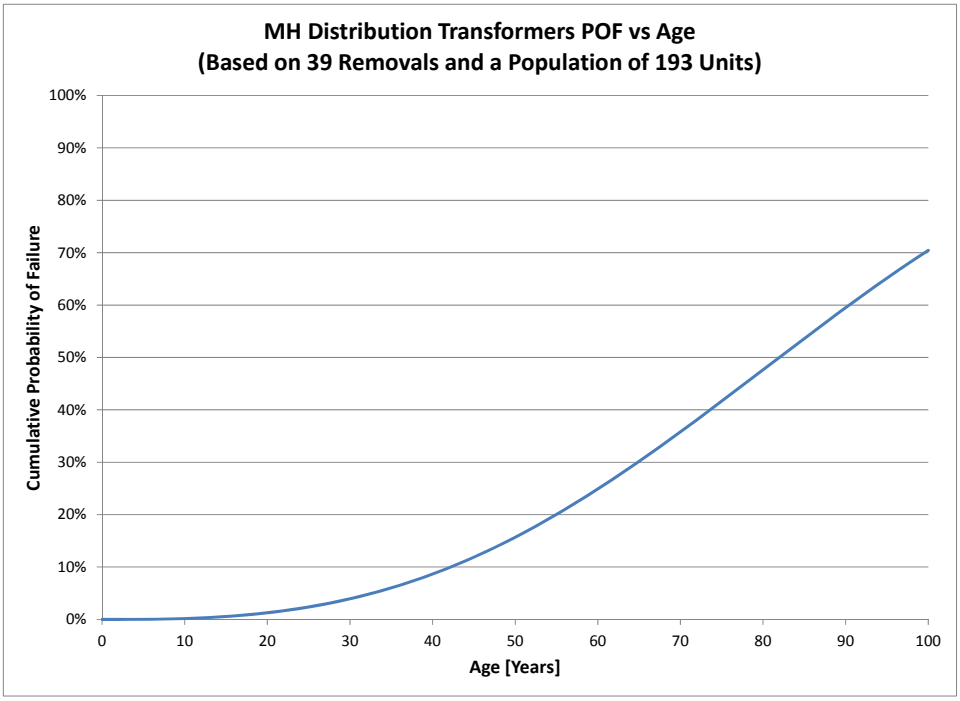

Figure 2-1 Cumulative Probability of Failure vs Age (Distribution Transformers)

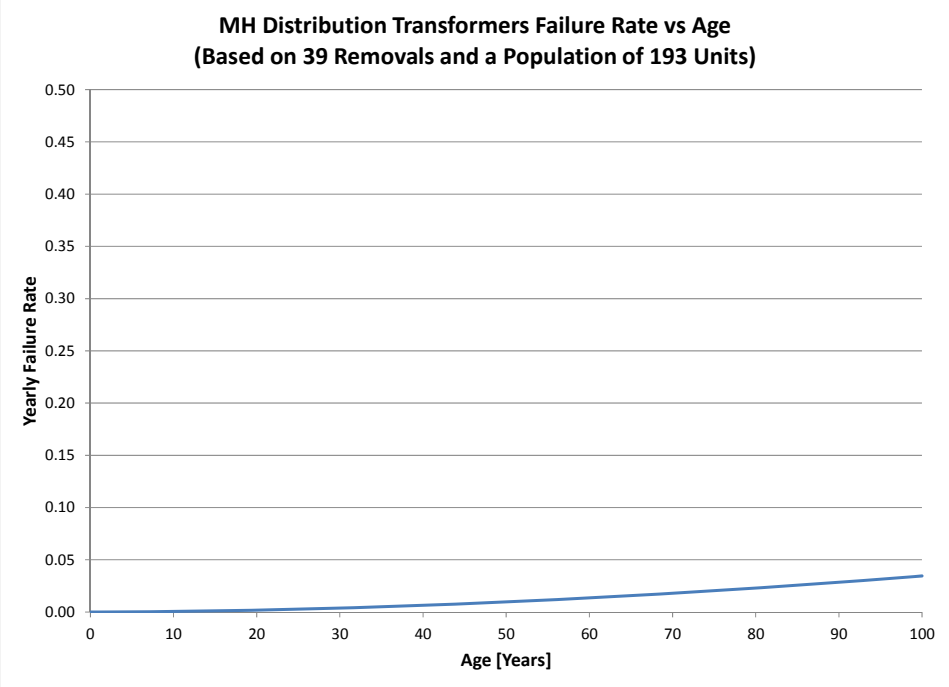

Figure 2-2 Annual Failure Rate vs Age (Distribution Transformers)

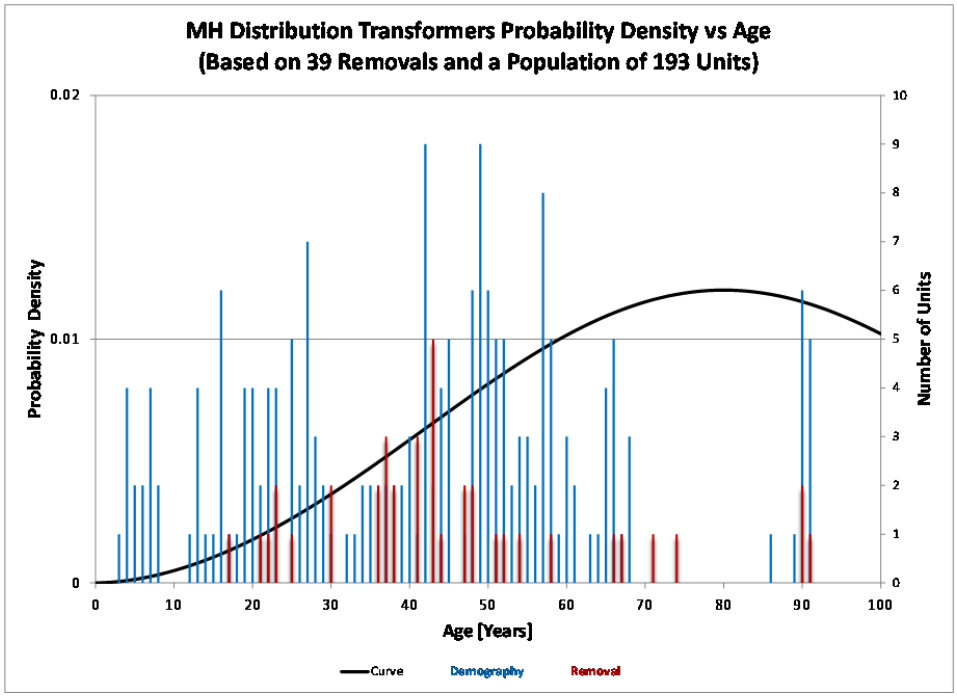

Figure 2-3 Failure Density Curve and Age Profile (Distribution Transformers)

2.3. Comparison of MH Curve with Industry Curves

The following diagram shows the comparison of MH curve with the ones from other utilities in industry.

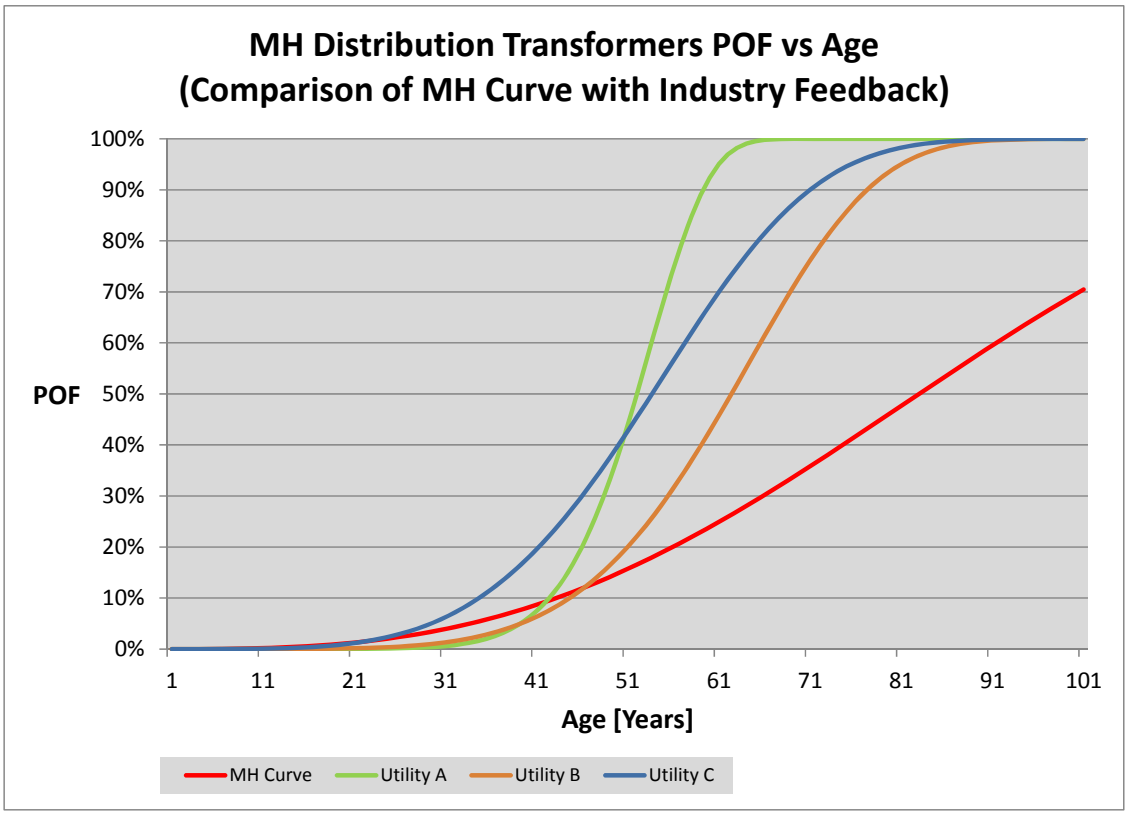

Figure 2-4 Comparison of MH Curve with Industry Experience (Distribution Transformers)

In the above diagram, MH curve is compared with the curves from 3 utilities in North America.

As shown in the diagram, MH curve shows much longer service life than the other 3 utilities.

2.4. Link AHI to Condition Based Failure Rate

Due to lack of data, no study was conducted on this asset category to link its AHI to failure rate.

3. GENERATION TRANSFORMERS

3.1. Removal Size and Population size

This asset group addresses the generator output transformers at MH generation stations.

For this asset category, there are 41 available removal records. They cover the units that were removed during the period of 1981 – 2016.

The root causes for the removals include:

- Unit failure
- Age and MH's other considerations

In this case, there is no exiting age profile incorporated in developing asset degradation curve.

There is no further sub-categorization by capacity, make, or location.

3.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

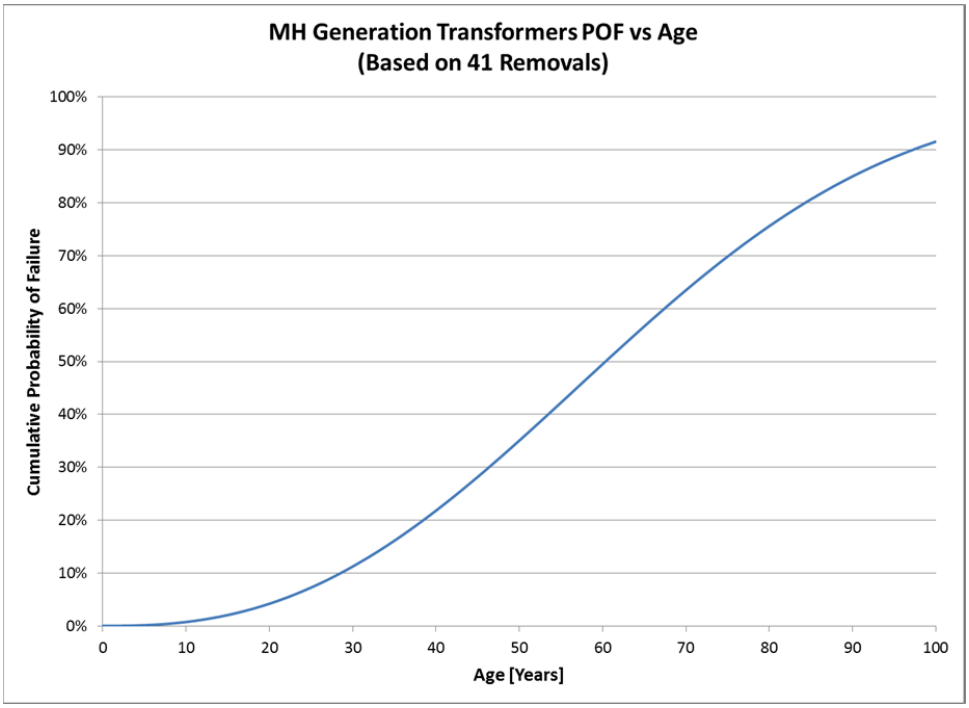

Figure 3-1 Cumulative Probability of Failure vs Age (Generation Transformers)

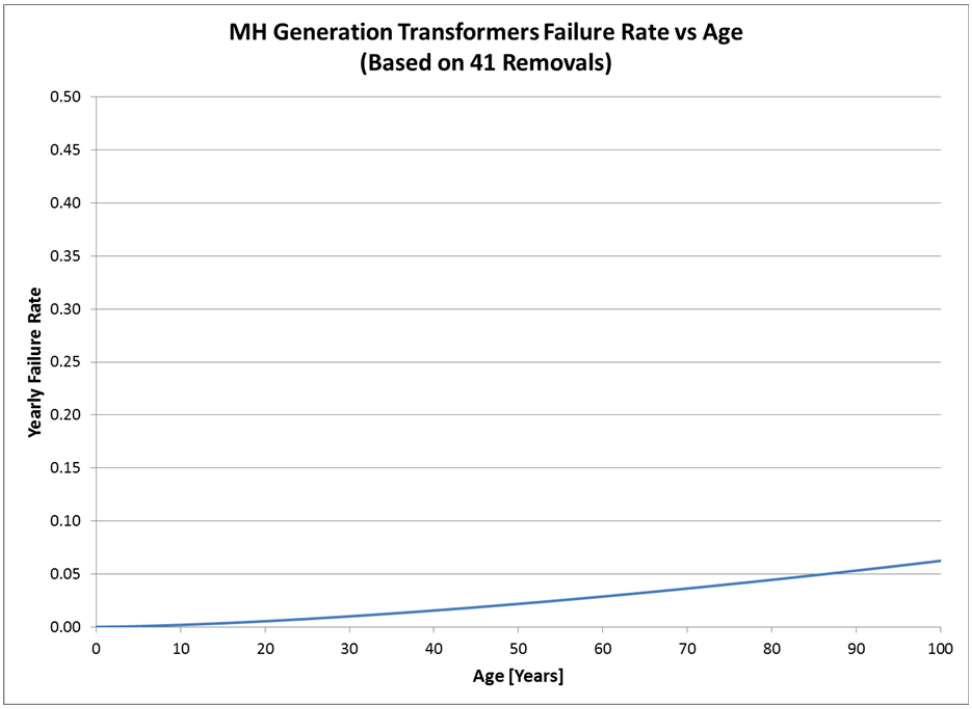

Figure 3-2 Annual Failure Rate vs Age (Generation Transformers)

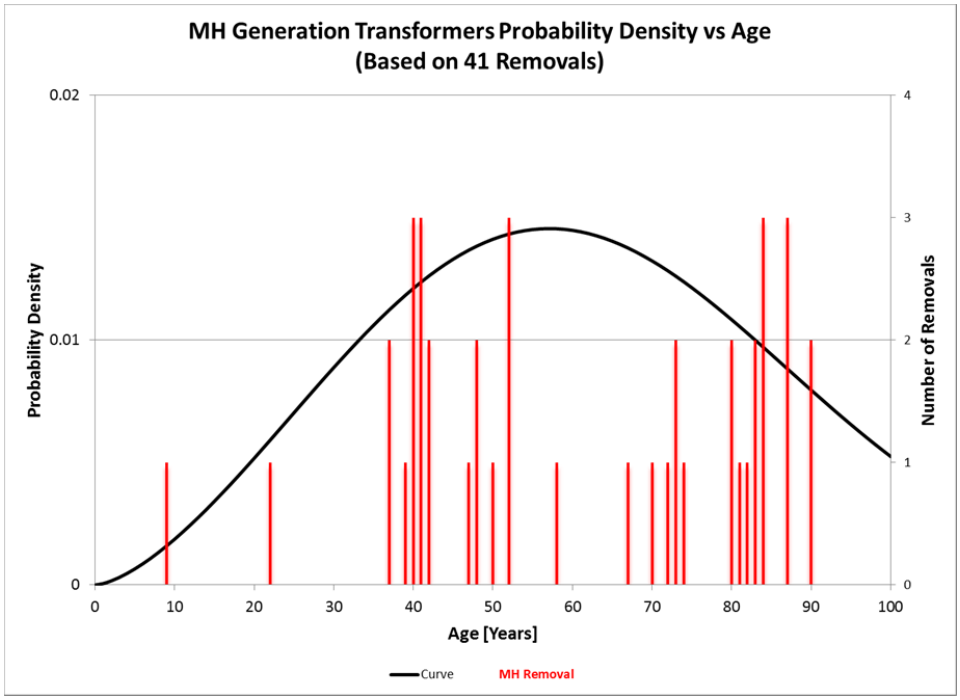

Figure 3-3 Failure Density Curve and Age Profile (Generation Transformers)

3.3. Comparison of MH Curve with Industry Curves

The following diagram shows the comparison of MH curve with the ones from other utilities in industry.

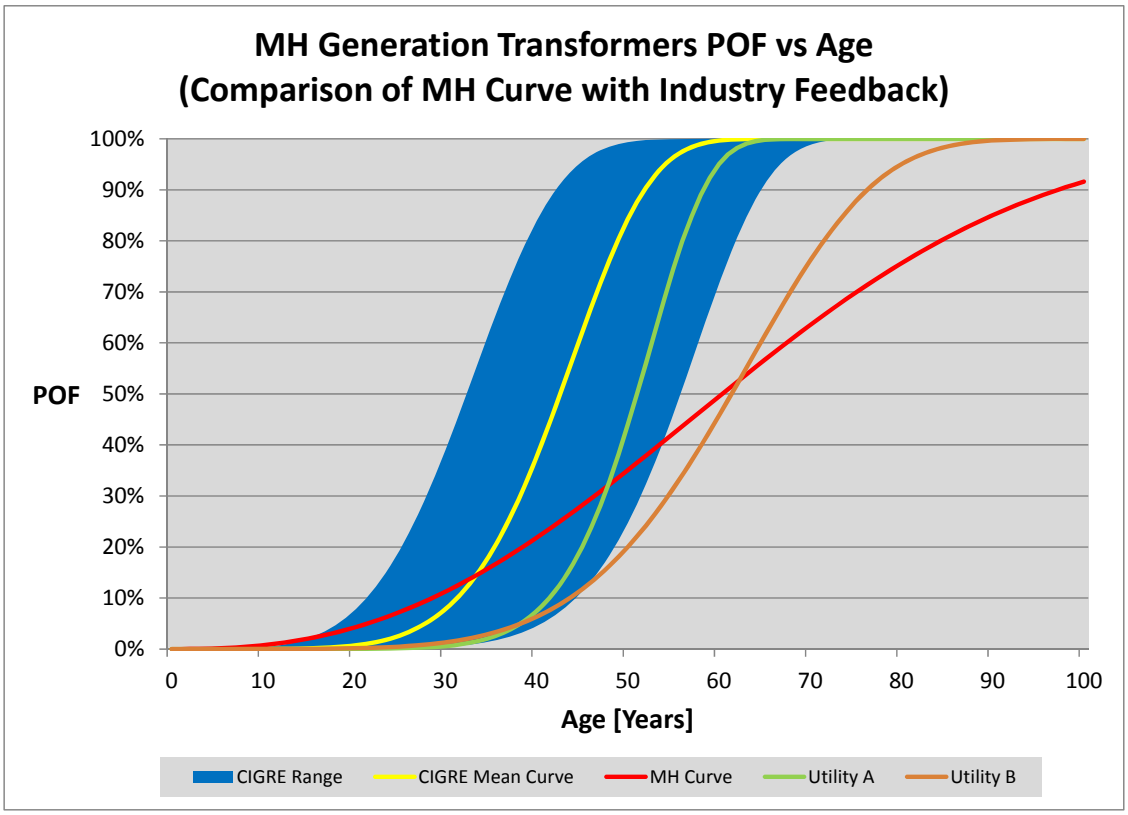

Figure 3-4 Comparison of MH Curve with Industry Experience (Generation Transformers)

In the above diagram, MH curve is compared with CIGRE statistics and the curves from 2 utilities in North America.

As shown in the diagram, MH curve is an outlier when compared with CIGRE curve range. It also shows much longer service life than the other 2 utilities.

3.4. Link AHI to Condition Based Failure Rate

Due to lack of data, no study was conducted on this asset category to link its AHI to failure rate.

This page is intentionally left blank.

4. TRANSMISSION OIL CIRCUIT BREAKERS

4.1. Removal Size and Population size

This asset group addresses the 110 kV and higher oil circuit breakers at MH transmission substations.

For this asset category, there are 34 available removal records. They cover the units that were removed during the period of 2007 – 2016.

The root causes for the removals include:

- Unit failure
- System expansion
- Economic end of life

Since the removal size is relatively small, the existing age profile of 159 units is also incorporated in developing asset degradation curve.

There is no further sub-categorization by capacity, make, or location.

4.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

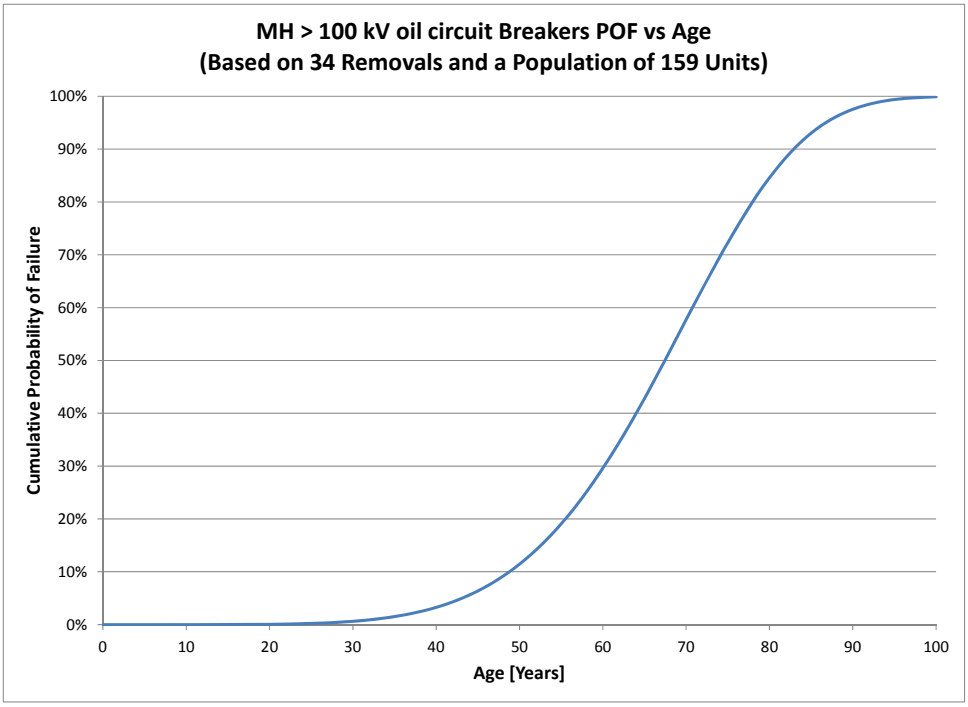

Figure 4-1 Cumulative Probability of Failure vs Age (Transmission Oil Circuit Breakers)

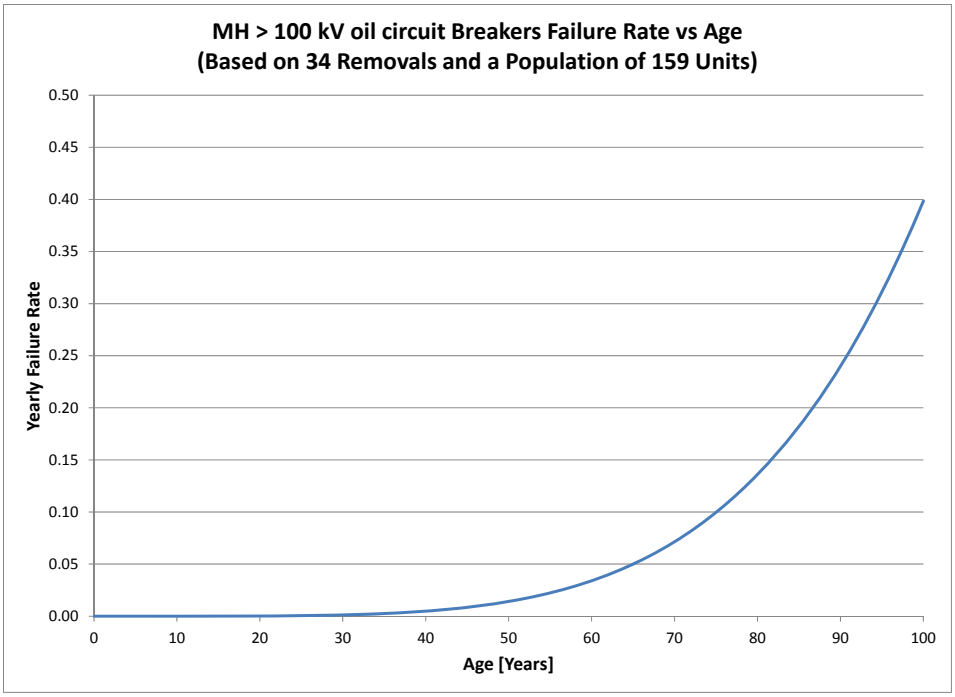

Figure 4-2 Annual Failure Rate vs Age (Transmission Oil Circuit Breakers)

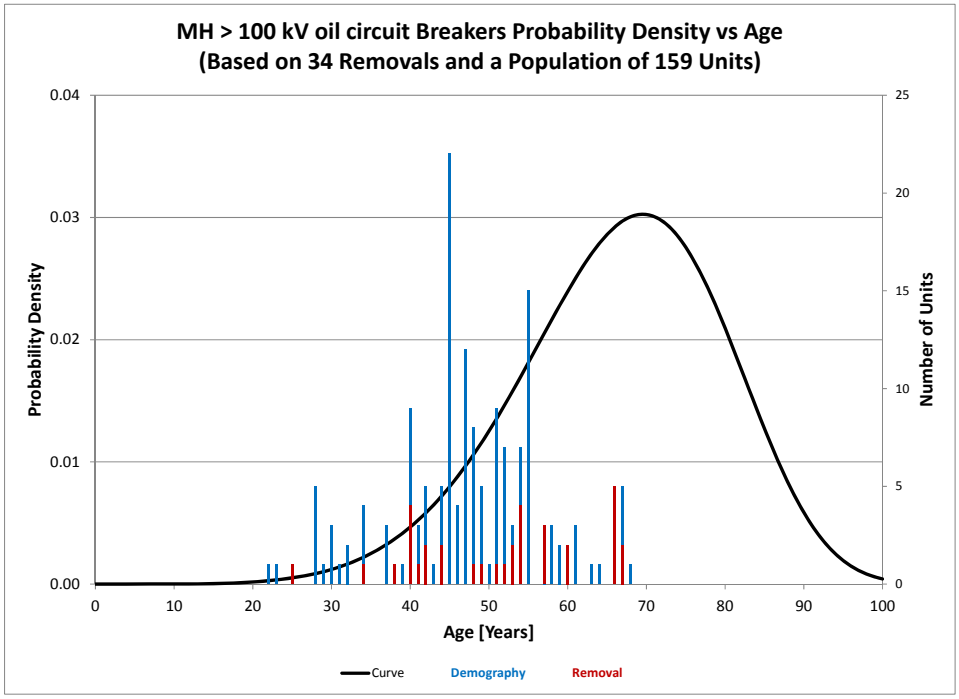

Figure 4-3 Failure Density Curve and Age Profile (Transmission Oil Circuit Breakers)

4.3. Comparison of MH Curve with Industry Curves

The following diagram shows the comparison of MH curve with the ones from other utilities in industry.

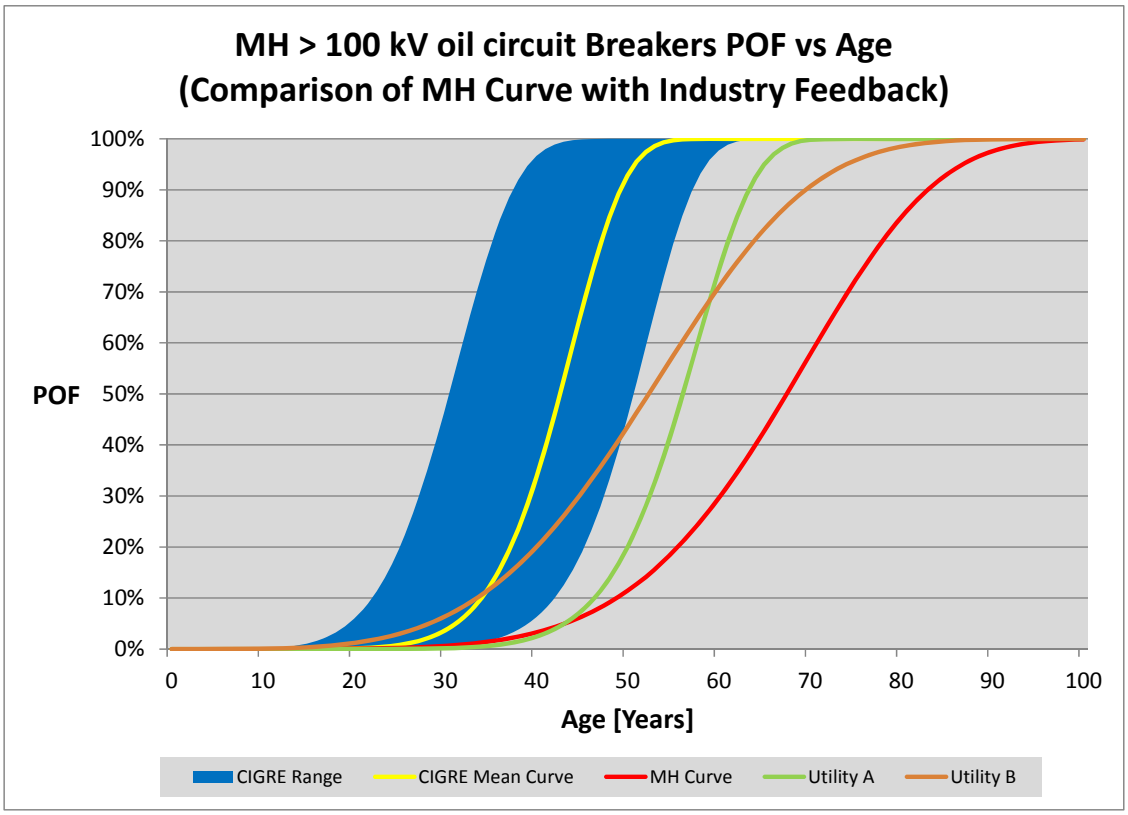

Figure 4-4 Comparison of MH Curve with Industry Experience (Transmission Oil Circuit Breakers)

In the above diagram, MH curve is compared with CIGRE statistics and the curves from 2 utilities in North America.

As shown in the diagram, MH curve is an outlier when compared with CIGRE curve range. It also shows much longer service life than the other 2 utilities.

4.4. Link AHI to Condition Based Failure Rate

The following diagrams show the series of developed curves linking AHI to condition based degradation curves.

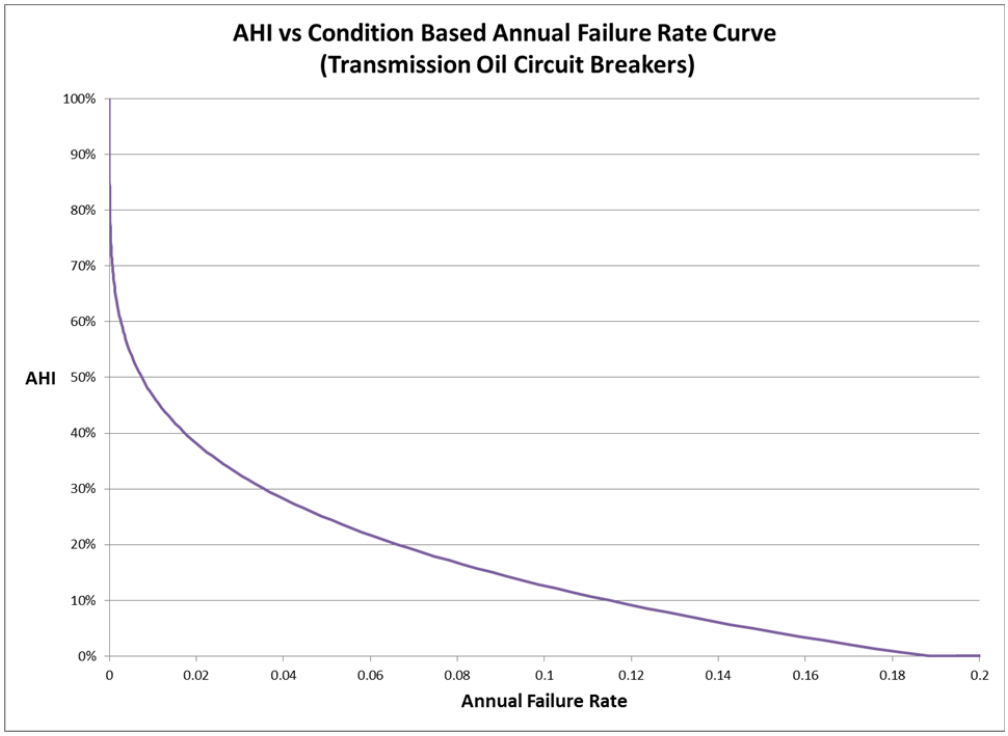

Figure 4-5 AHI vs Annual Failure Rate (Transmission Oil Circuit Breakers)

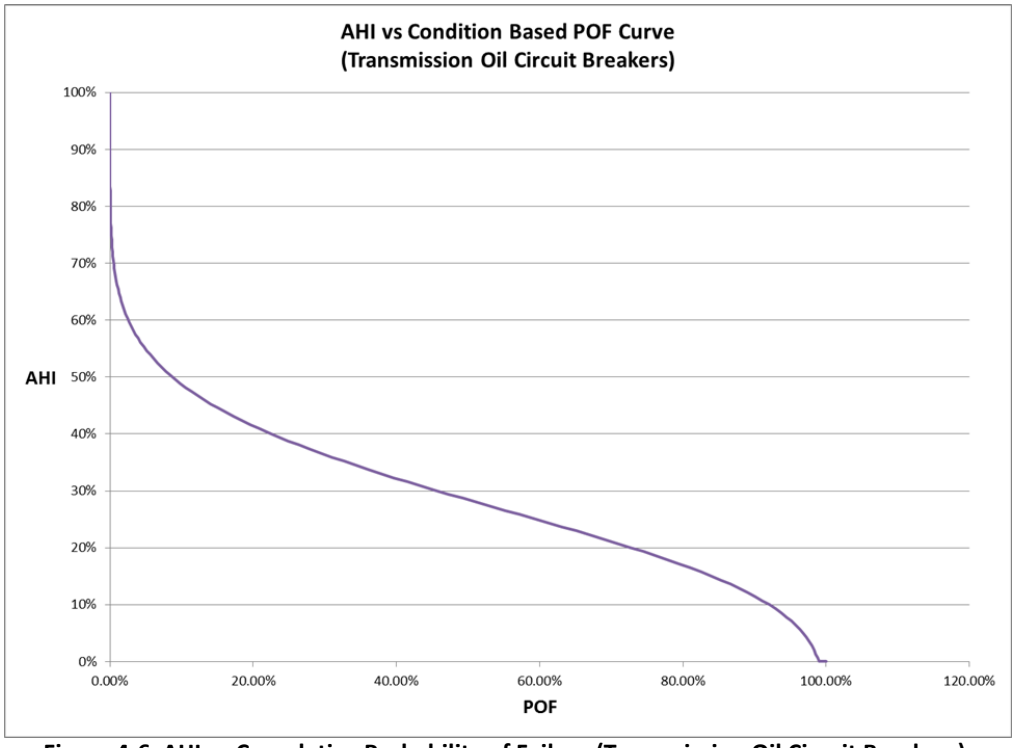

Figure 4-6 AHI vs Cumulative Probability of Failure (Transmission Oil Circuit Breakers)

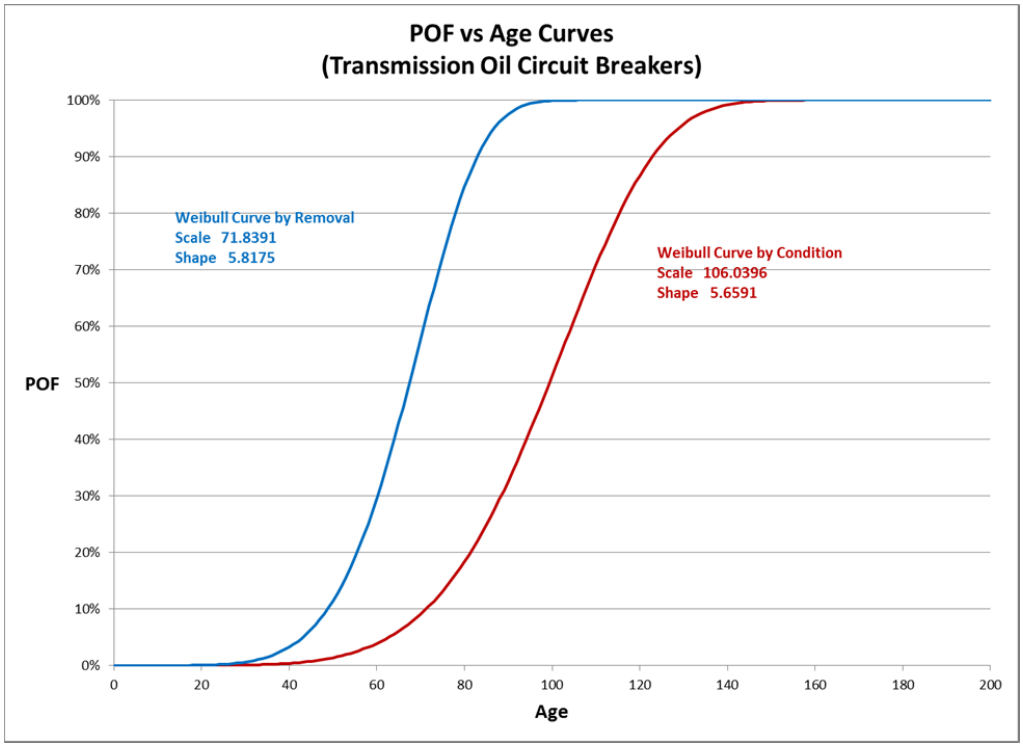

Figure 4-7 Removal Based vs Condition Based POF Curves (Transmission Oil Circuit Breakers)

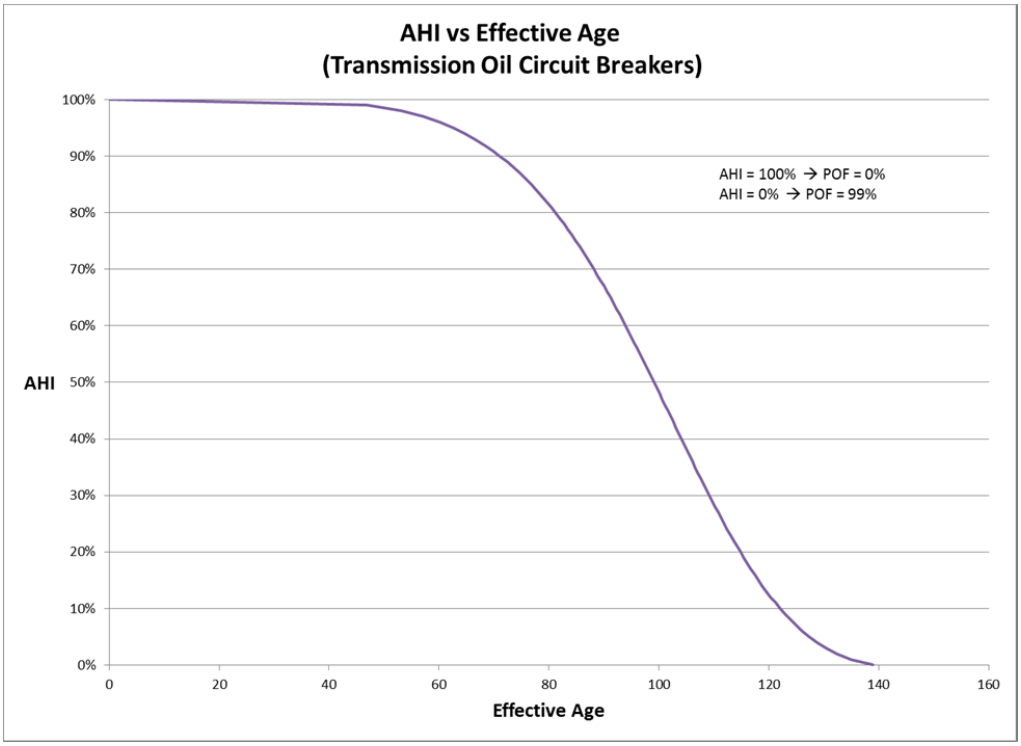

Figure 4-8 AHI vs Effective Age (Transmission Oil Circuit Breakers)

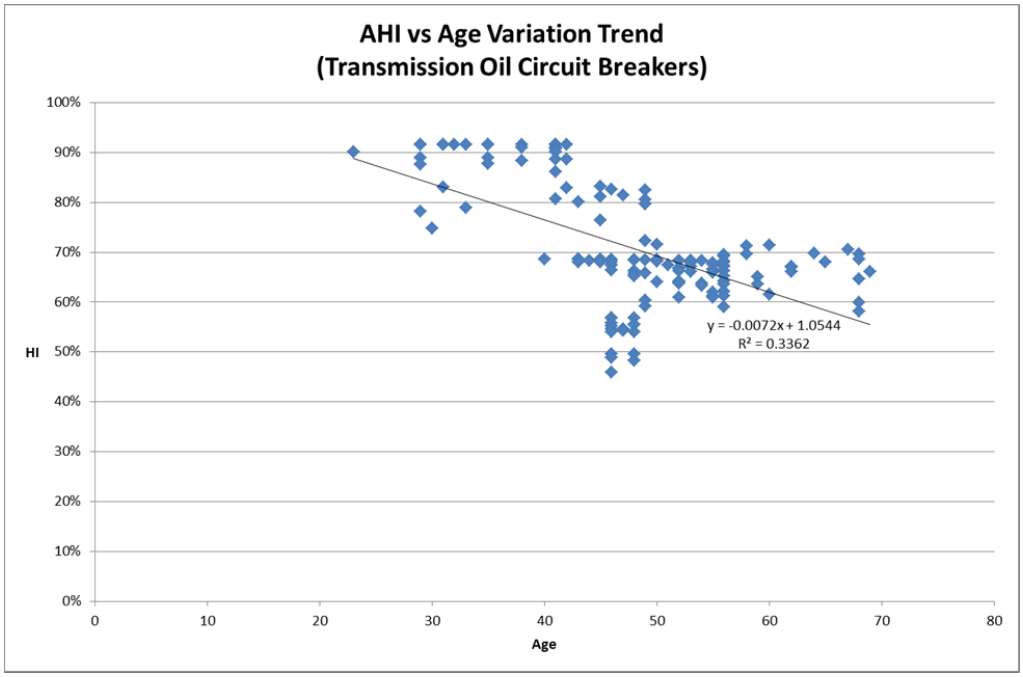

Figure 4-9 AHI vs Age Variation Trend (Transmission Oil Circuit Breakers)

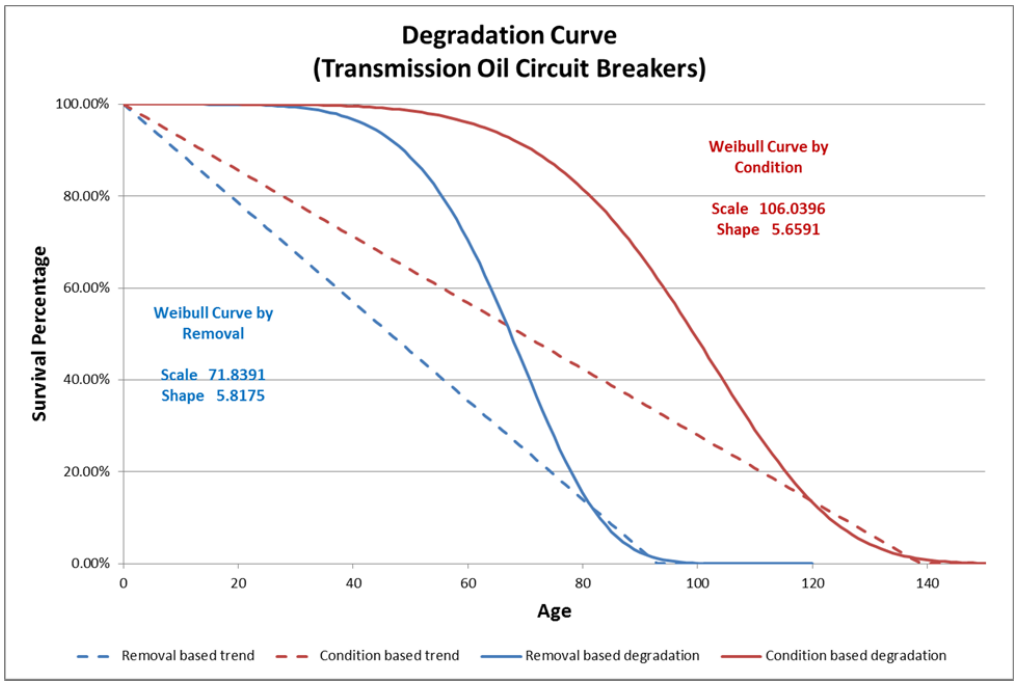

Figure 4-10 Removal Based vs Condition Based Degradation Curves (Transmission Oil Circuit Breakers)

This page is intentionally left blank.

5. TRANSMISSION AIR CIRCUIT BREAKERS

5.1. Removal Size and Population size

This asset group addresses the 110 kV and higher air circuit breakers at MH transmission substations.

For this asset category, there are 8 available removal records. They cover the units that were removed during the period of 2013 – 2016.

The root causes for the removals include:

- System expansion
- Economic end of life

Since the removal size is relatively small, the existing age profile of 23 units is also incorporated in developing asset degradation curve.

There is no further sub-categorization by capacity, make, or location.

5.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

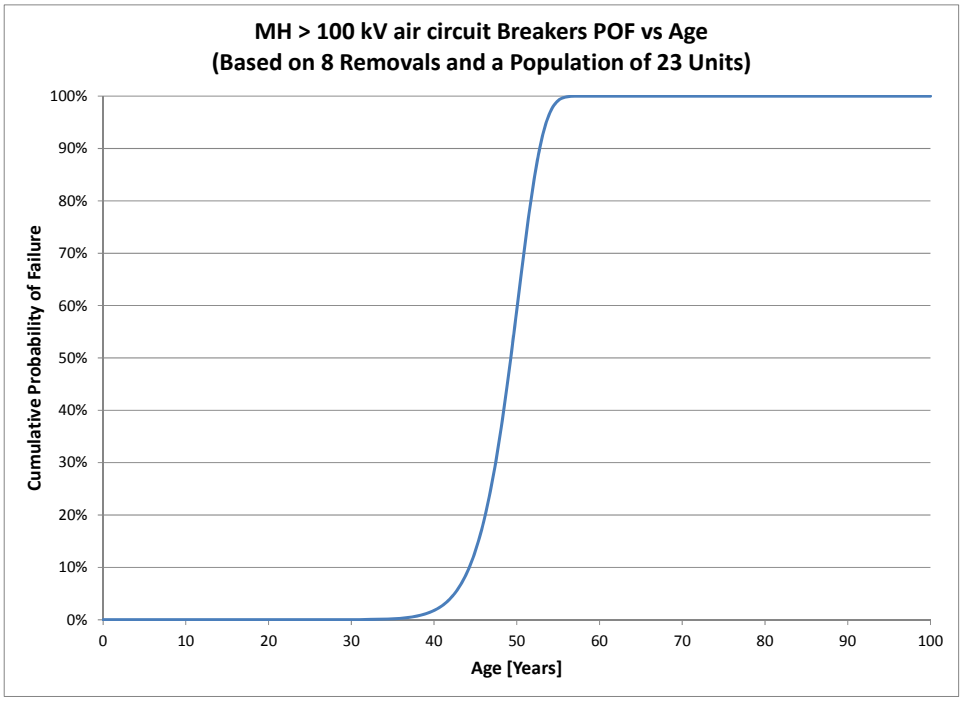

Figure 5-1 Cumulative Probability of Failure vs Age (Transmission Air Circuit Breakers)

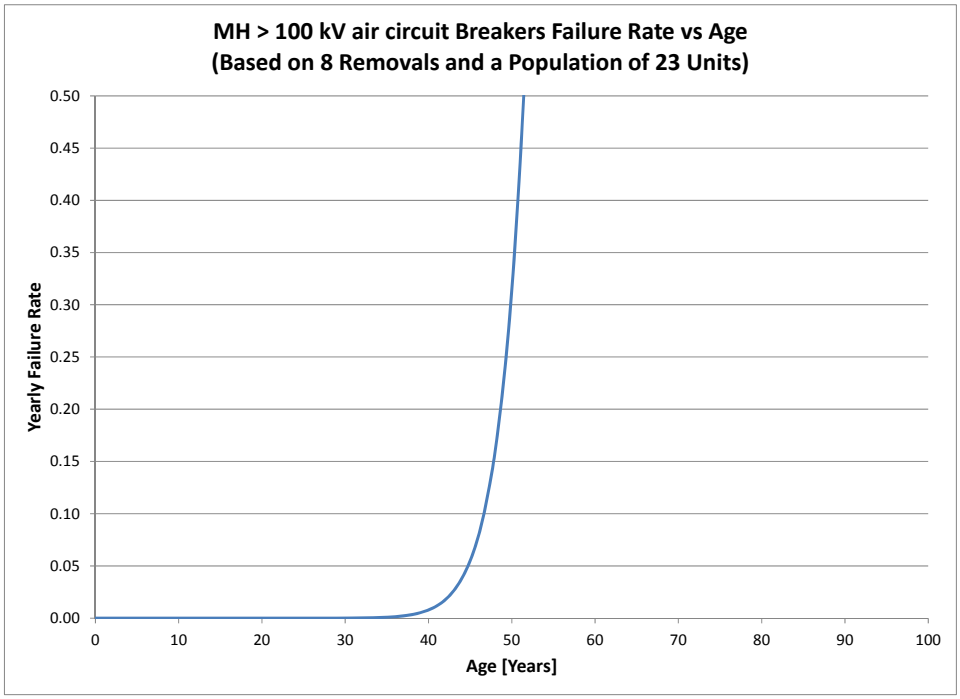

Figure 5-2 Annual Failure Rate vs Age (Transmission Air Circuit Breakers)

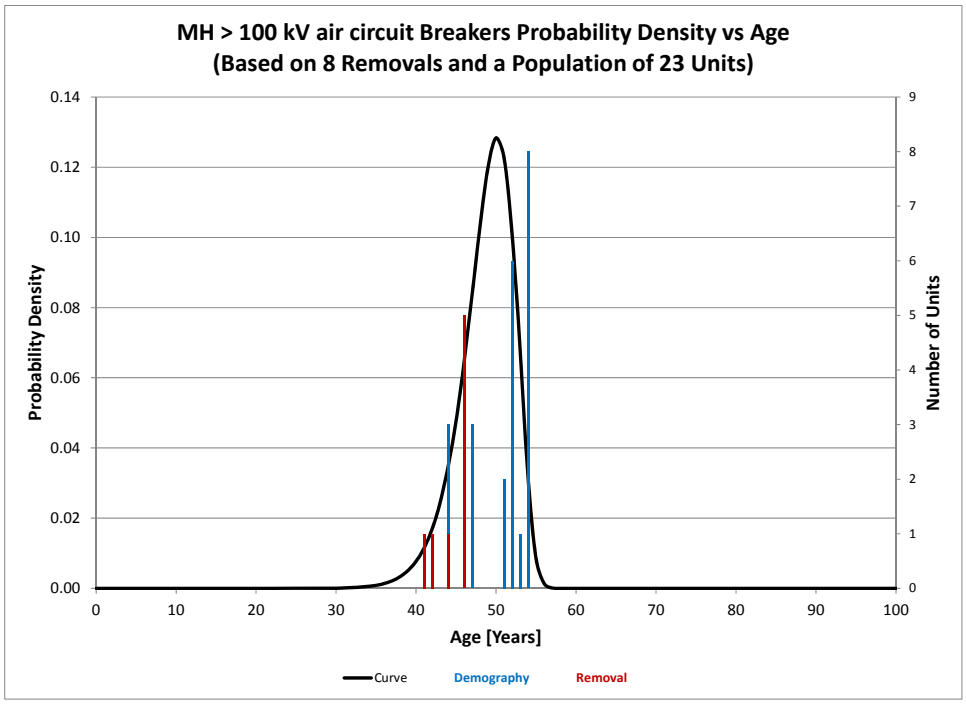

Figure 5-3 Failure Density Curve and Age Profile (Transmission Air Circuit Breakers)

5.3. Comparison of MH Curve with Industry Curves

The following diagram shows the comparison of MH curve with the ones from other utilities in industry.

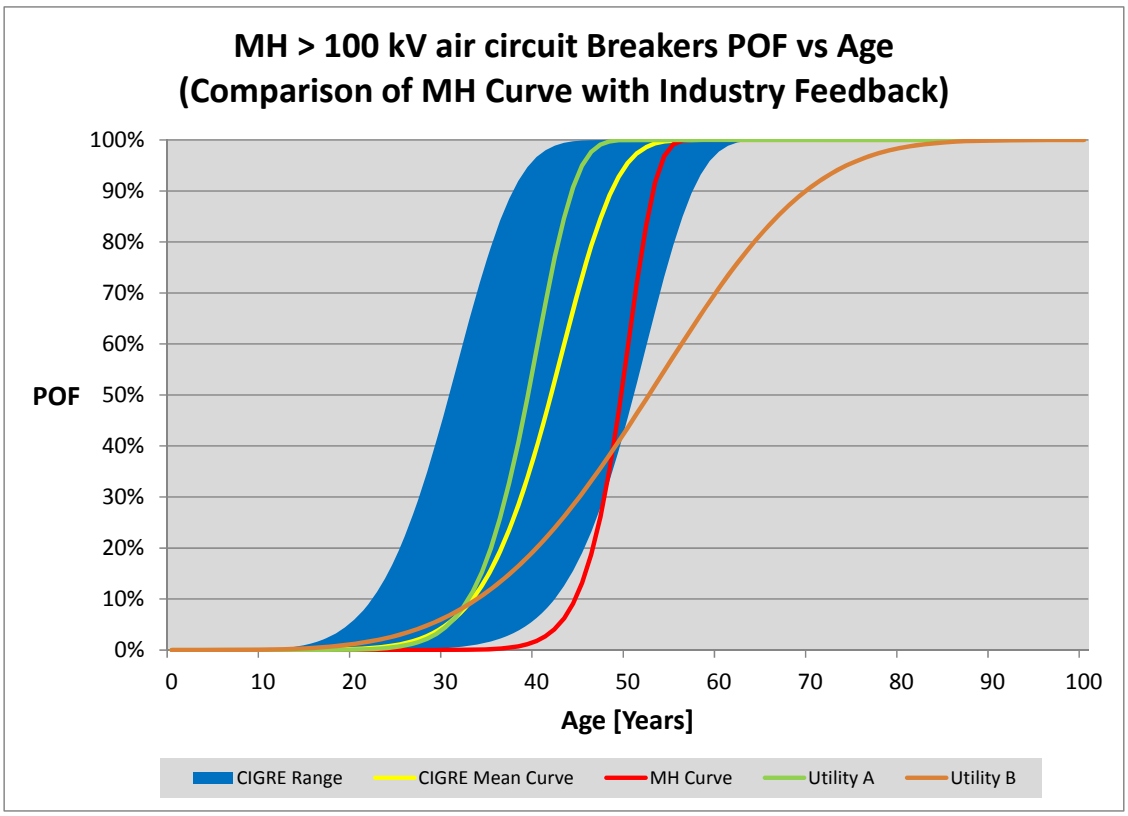

Figure 5-4 Comparison of MH Curve with Industry Experience (Transmission Air Circuit Breakers)

In the above diagram, MH curve is compared with CIGRE statistics and the curves from 2 utilities in North America.

As shown in the diagram, MH curve is at the outer border of CIGRE curve range. It also shows 1 utility has longer service life than MH for this asset category.

5.4. Link AHI to Condition Based Failure Rate

There were AHI data provided by MH. However, due to issue with AHI vs age trend indication, no study was conducted on this asset category to link its AHI to failure rate. MH is recommended to review and validate the AHI data for this asset group. Such auditing would lead to revised AHI results that could eventually enable linking AHI to condition based failure rate in the future. For the purpose of long term investment planning using the existing data, MH could use the developed removal based failure curves and link them to AHI by assuming AHI = 100% -

POF. This would be a conservative approximation and requires calibration based on the AHI auditing results.

6. TRANSMISSION SF6 CIRCUIT BREAKERS

6.1. Removal Size and Population size

This asset group addresses the 110 kV and higher SF6 circuit breakers at MH transmission substations.

For this asset category, there are only 5 available removal records. They cover the units that were removed during the period of 2012 – 2013.

The root causes for the removals include:

- System expansion

Since the removal size is too small and all were removed shortly after installation (less than 3 years), they cannot be adopted in developing asset degradation curve.

There is no further sub-categorization by capacity, make, or location.

6.2. Developed Removal Based Degradation Curves

Due to above reasons, there is no curve developed based on MH data. CIGRE curve is adopted for the reference of MH. The following diagrams show the series of CIGRE average degradation curves based on statistics of multiple utilities.

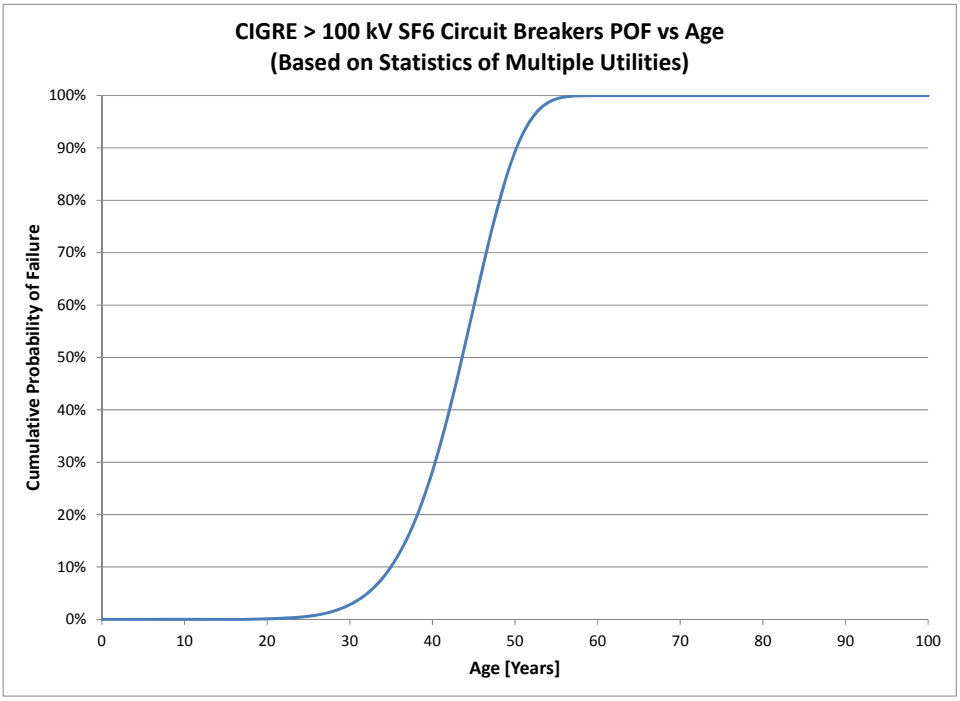

Figure 6-1 Cumulative Probability of Failure vs Age (Transmission SF6 Circuit Breakers)

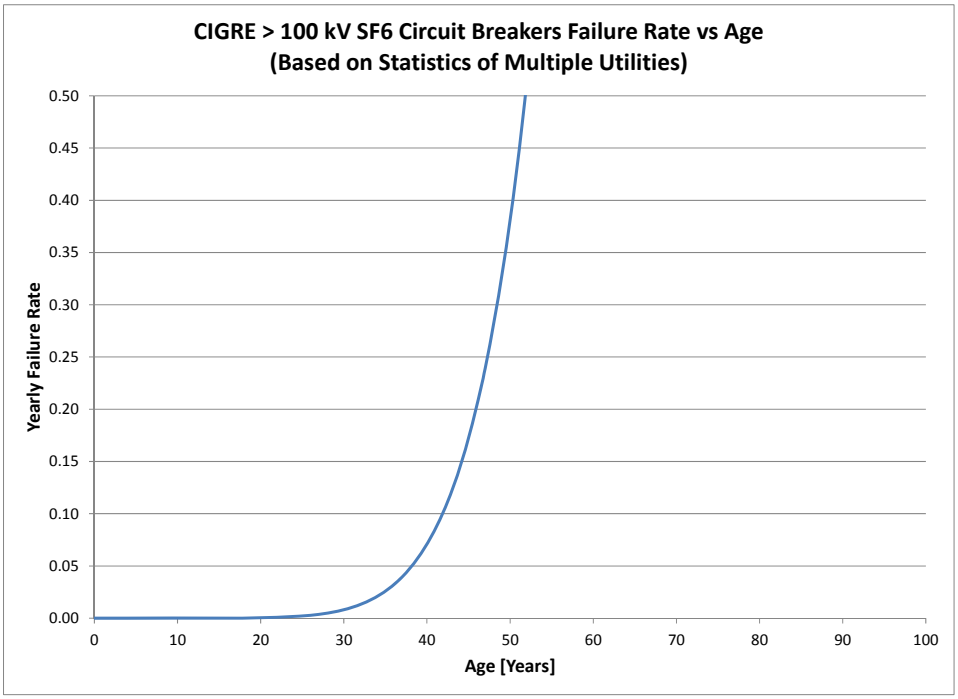

Figure 6-2 Annual Failure Rate vs Age (Transmission SF6 Circuit Breakers)

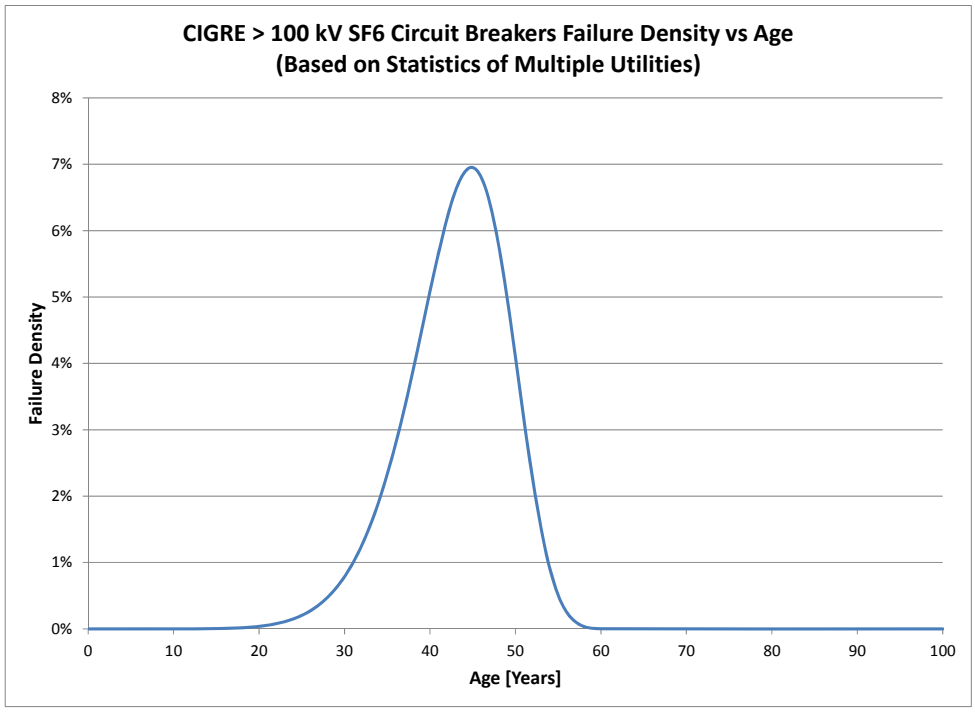

Figure 6-3 Failure Density Curve (Transmission SF6 Circuit Breakers)

6.3. Comparison of MH Curve with Industry Curves

As there is no MH data based curve, the following diagram shows the comparison of CIGRE curve with the ones from other utilities in industry.

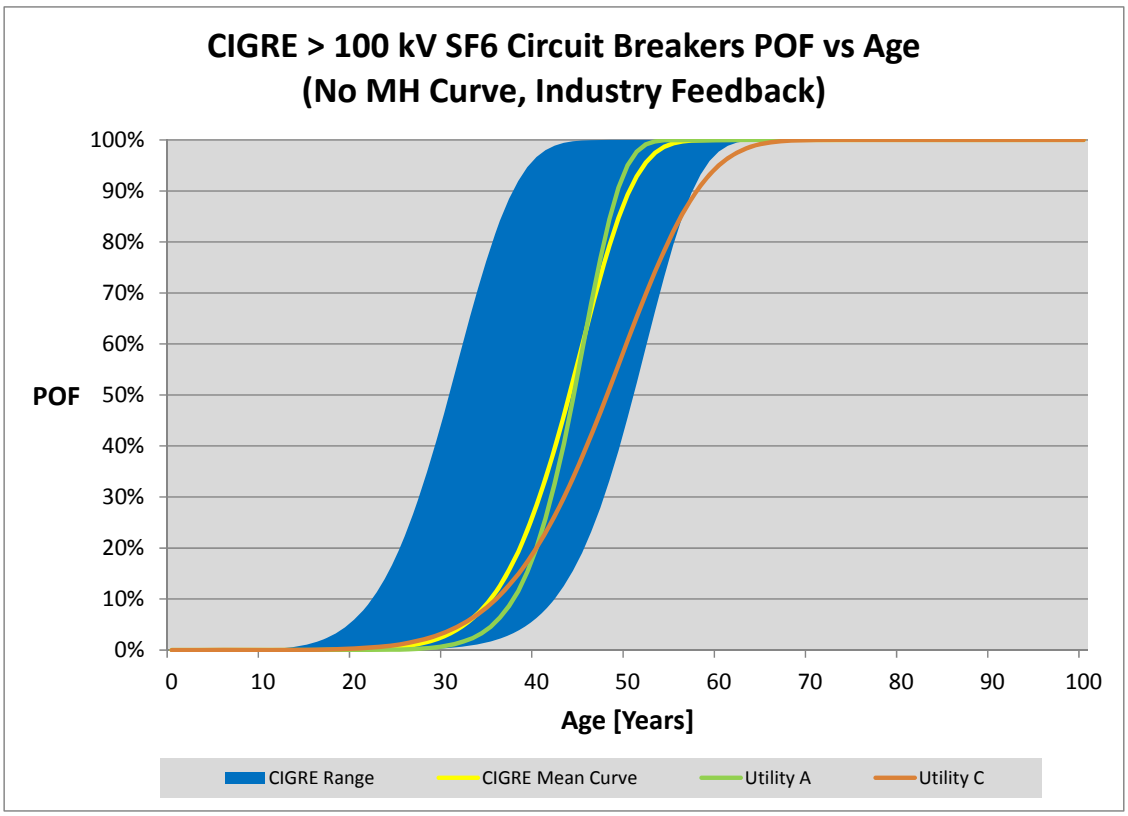

Figure 6-4 Comparison of CIGRE Curve with Industry Experience (Transmission SF6 Circuit Breakers)

In the above diagram, CIGRE curve is compared with the curves from 2 utilities in North America.

As shown in the diagram, the curves from the 2 utilities are within CIGRE curve range.

6.4. Link AHI to Condition Based Failure Rate

There were AHI data provided by MH. However, due to issue with AHI vs age trend indication, no study was conducted on this asset category to link its AHI to failure rate. MH is recommended to review and validate the AHI data for this asset group. Such auditing would lead to revised AHI results that could eventually enable linking AHI to condition based failure rate in the future. For the purpose of long term investment planning using the existing data, MH could use the developed removal based failure curves and link them to AHI by assuming AHI = 100% - POF. This would be a conservative approximation and requires calibration based on the AHI auditing results.

This page is intentionally left blank.

7. GENERATION AIR CIRCUIT BREAKERS

7.1. Removal Size and Population size

This asset group addresses the generator output air circuit breakers at MH generation stations.

For this asset category, there are 30 available removal records. They cover the units that were removed during the period of 2004 – 2008.

The root causes for the removals include:

- System expansion (short circuit exceeded)
- End of life as per MH

Since the removal size is relatively small, the existing age profile of 24 units is also incorporated in developing asset degradation curve.

There is no further sub-categorization by capacity, make, or location.

7.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

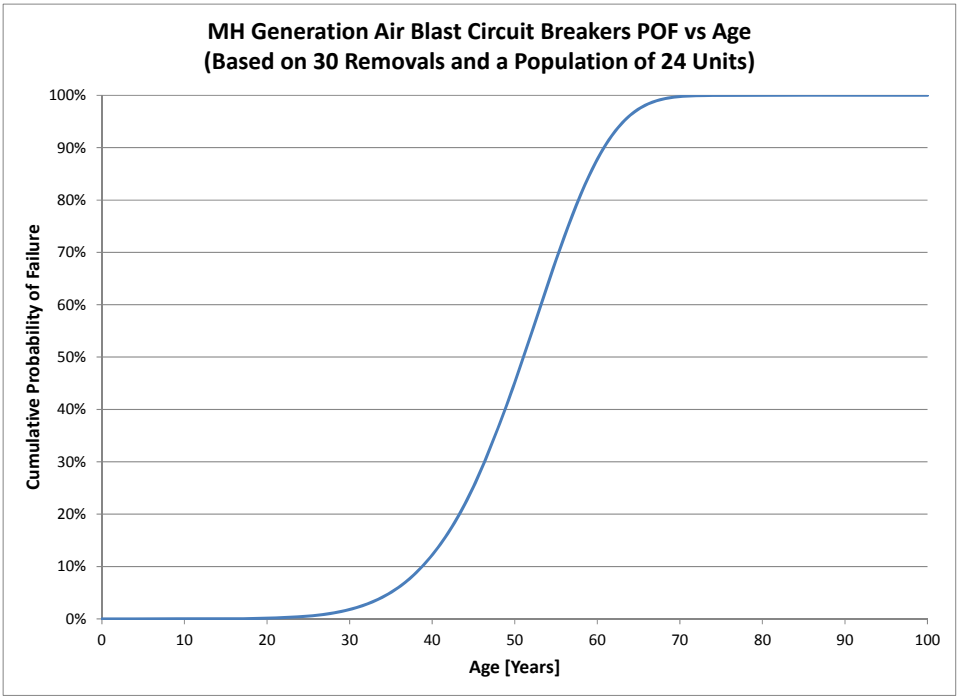

Figure 7-1 Cumulative Probability of Failure vs Age (Generation Air Circuit Breakers)

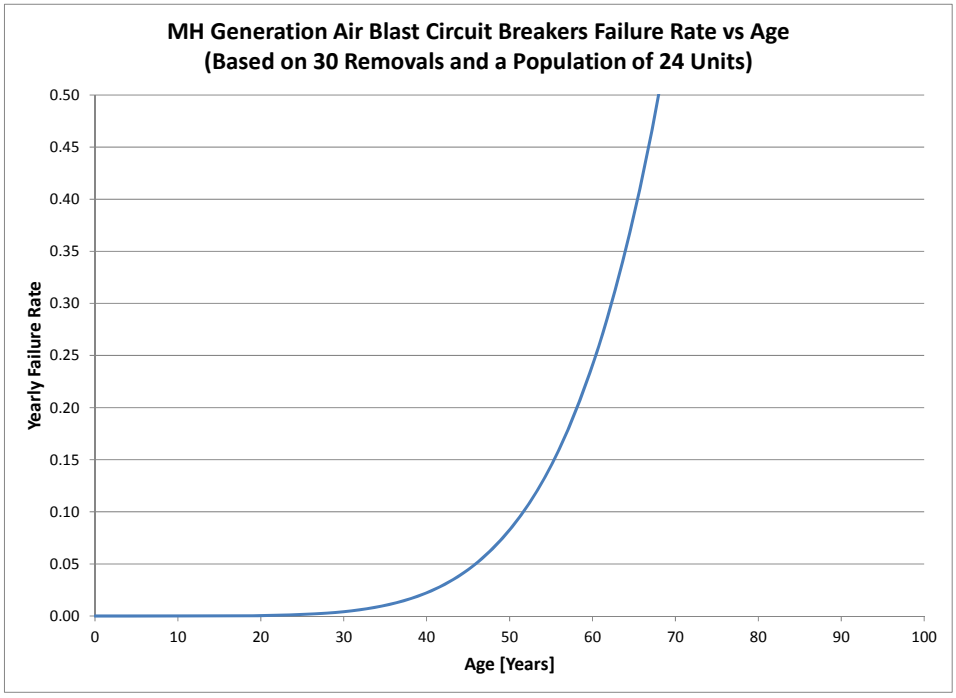

Figure 7-2 Annual Failure Rate vs Age (Generation Air Circuit Breakers)

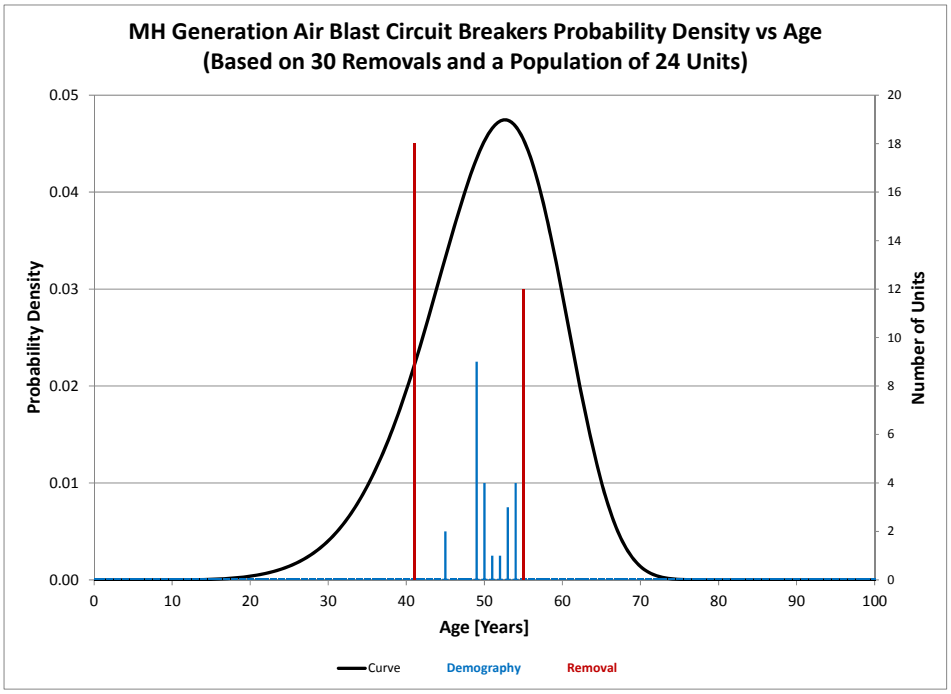

Figure 7-3 Failure Density Curve and Age Profile (Generation Air Circuit Breakers)

7.3. Comparison of MH Curve with Industry Curves

The following diagram shows the comparison of MH curve with the ones from other utilities in industry.

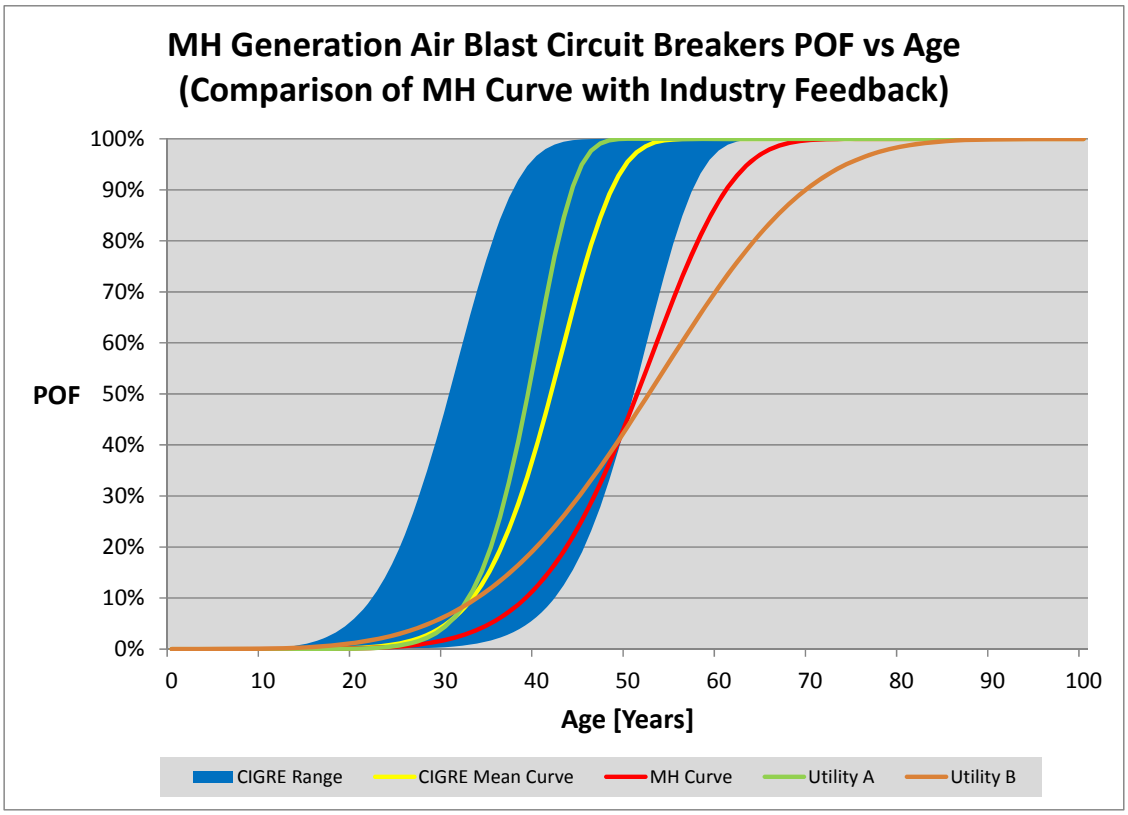

Figure 7-4 Comparison of MH Curve with Industry Experience (Generation Air Circuit Breakers)

In the above diagram, MH curve is compared with CIGRE statistics and the curves from 2 utilities in North America.

As shown in the diagram, MH curve is at the outer border of CIGRE curve range. It is also quite close to the curve of 1 utility.

7.4. Link AHI to Condition Based Failure Rate

Due to lack of data, no study was conducted on this asset category to link its AHI to failure rate.

This page is intentionally left blank.

8. GENERATION OIL CIRCUIT BREAKERS

8.1. Removal Size and Population size

This asset group addresses the generator output oil circuit breakers at MH generation stations.

For this asset category, there are 22 available removal records. They cover the units that were removed during the period of 2010 – 2016.

The root causes for the removals include:

- Unit failure
- System expansion (short circuit capacity exceeded)
- End of life as per MH

Since the removal size is relatively small, the existing age profile of 33 units is also incorporated in developing asset degradation curve.

There is no further sub-categorization by capacity, make, or location.

8.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

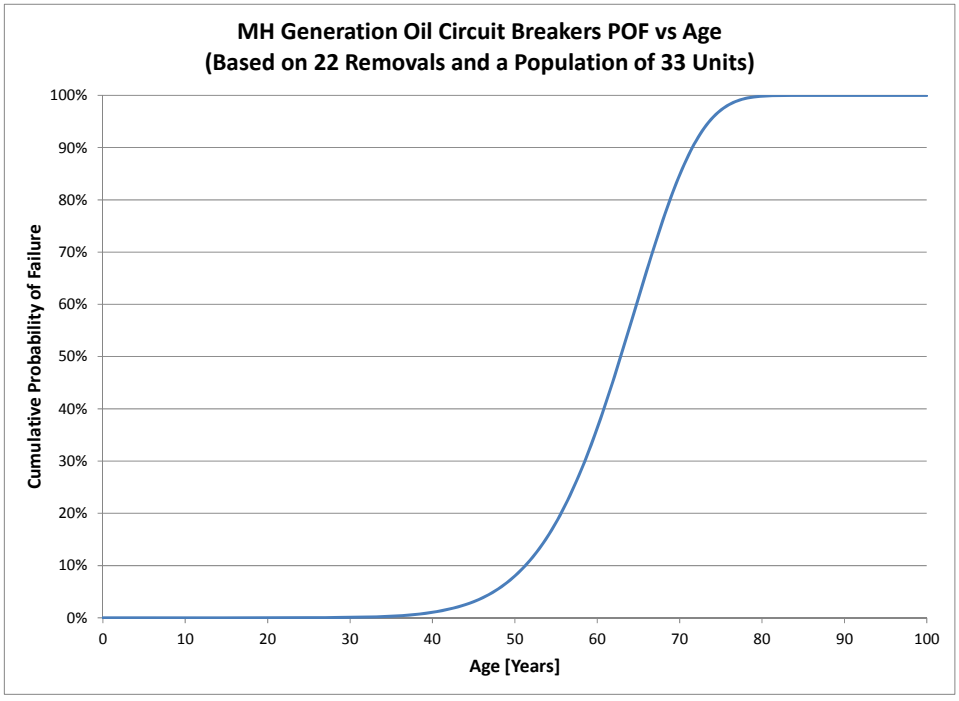

Figure 8-1 Cumulative Probability of Failure vs Age (Generation Oil Circuit Breakers)

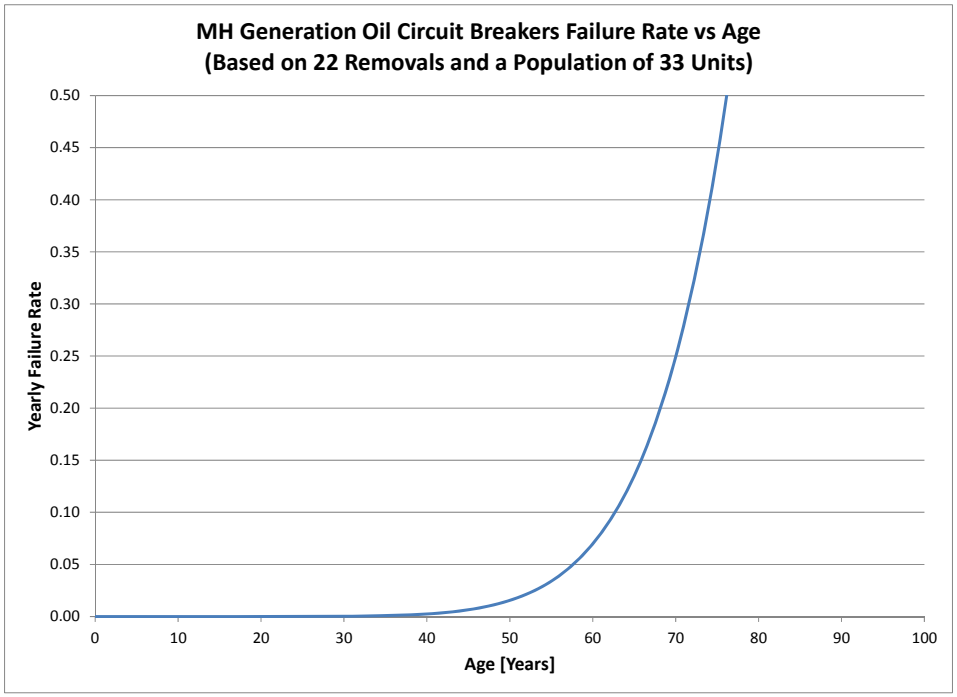

Figure 8-2 Annual Failure Rate vs Age (Generation Oil Circuit Breakers)

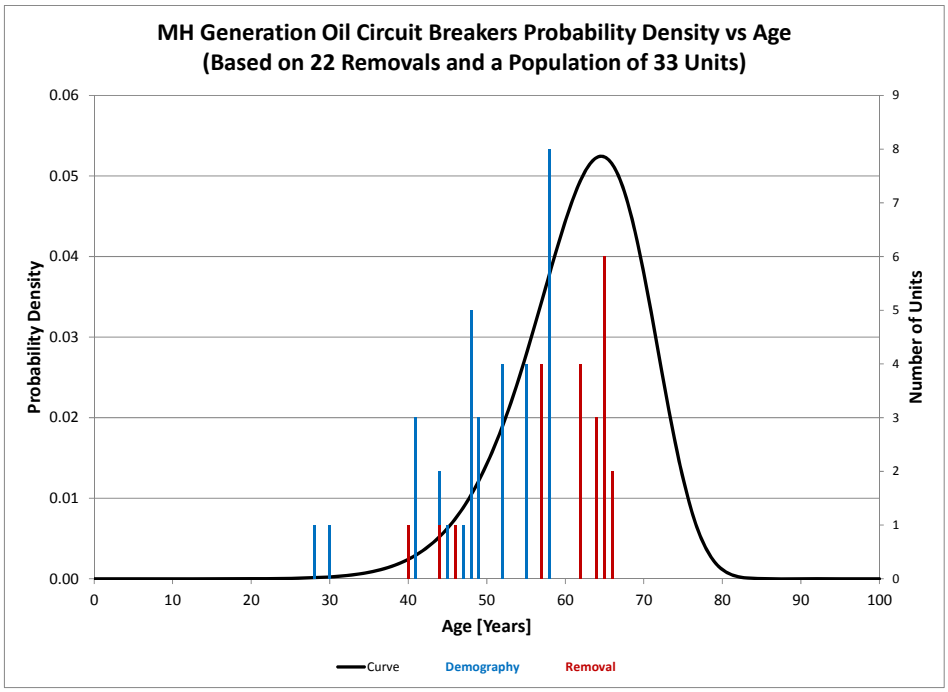

Figure 8-3 Failure Density Curve and Age Profile (Generation Oil Circuit Breakers)

8.3. Comparison of MH Curve with Industry Curves

The following diagram shows the comparison of MH curve with the ones from other utilities in industry.

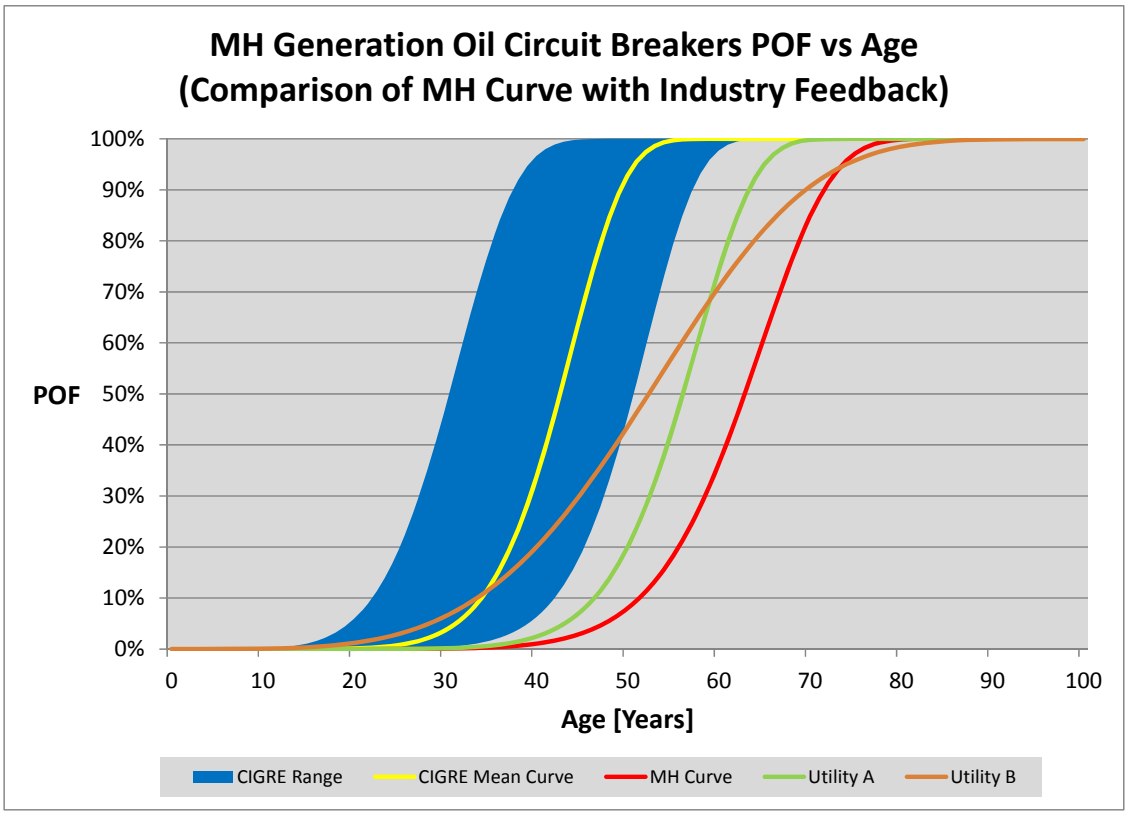

Figure 8-4 Comparison of MH Curve with Industry Experience (Generation Oil Circuit Breakers)

In the above diagram, MH curve is compared with CIGRE statistics and the curves from 2 utilities in North America.

As shown in the diagram, MH curve is an outlier to CIGRE curve range. It also shows longer service life than the curves of the 2 utilities.

8.4. Link AHI to Condition Based Failure Rate

Due to lack of data, no study was conducted on this asset category to link its AHI to failure rate.

This page is intentionally left blank.

9. CONDUCTORS

9.1. Removal Size and Population size

This asset group addresses the overhead conductors in MH transmission system.

For this asset category, there are no available removal records from MH.

There is no further sub-categorization by capacity, make, or location.

9.2. Developed Removal Based Degradation Curves

Due to above reasons, there is no curve developed based on MH data. CIGRE curve is adopted for the reference of MH. The following diagrams show the series of CIGRE average degradation curves based on statistics of multiple utilities.

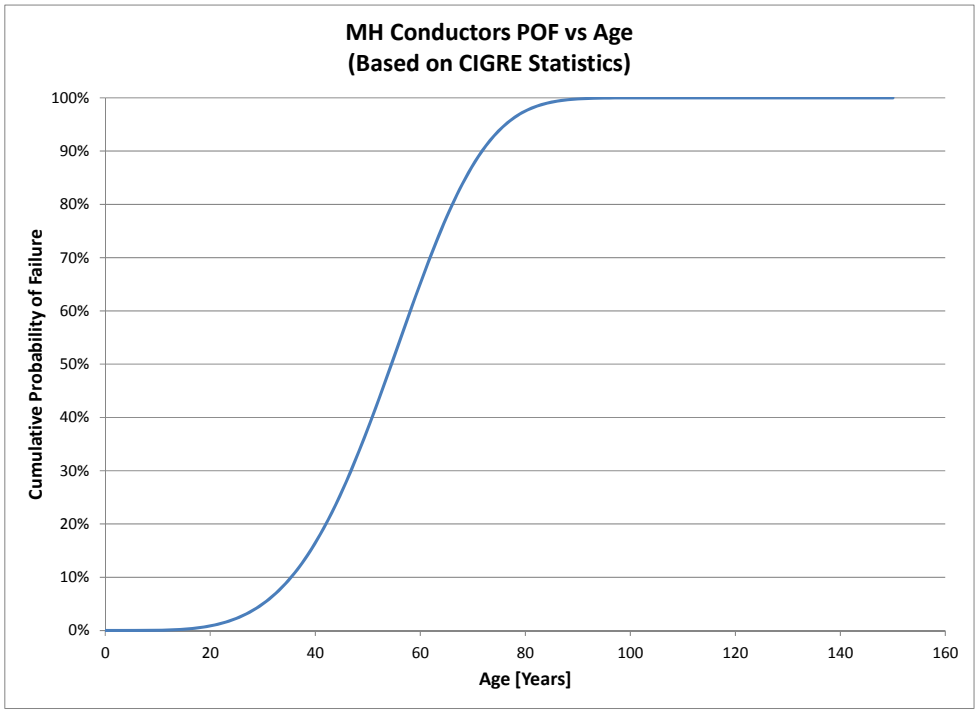

Figure 9-1 Cumulative Probability of Failure vs Age (Conductors)

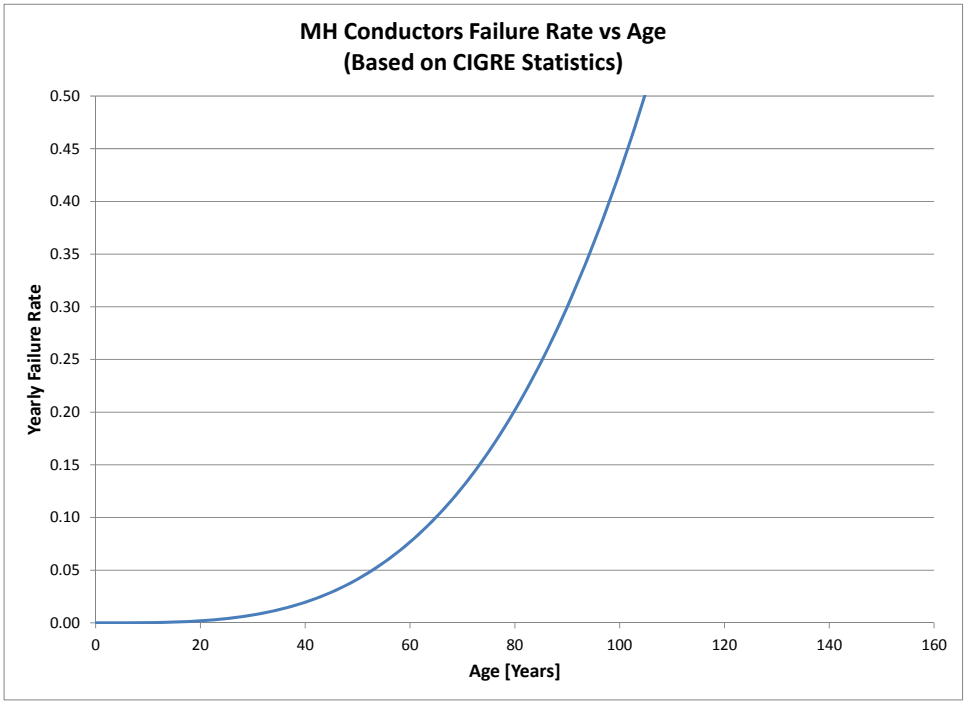

Figure 9-2 Annual Failure Rate vs Age (Conductors)

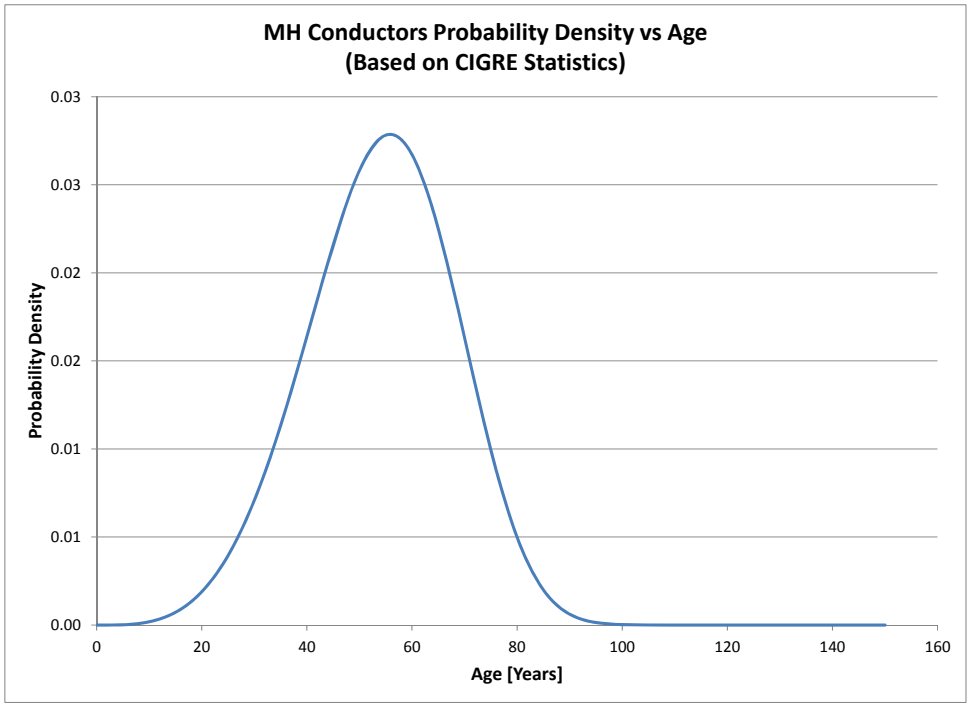

Figure 9-3 Failure Density Curve (Conductors)

9.3. Comparison of MH Curve with Industry Curves

As there is no MH data based curve, the following diagram shows the comparison of CIGRE curve with the ones from other utilities in industry.

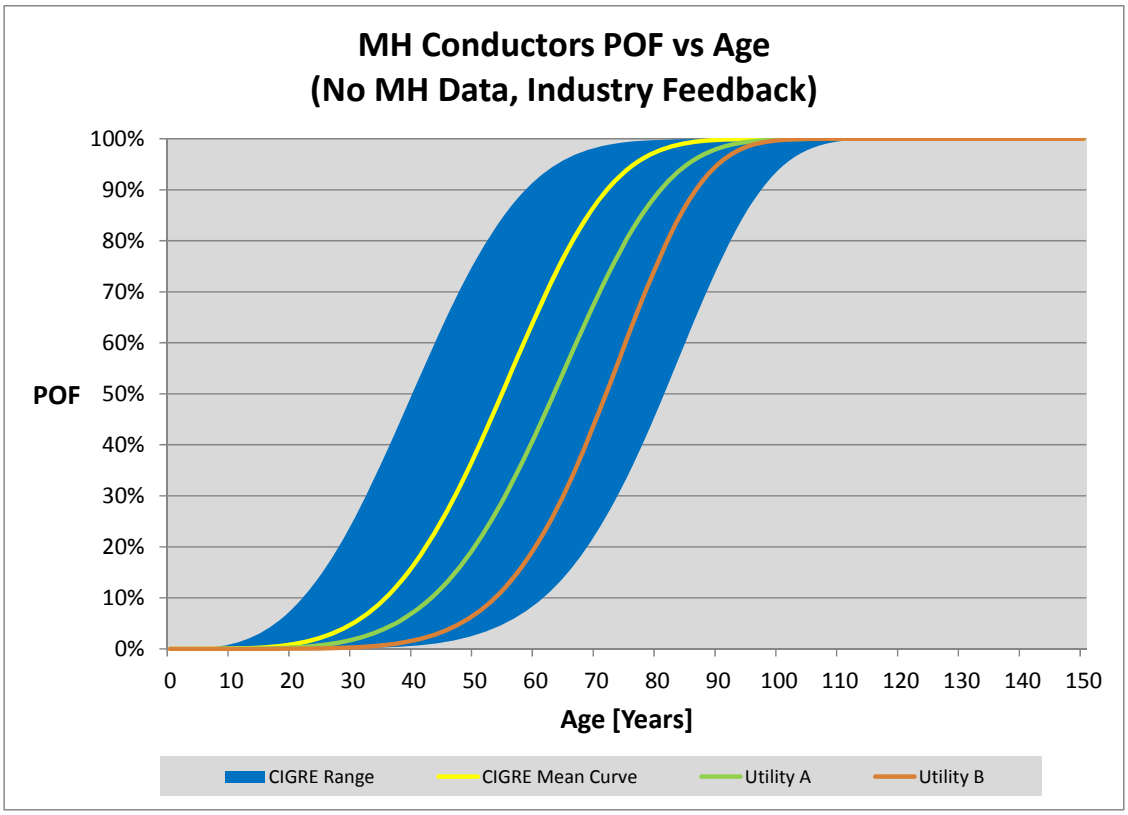

Figure 9-4 Comparison of CIGRE Curve with Industry Experience (Conductors)

In the above diagram, CIGRE curve is compared with the curves from 2 utilities in North America.

As shown in the diagram, the curves from the 2 utilities are within CIGRE curve range.

9.4. Link AHI to Condition Based Failure Rate

Due to lack of data, no study was conducted on this asset category to link its AHI to failure rate. MH is recommended to conduct an AHI study for this asset group in the future. For the purpose of long term investment planning using the existing data, MH could use the CIGRE mean failure curves and link them to AHI by assuming AHI = 100% - POF. This would be a conservative approximation and requires calibration based on the AHI results.

This page is intentionally left blank.

10. WOOD POLES

10.1. Removal Size and Population size

This asset group addresses the wood pole structures in MH transmission system.

For this asset category, there are 560 available removal records. They cover the units that were removed during the period of 1996 – 2016.

The root causes for the removals include:

- "Near end of life" due to shell rot based on the test results

In this case, there is no exiting age profile incorporated in developing asset degradation curve.

There is no further sub-categorization by species, height, or voltage class.

10.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

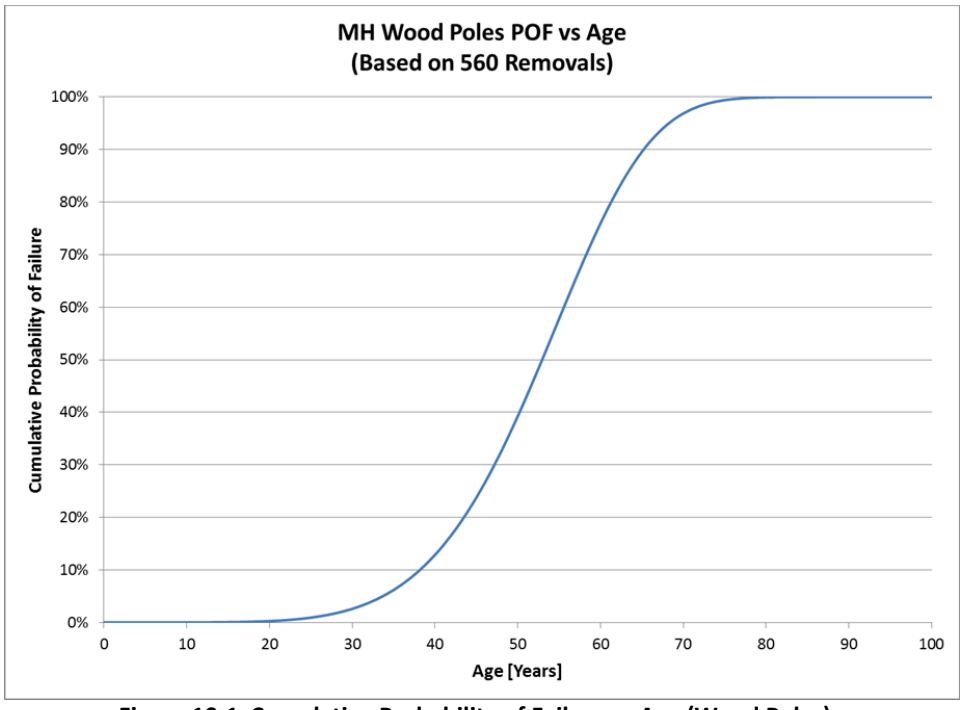

Figure 10-1 Cumulative Probability of Failure vs Age (Wood Poles)

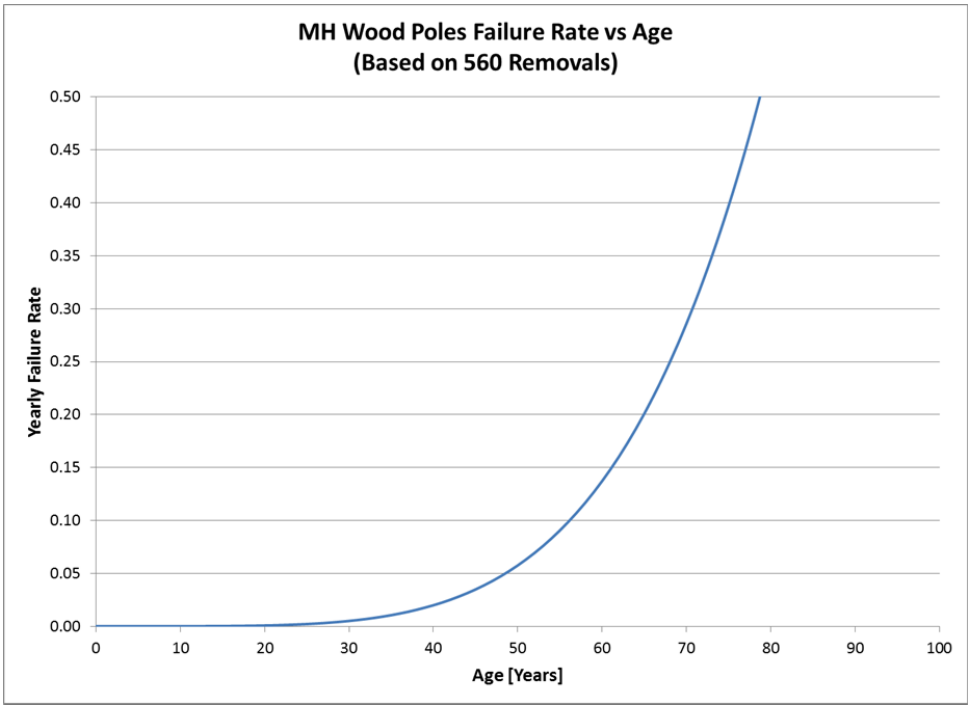

Figure 10-2 Annual Failure Rate vs Age (Wood Poles)

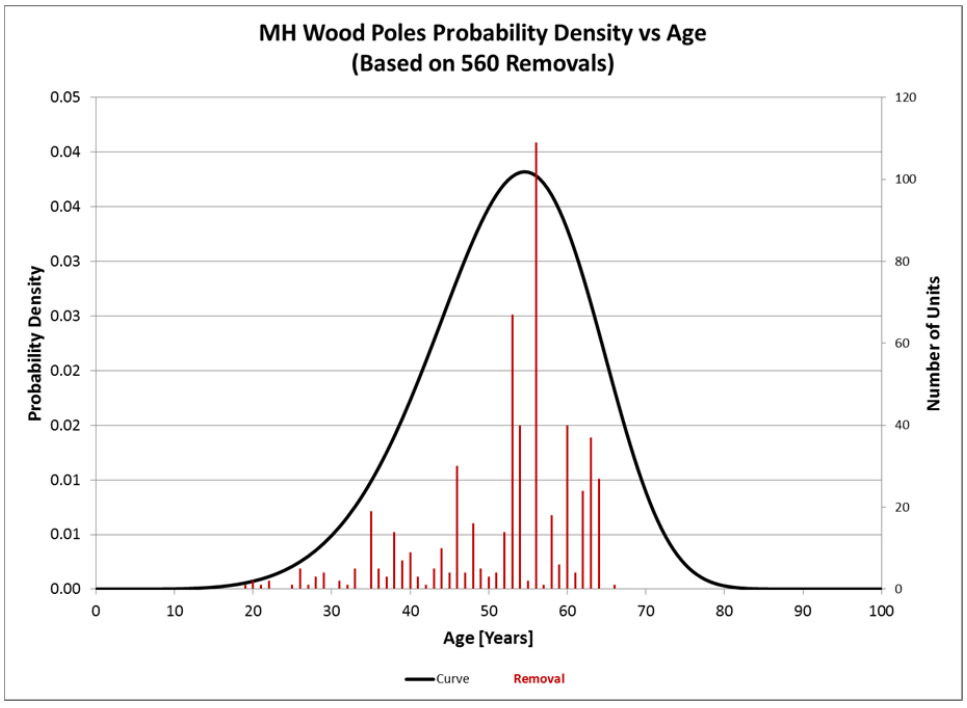

Figure 10-3 Failure Density Curve and Age Profile (Wood Poles)

10.3. Comparison of MH Curve with Industry Curves

The following diagram shows the comparison of MH curve with the ones from other utilities in industry.

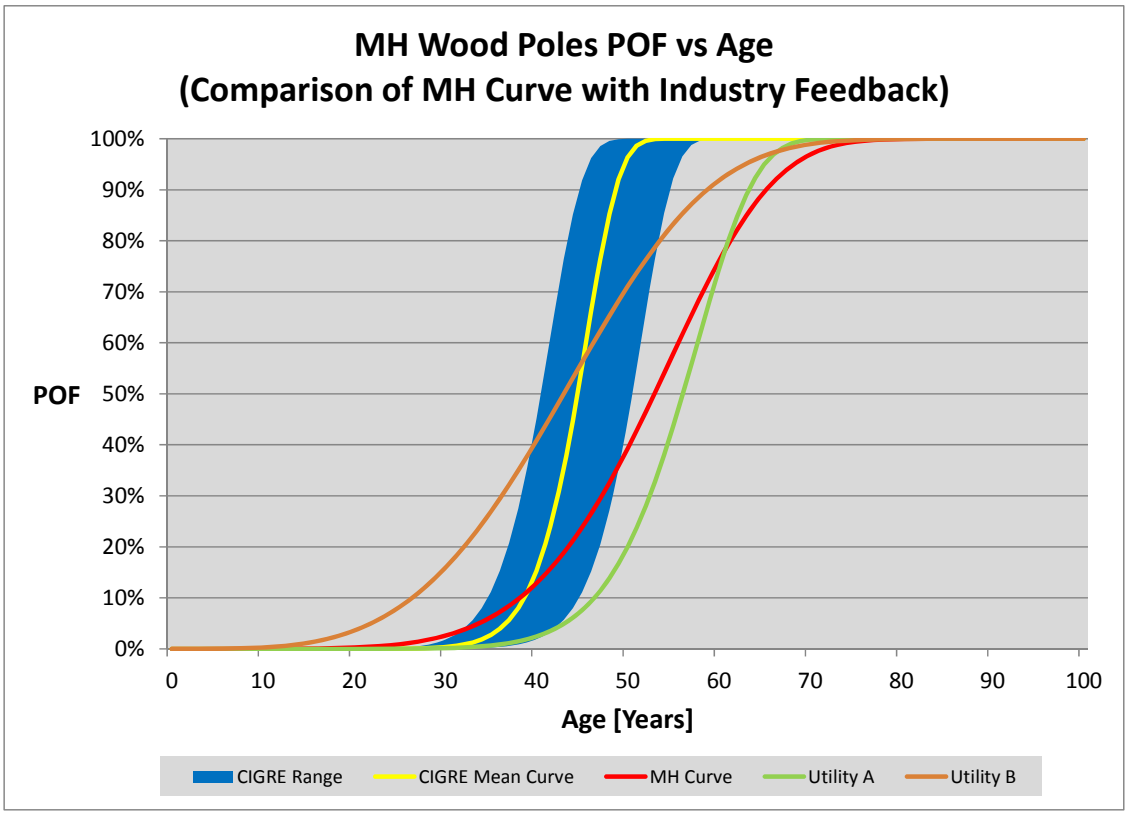

Figure 10-4 Comparison of MH Curve with Industry Experience (Wood Poles)

In the above diagram, MH curve is compared with CIGRE statistics and the curves from 2 utilities in North America.

As shown in the diagram, MH curve is an outlier when compared with CIGRE curve range. It also shows a service life between the ones of the other 2 utilities.

10.4. Link AHI to Condition Based Failure Rate

The following diagrams show the series of developed curves linking AHI to condition based degradation curves.

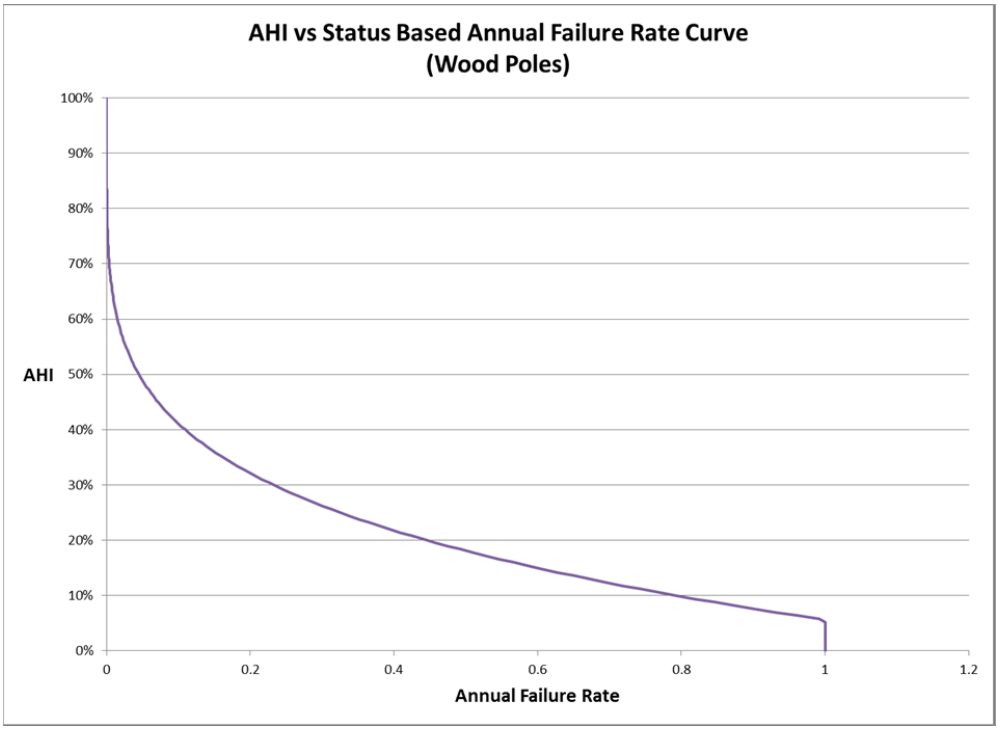

Figure 10-5 AHI vs Annual Failure Rate (Wood Poles)

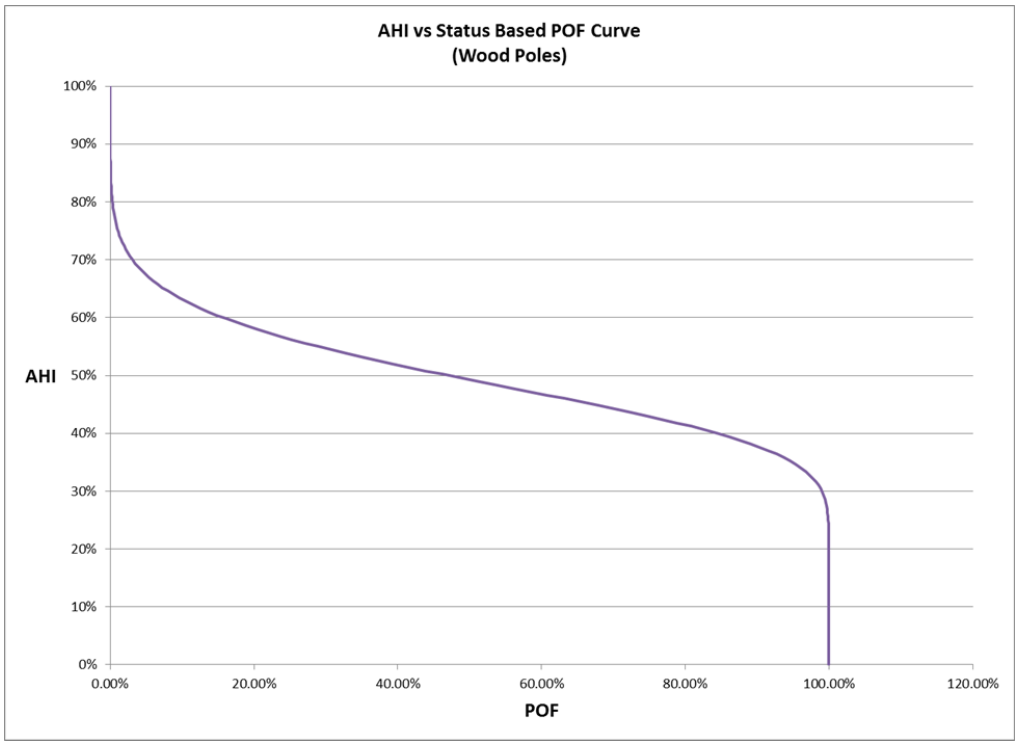

Figure 10-6 AHI vs Cumulative Probability of Failure (Wood Poles)

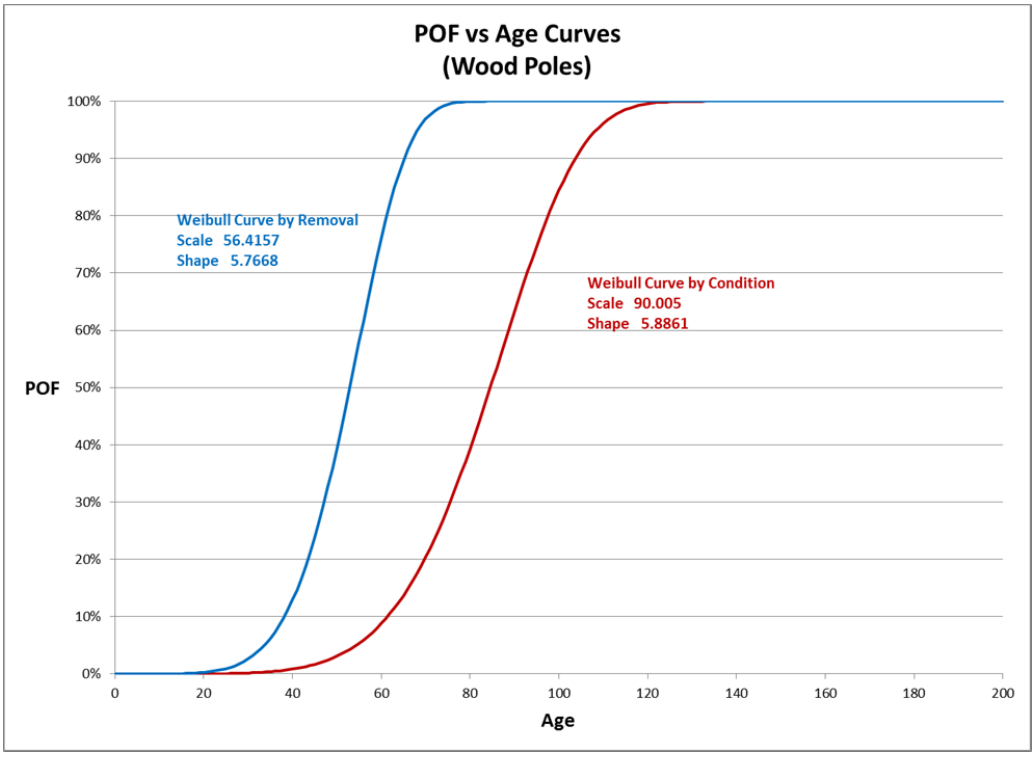

Figure 10-7 Removal Based vs Condition Based POF Curves (Wood Poles)

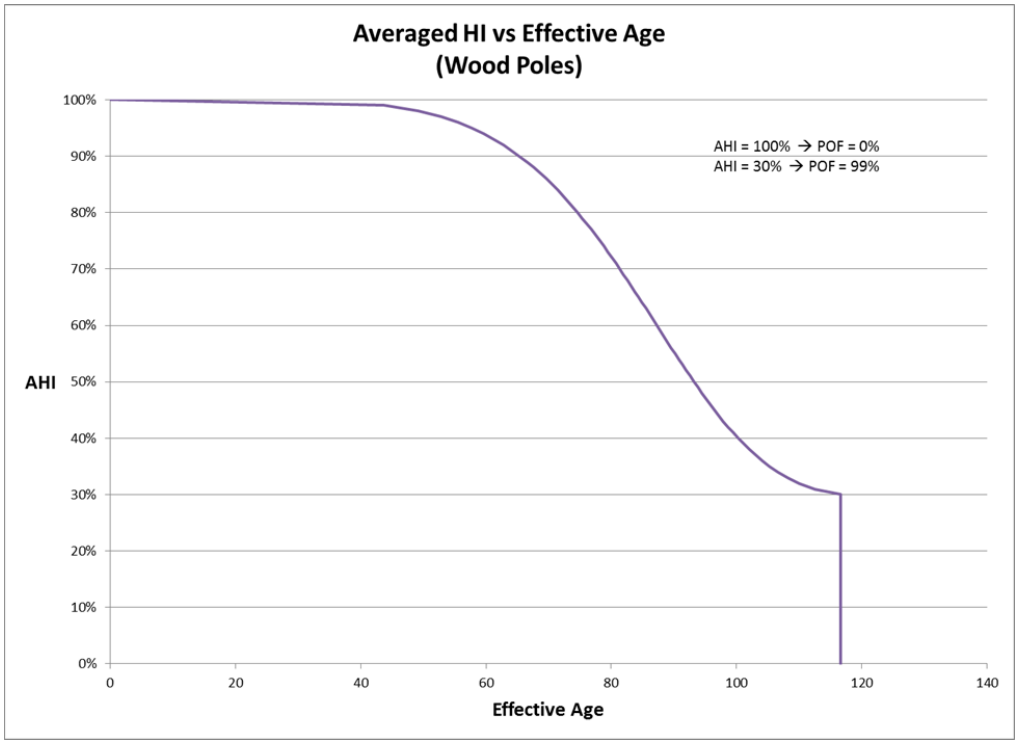

Figure 10-8 AHI vs Effective Age (Wood Poles)

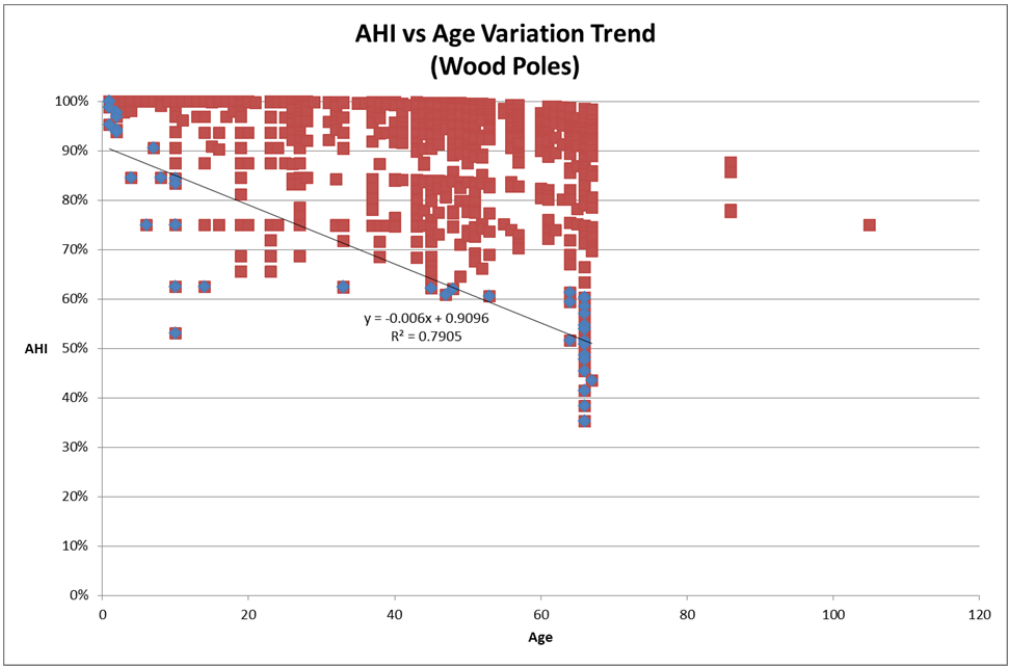

Figure 10-9 AHI vs Age Variation Trend (Wood Poles)

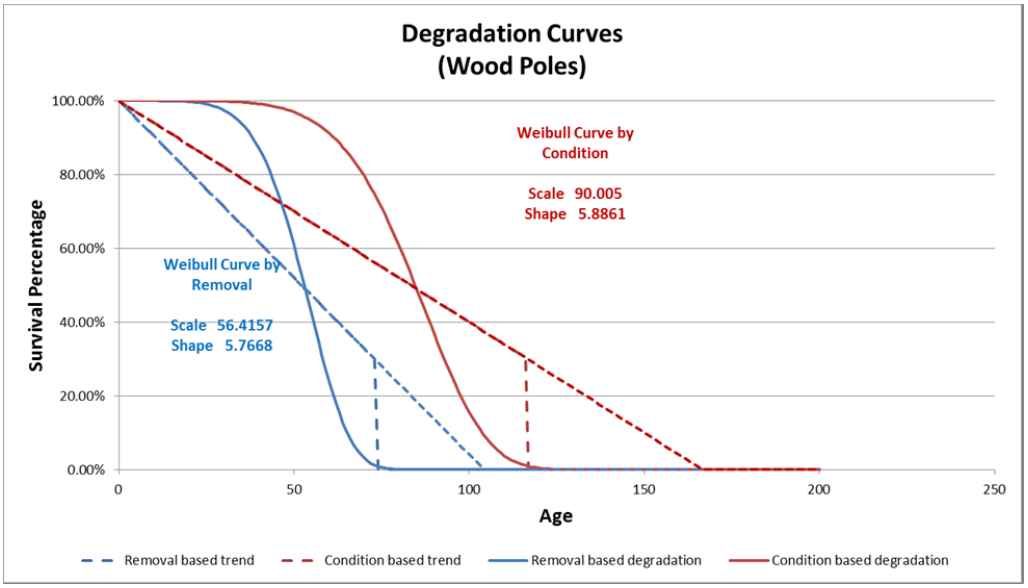

Figure 10-10 Removal Based vs Condition Based Degradation Curves (Wood Poles)

11. ELECTROMECHANICAL RELAYS

11.1. Removal Size and Population size

This asset group addresses the electromechanical relays in MH transmission system.

For this asset category, there are 2345 available removal records. They cover the units that were removed during the period of 2001 – 2016.

The root causes for the removals include:

- Functional obsolescence
- Components failure
- Age

In this case, there is no exiting age profile incorporated in developing asset degradation curve.

There is no further sub-categorization by make or family.

11.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

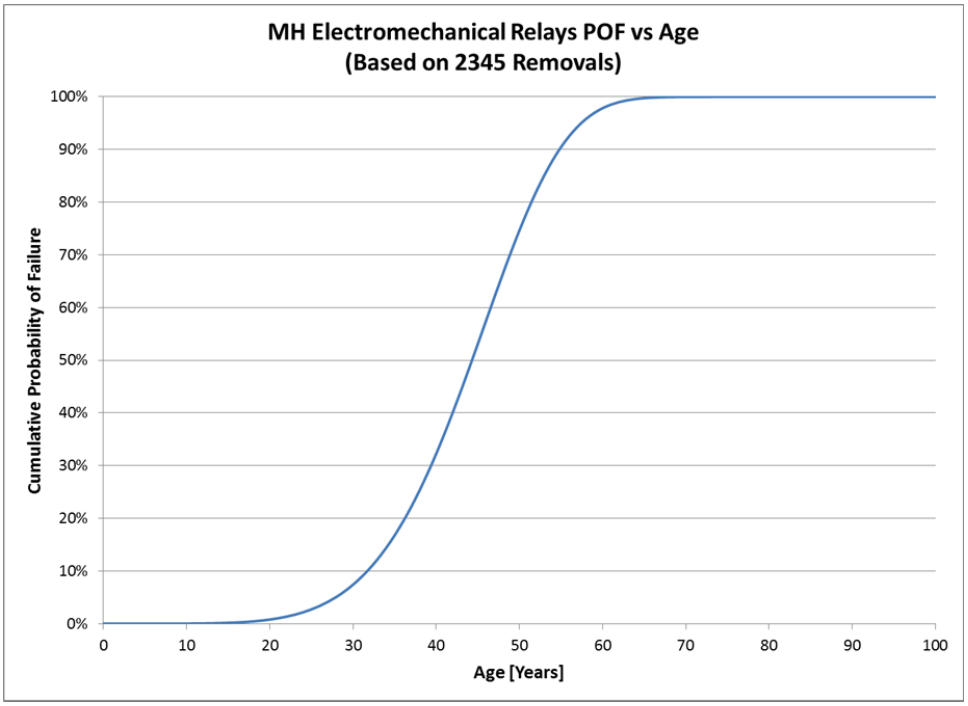

Figure 11-1 Cumulative Probability of Failure vs Age (Electromechanical Relays)

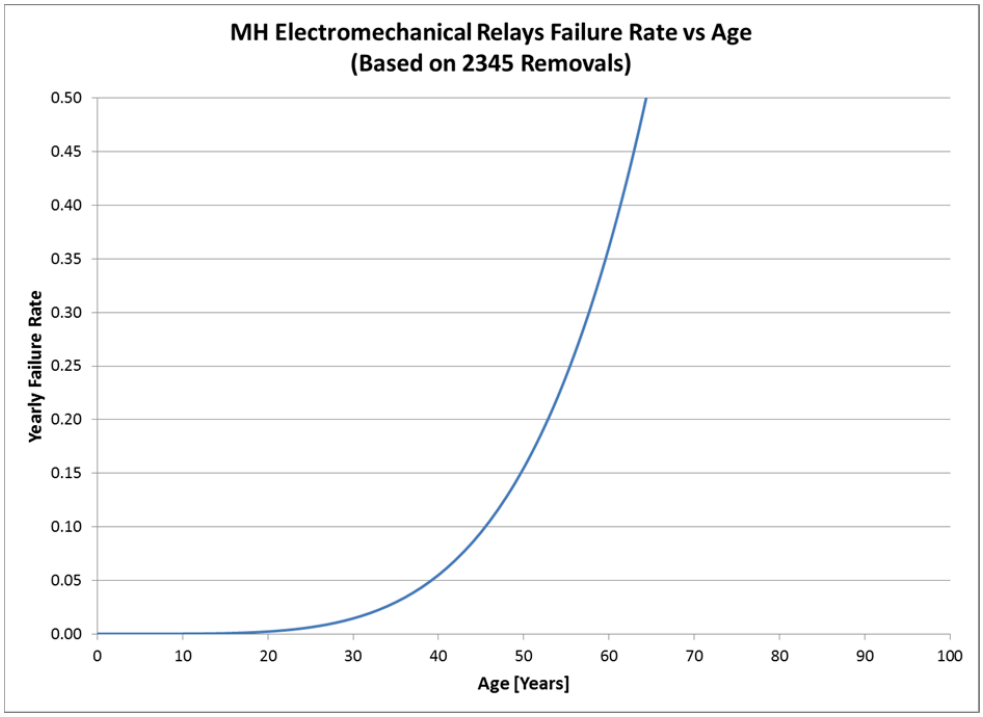

Figure 11-2 Annual Failure Rate vs Age (Electromechanical Relays)

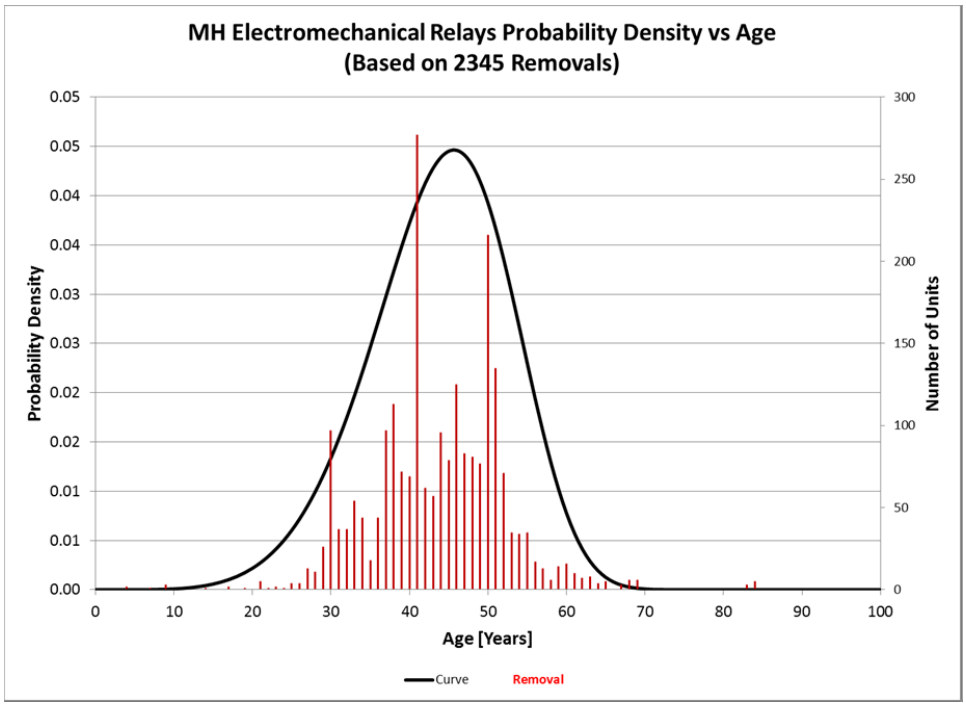

Figure 11-3 Failure Density Curve and Age Profile (Electromechanical Relays)

11.3. Comparison of MH Curve with Industry Curves

The following diagram shows the comparison of MH curve with the ones from other utilities in industry.

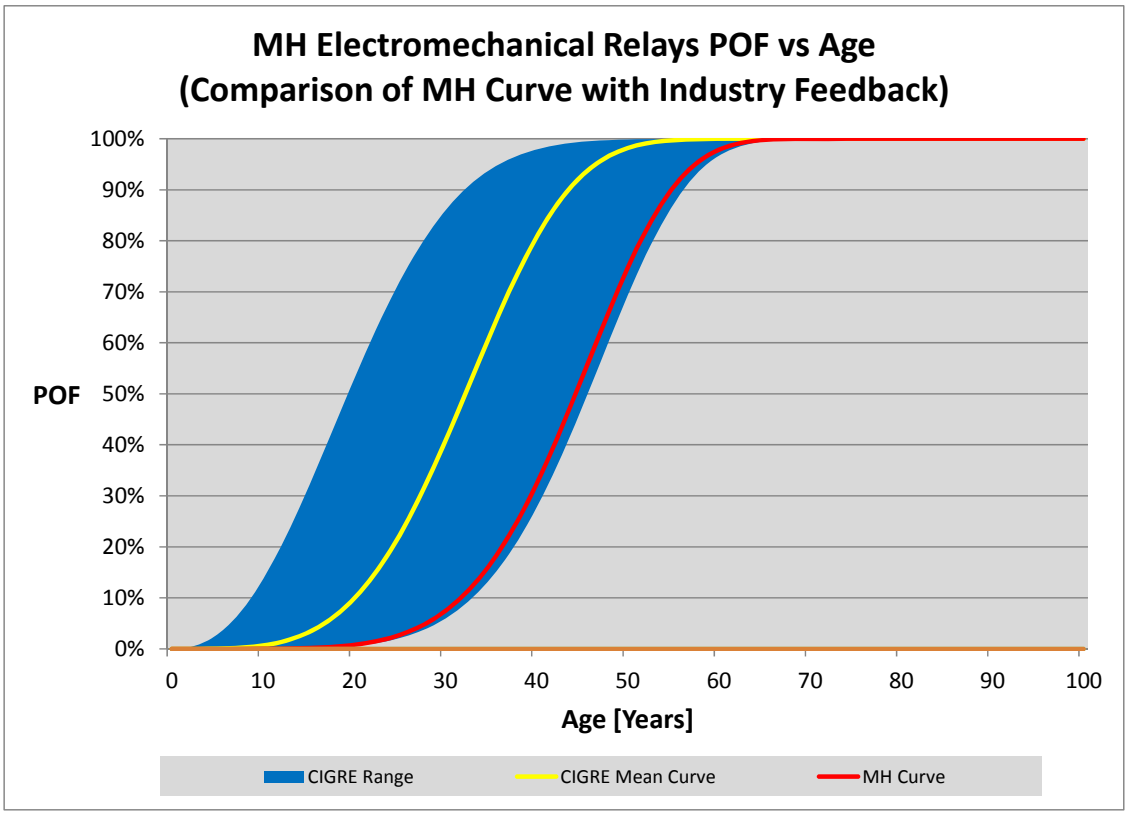

Figure 11-4 Comparison of MH Curve with Industry Experience (Electromechanical Relays)

In the above diagram, MH curve is compared with CIGRE statistics.

As shown in the diagram, MH curve is at the outer border of CIGRE curve range.

11.4. Link AHI to Condition Based Failure Rate

The following diagrams show the series of developed curves linking AHI to condition based degradation curves.

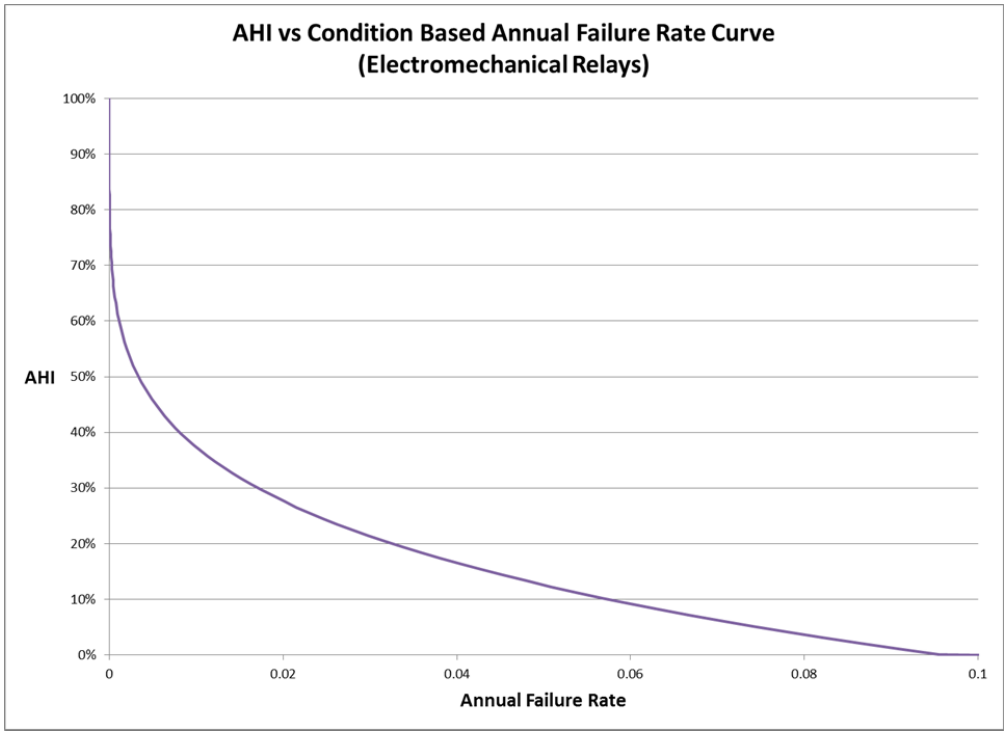

Figure 11-5 AHI vs Annual Failure Rate (Electromechanical Relays)

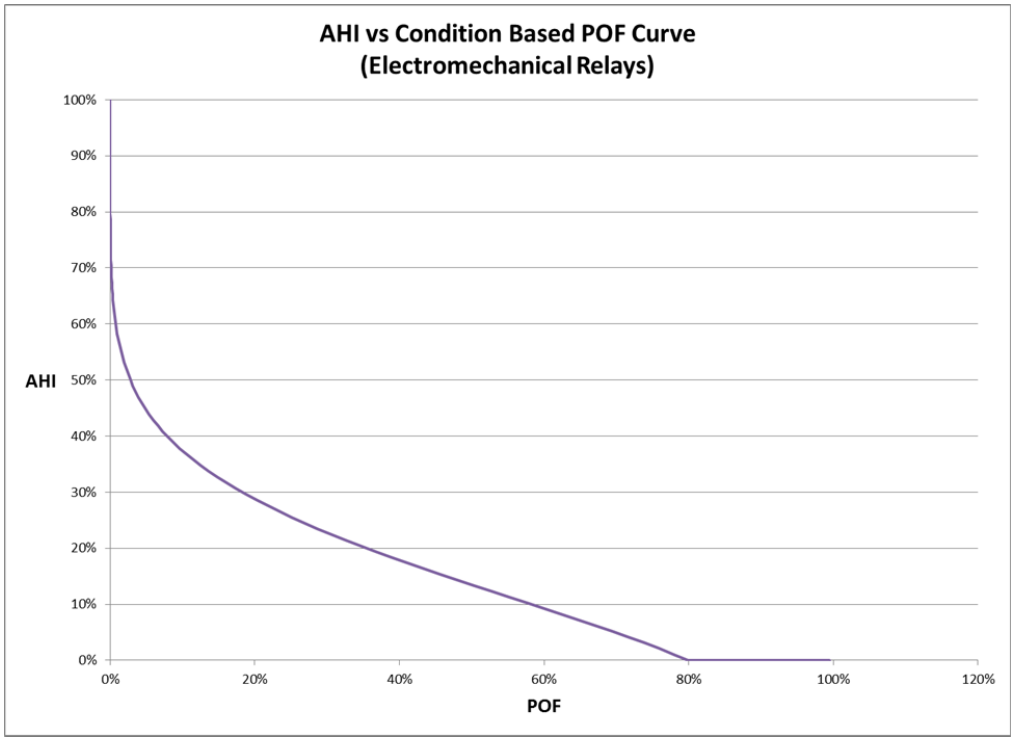

Figure 11-6 AHI vs Cumulative Probability of Failure (Electromechanical Relays)

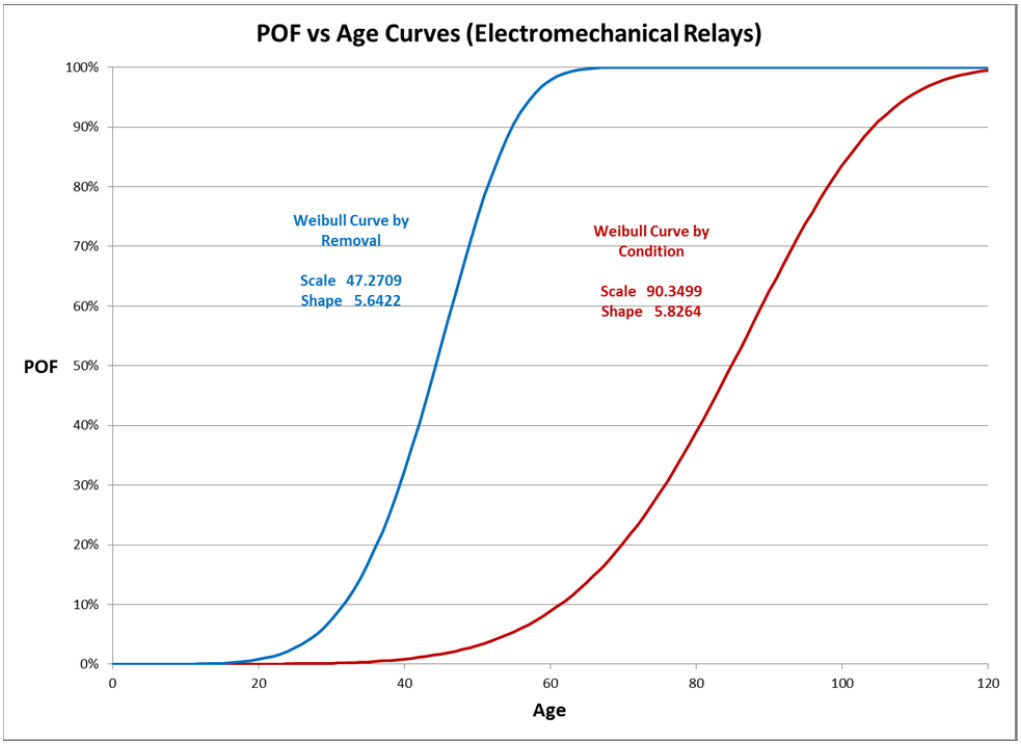

Figure 11-7 Removal Based Curve vs Condition Based Curve (Electromechanical Relays)

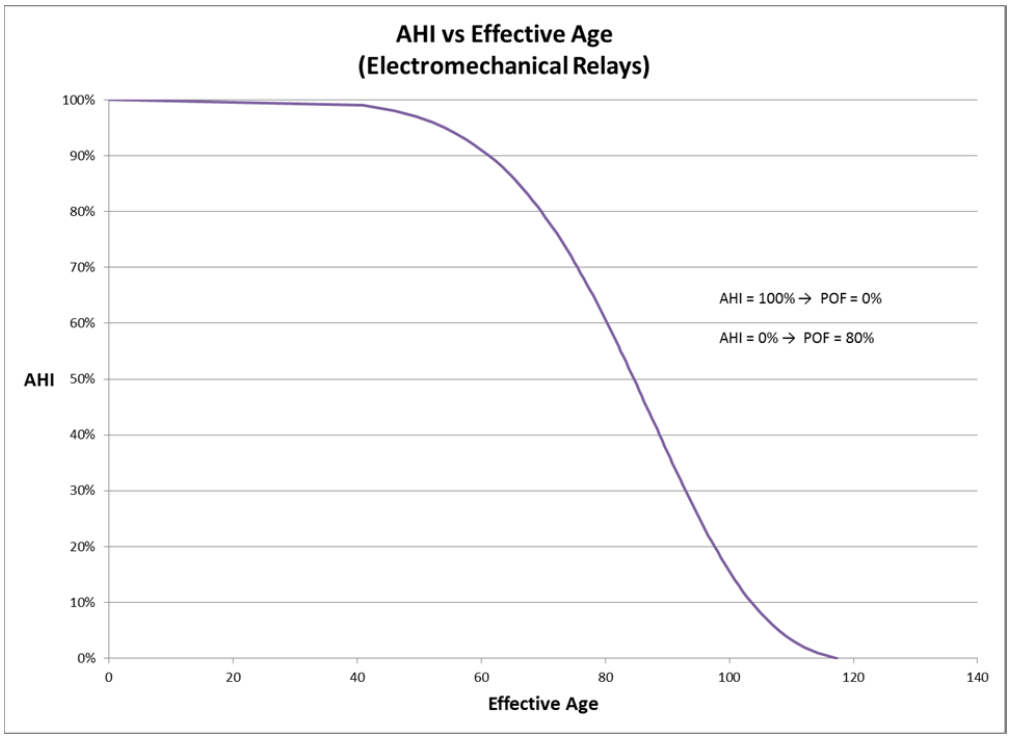

Figure 11-8 AHI vs Effective Age (Electromechanical Relays)

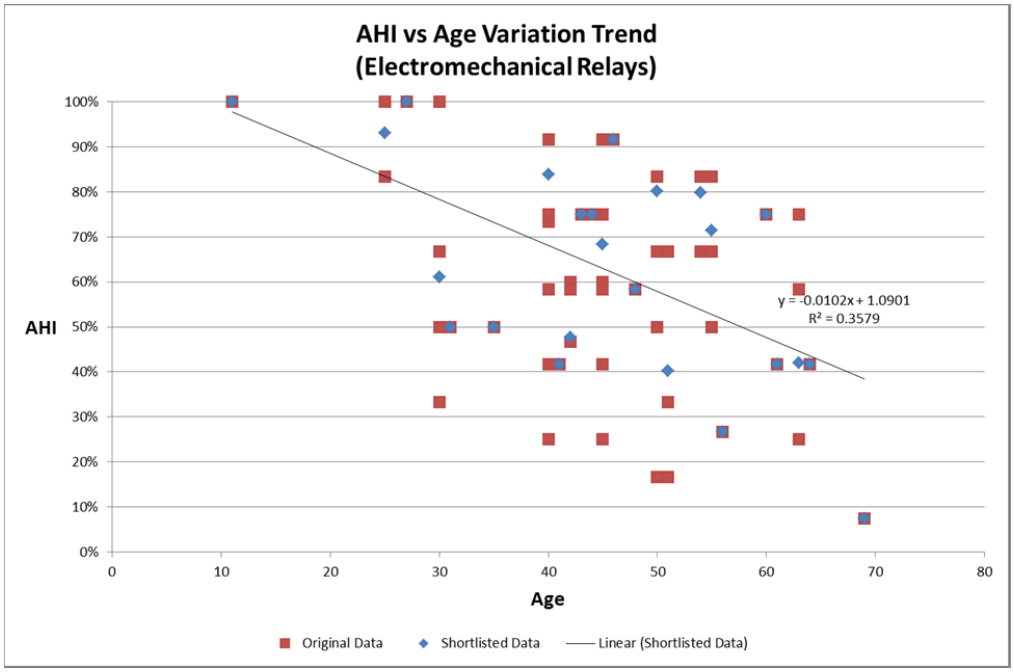

Figure 11-9 AHI vs Age Variation Trend (Electromechanical Relays)

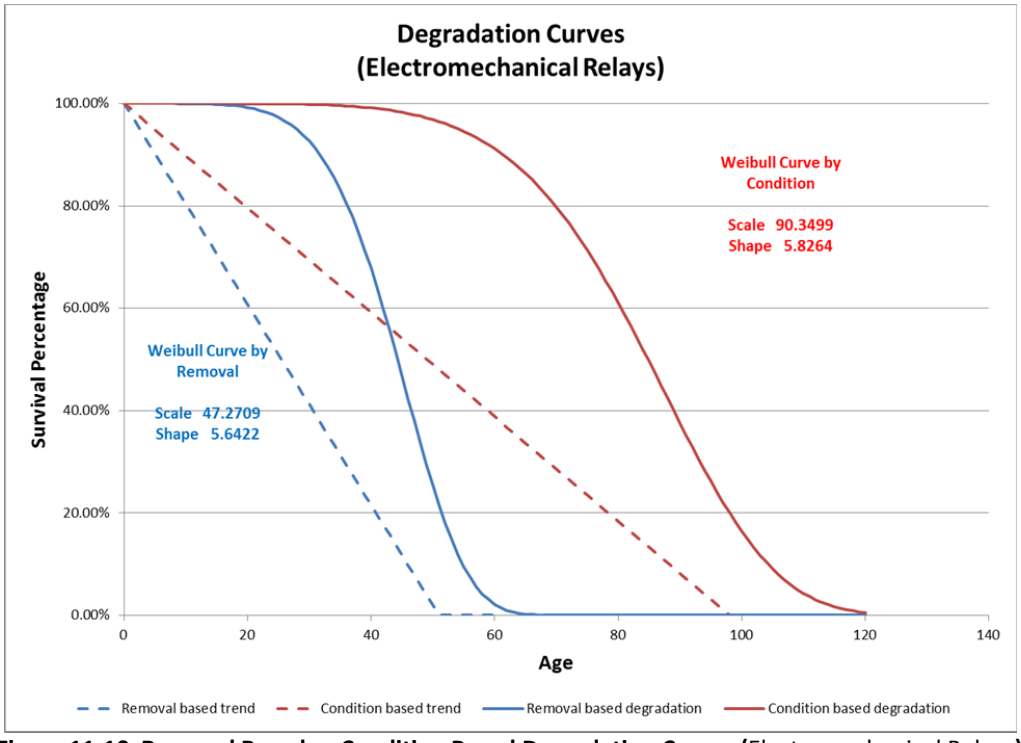

Figure 11-10 Removal Based vs Condition Based Degradation Curves (Electromechanical Relays**)**

12. SOLID STATE RELAYS

12.1. Removal Size and Population size

This asset group addresses the solid state relays in MH transmission system.

For this asset category, there are 391 available removal records. They cover the units that were removed during the period of 2001 – 2016.

The root causes for the removals include:

- Unit failure
- Age and MH's non-condition assessment

In this case, there is no exiting age profile incorporated in developing asset degradation curve.

There is no further sub-categorization by make or family.

12.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

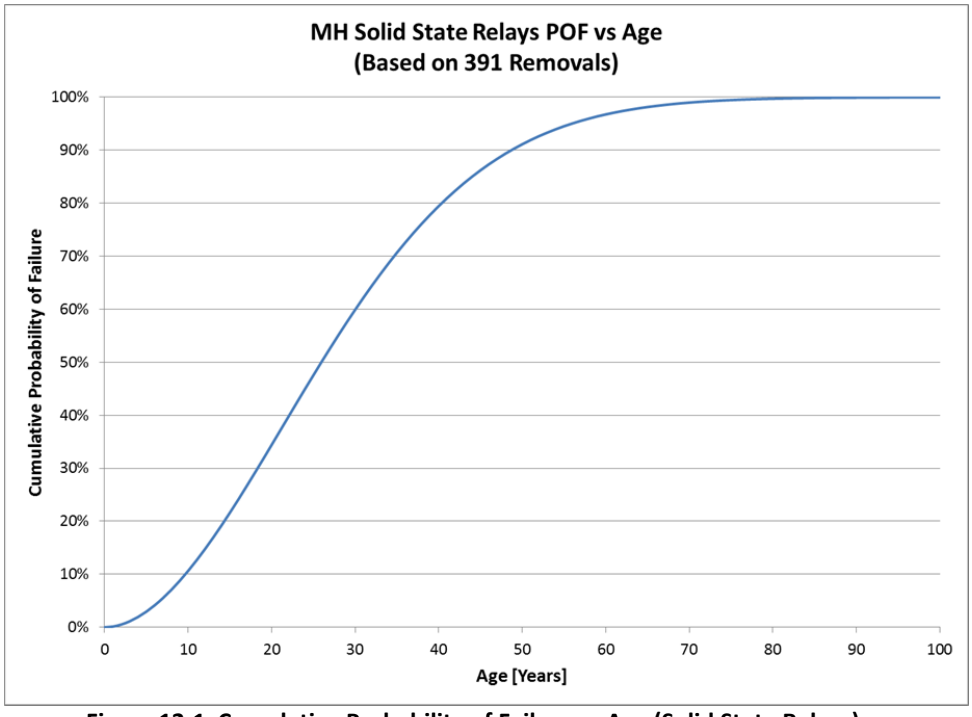

Figure 12-1 Cumulative Probability of Failure vs Age (Solid State Relays)

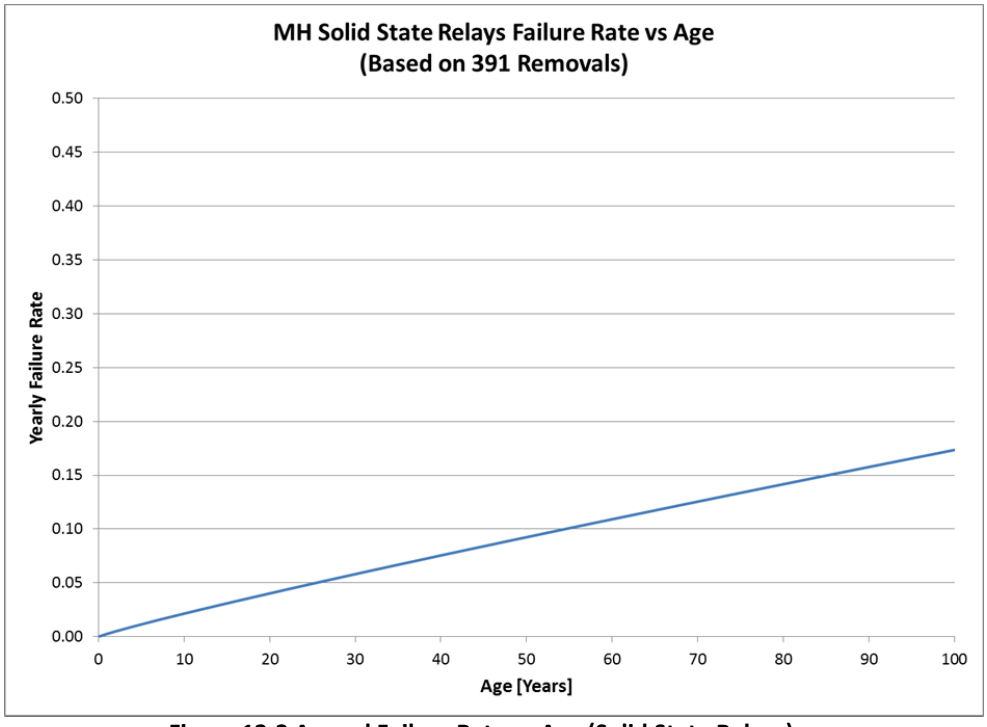

Figure 12-2 Annual Failure Rate vs Age (Solid State Relays)

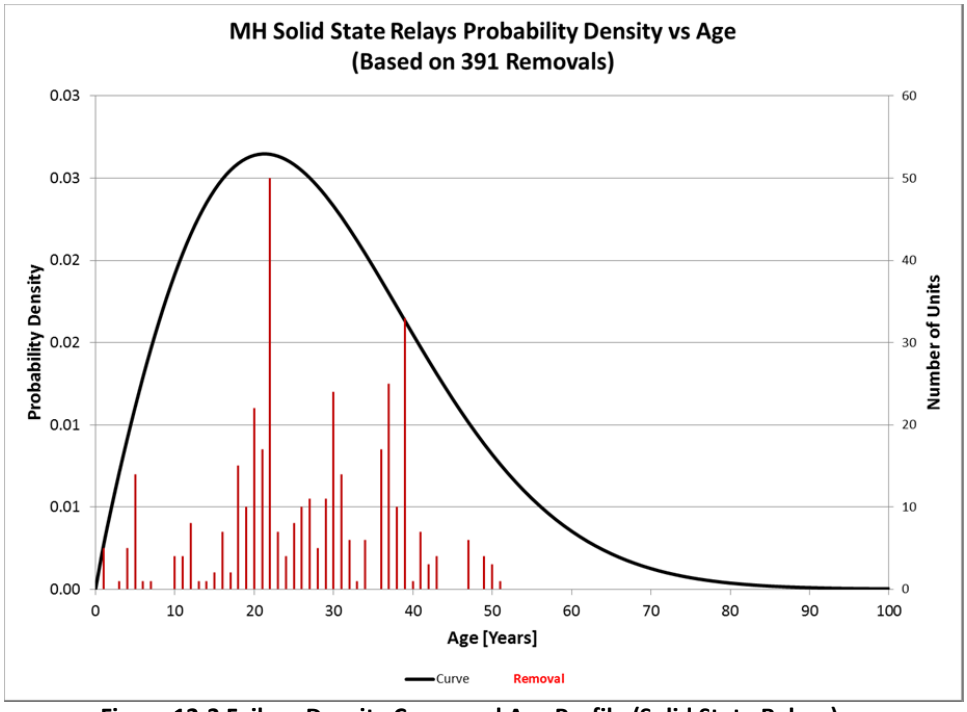

Figure 12-3 Failure Density Curve and Age Profile (Solid State Relays)

12.3. Comparison of MH Curve with Industry Curves

There are no industry practice curves for comparison with MH curves.

12.4. Link AHI to Condition Based Failure Rate

The following diagrams show the series of developed curves linking AHI to condition based degradation curves.

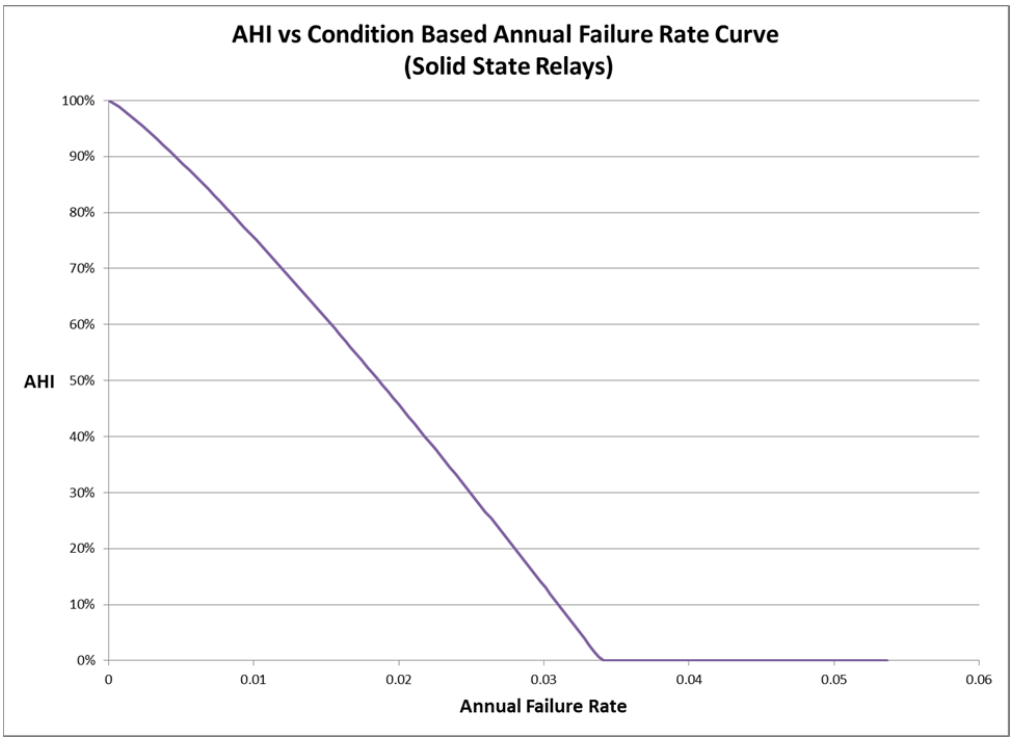

Figure 12-4 AHI vs Annual Failure Rate (Solid State Relays)

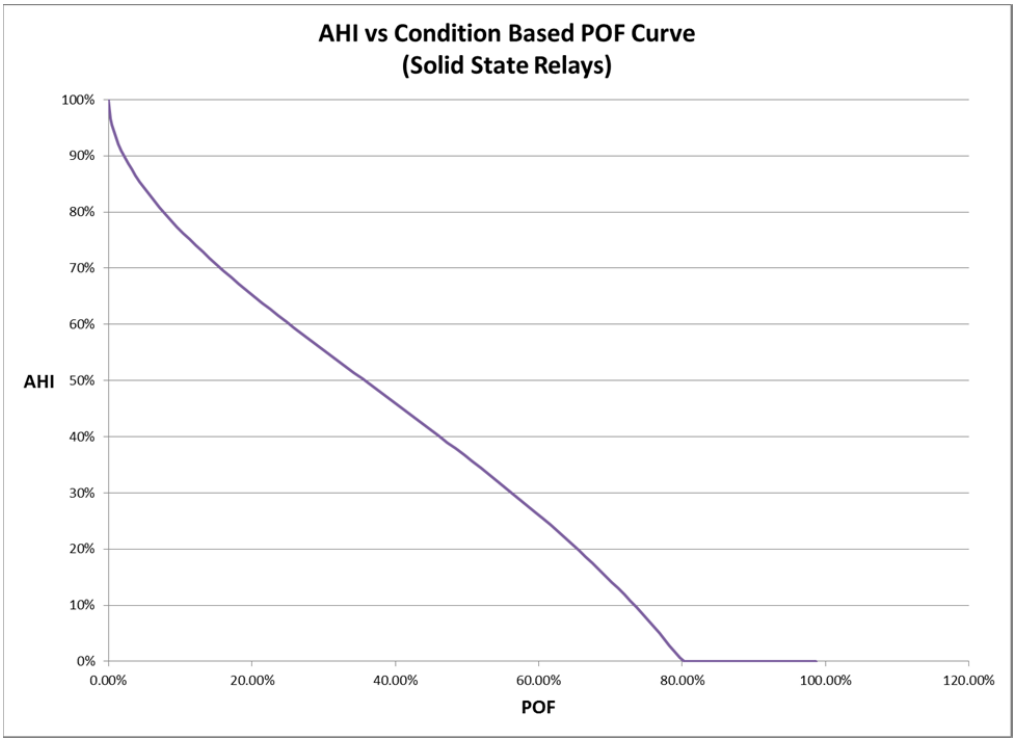

Figure 12-5 AHI vs Cumulative Probability of Failure (Solid State Relays)

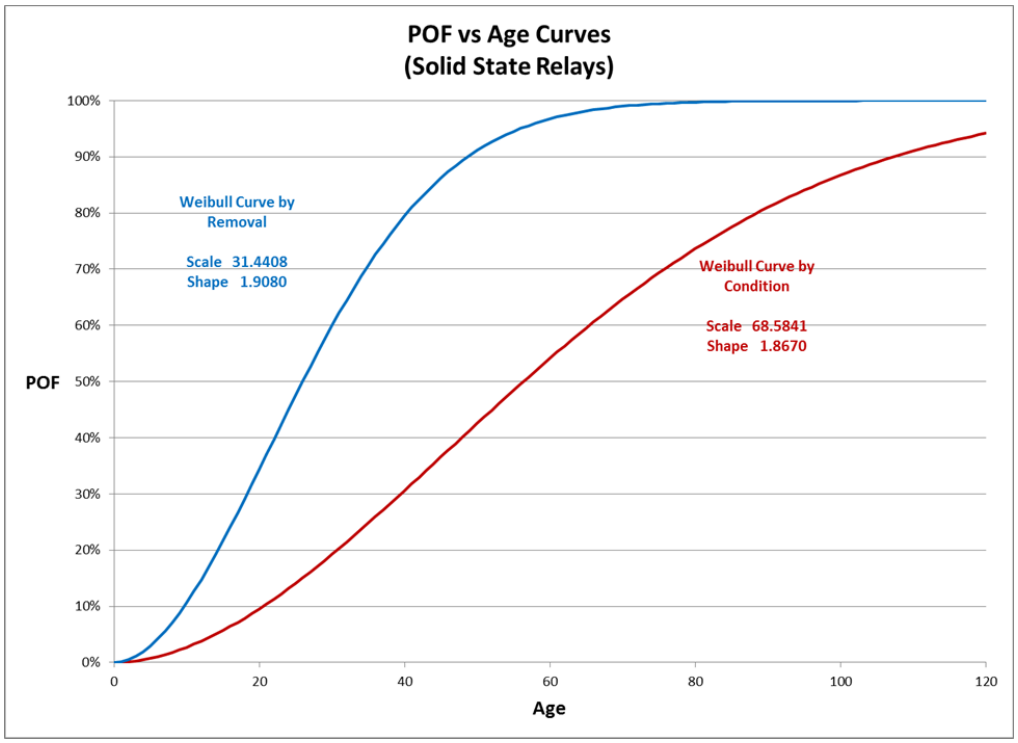

Figure 12-6 Removal Based vs Condition Based Curves (Solid State Relays)

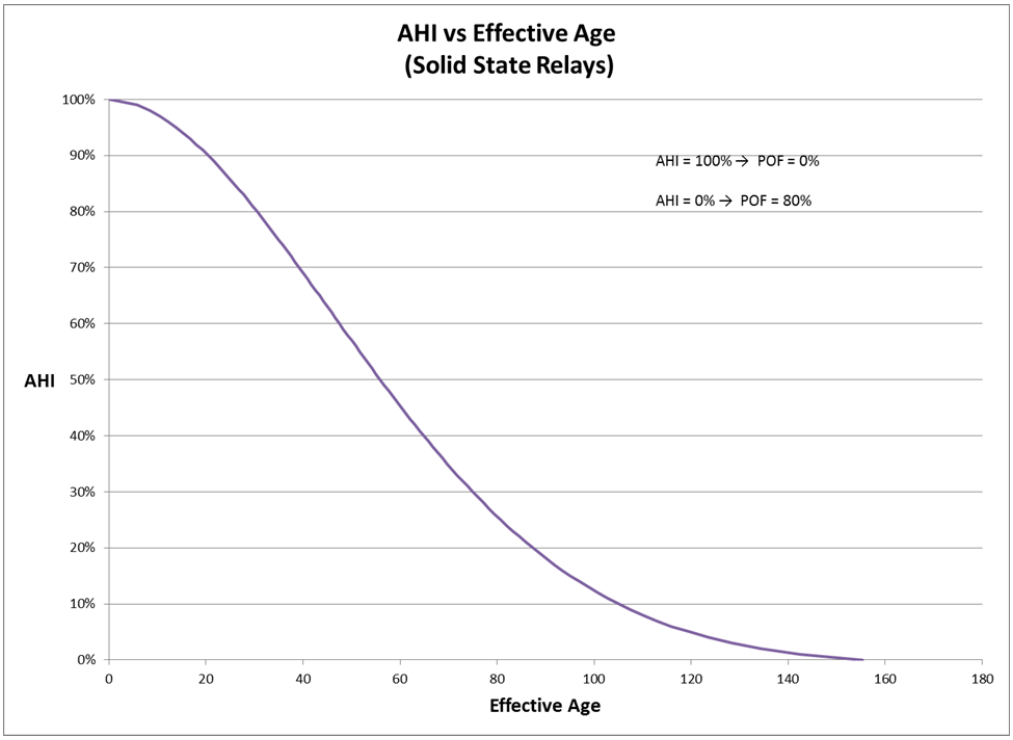

Figure 12-7 AHI vs Effective Age (Solid State Relays)

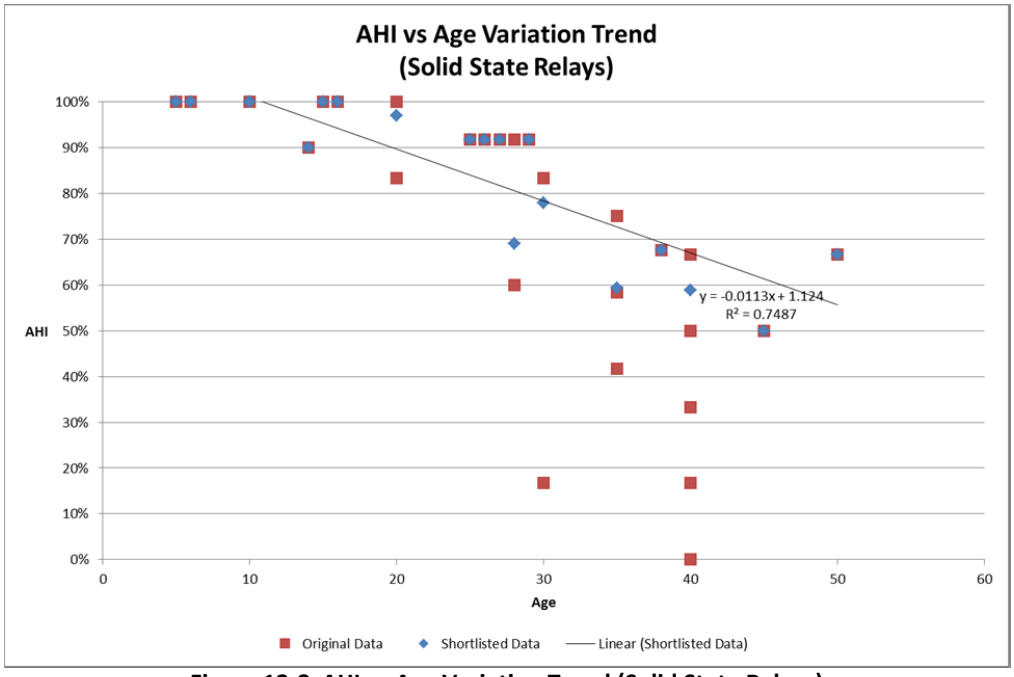

Figure 12-8 AHI vs Age Variation Trend (Solid State Relays)

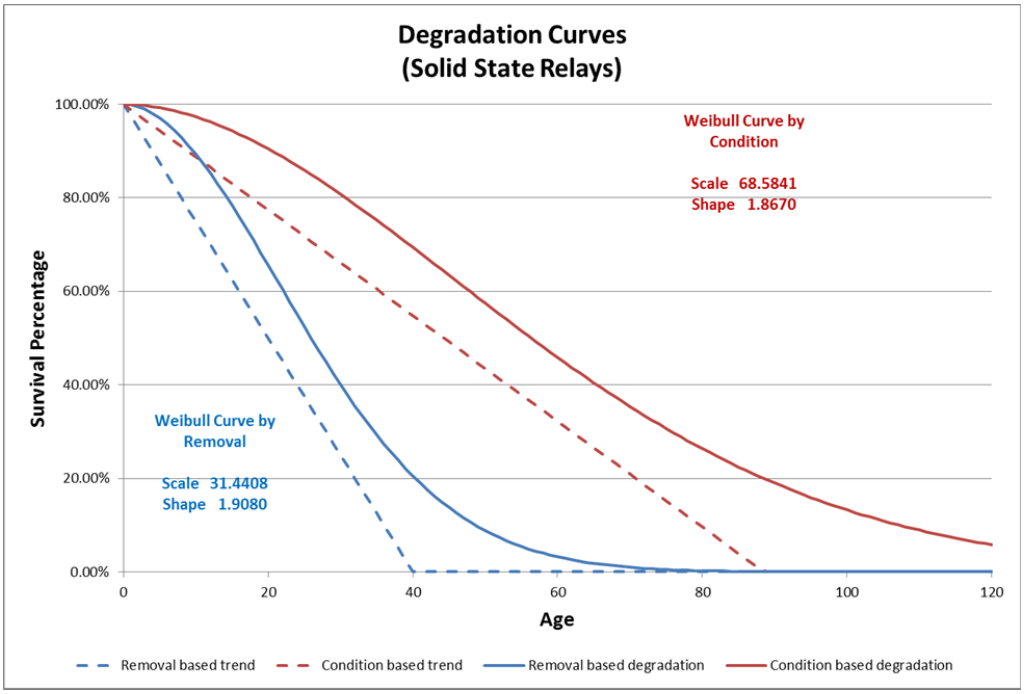

Figure 12-9 Removal Based vs Condition Based Degradation Curves (Solid State Relays)

13. DIGITAL RELAYS

13.1. Removal Size and Population size

This asset group addresses the digital relays in MH transmission system.

For this asset category, there are 98 available removal records. To filter out the infant mortality factor, only 60 of them are adopted for curve fitting. They cover the units that were removed during the period of 2004 – 2016.

The root causes for the removals include:

- Unit failure
- Age and MH's AHI assessment (including non-condition information)

Since the removal size is relatively small, the existing age profile of 3686 units is also incorporated in developing asset degradation curve.

There is no further sub-categorization by make or family.

13.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

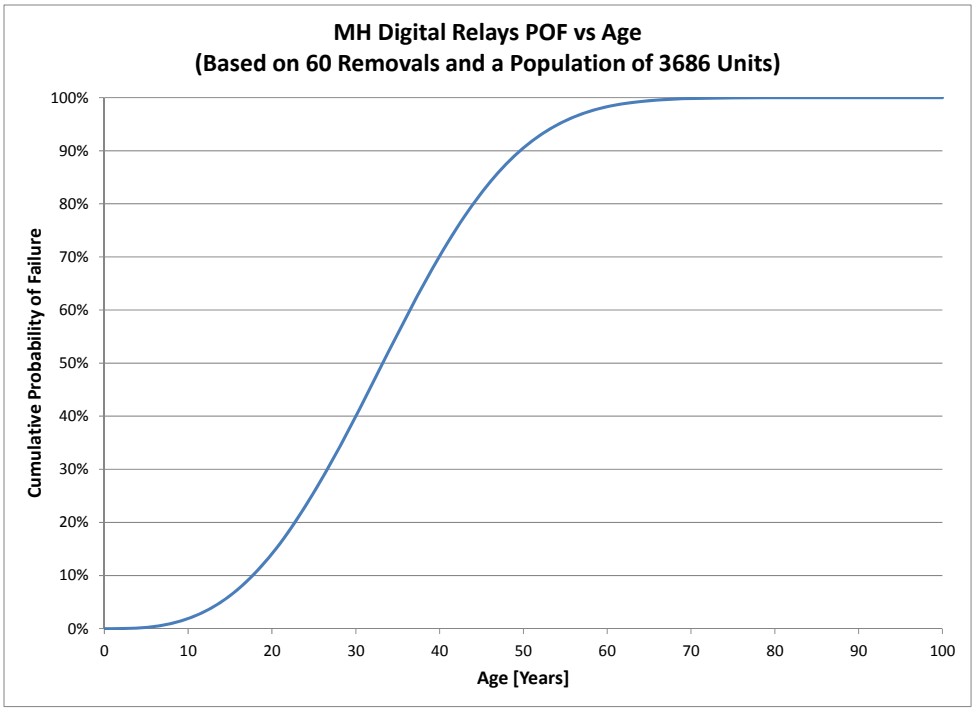

Figure 13-1 Cumulative Probability of Failure vs Age (Digital Relays)

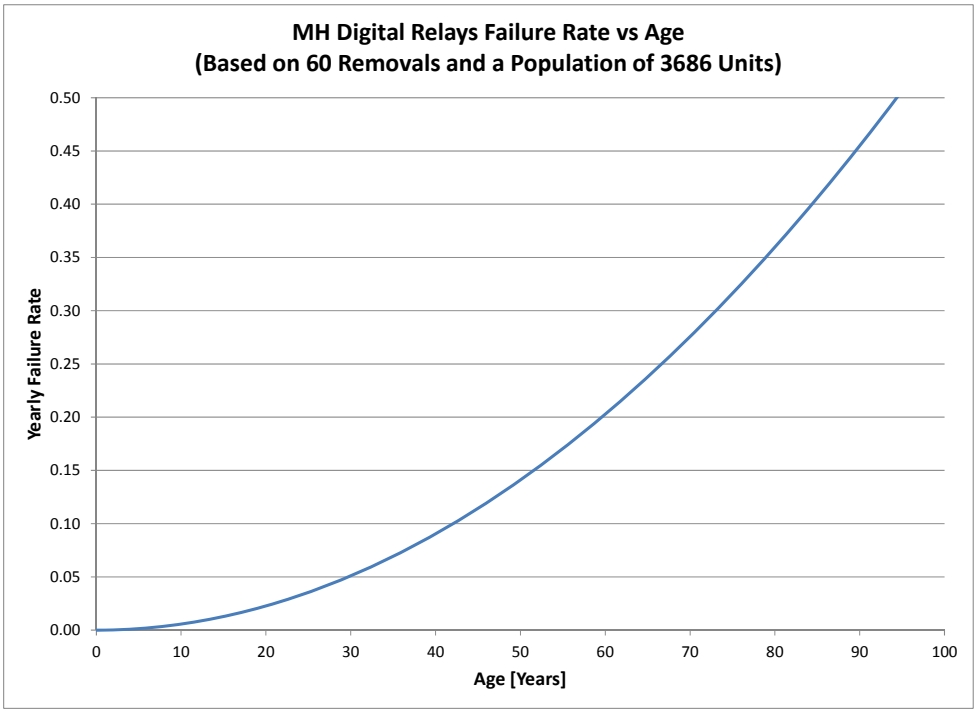

Figure 13-2 Annual Failure Rate vs Age (Digital Relays)

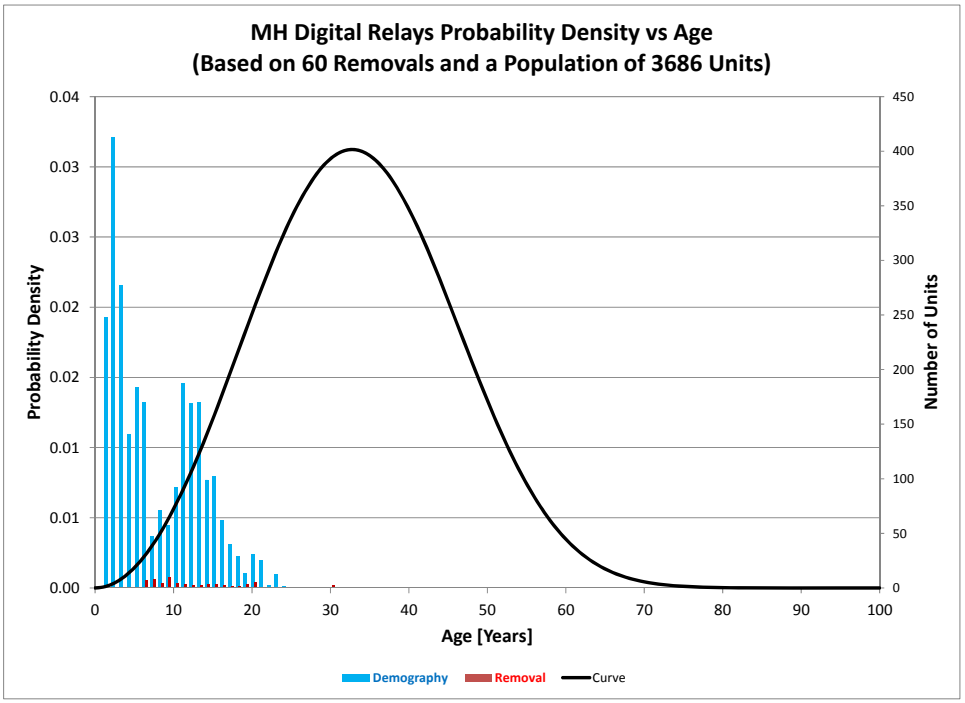

Figure 13-3 Failure Density Curve and Age Profile (Digital Relays)

13.3. Comparison of MH Curve with Industry Curves

There are no industry practice curves for comparison with MH curves.

13.4. Link AHI to Condition Based Failure Rate

The following diagrams show the series of developed curves linking AHI to condition based degradation curves.

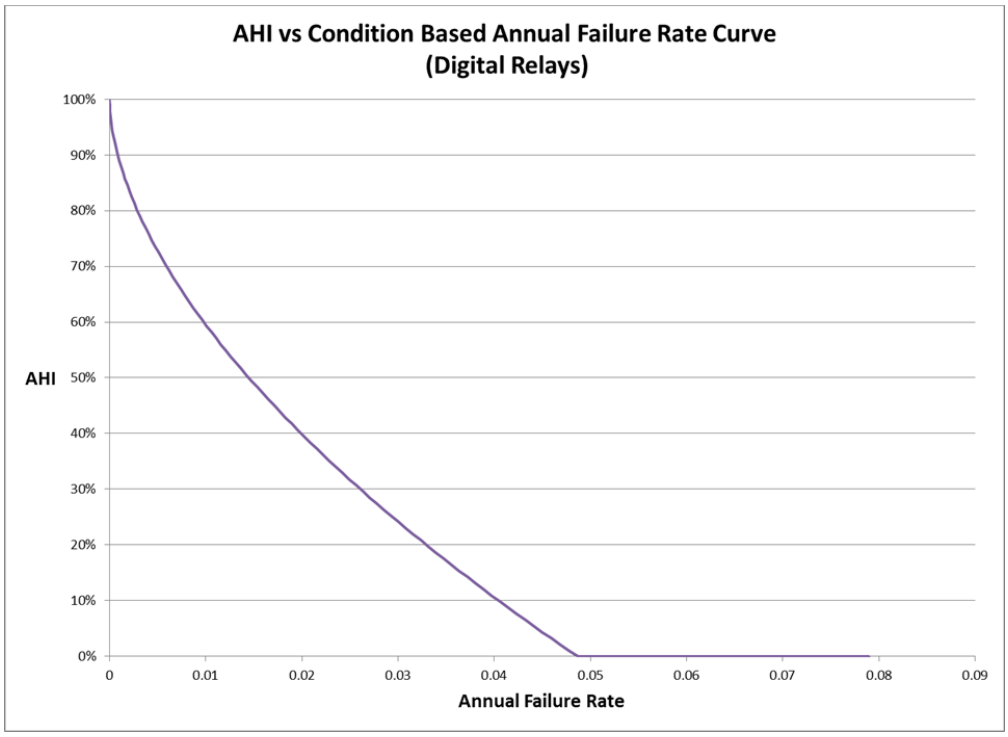

Figure 13-4 AHI vs Annual Failure Rate (Digital Relays)

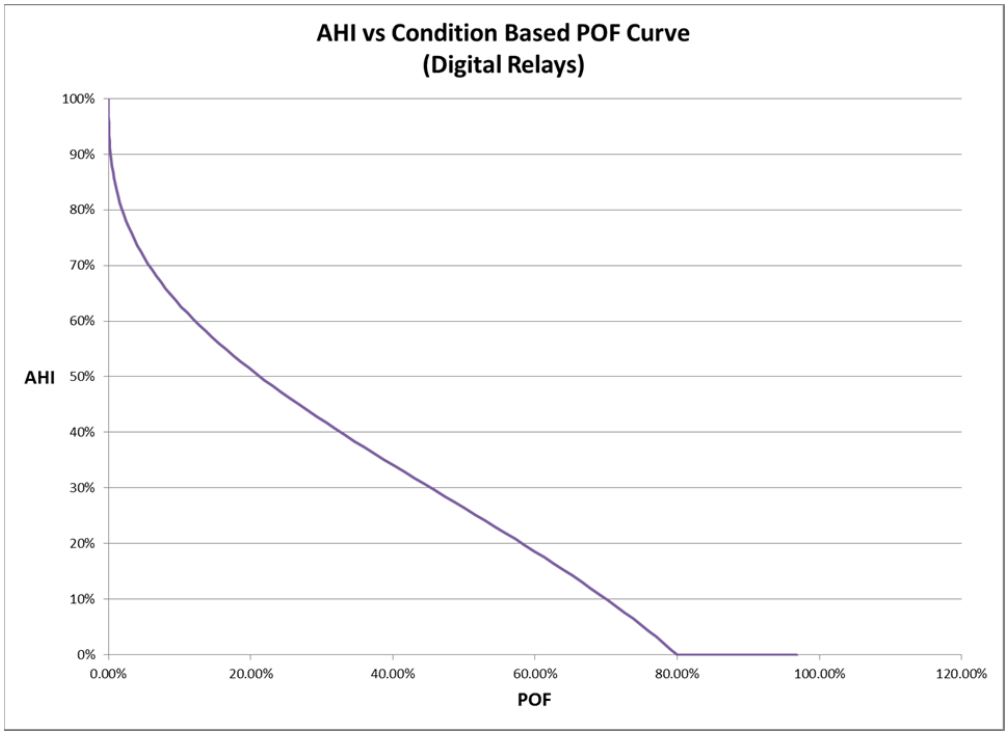

Figure 13-5 AHI vs Cumulative Probability of Failure (Digital Relays)

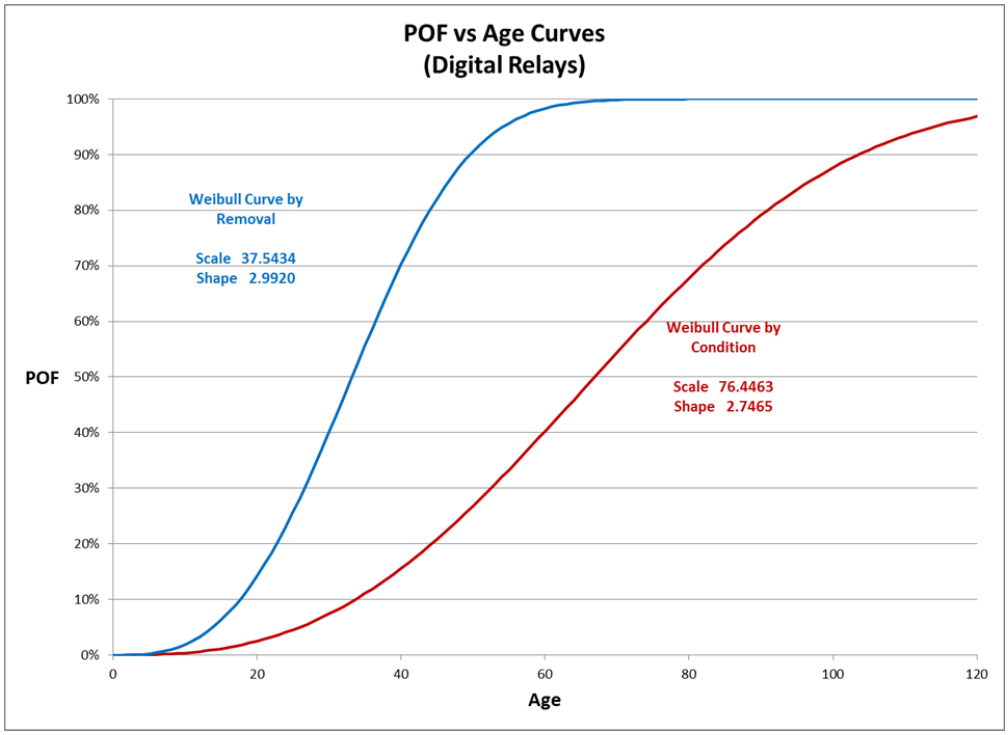

Figure 13-6 Removal Based vs Condition Based Curves (Digital Relays)

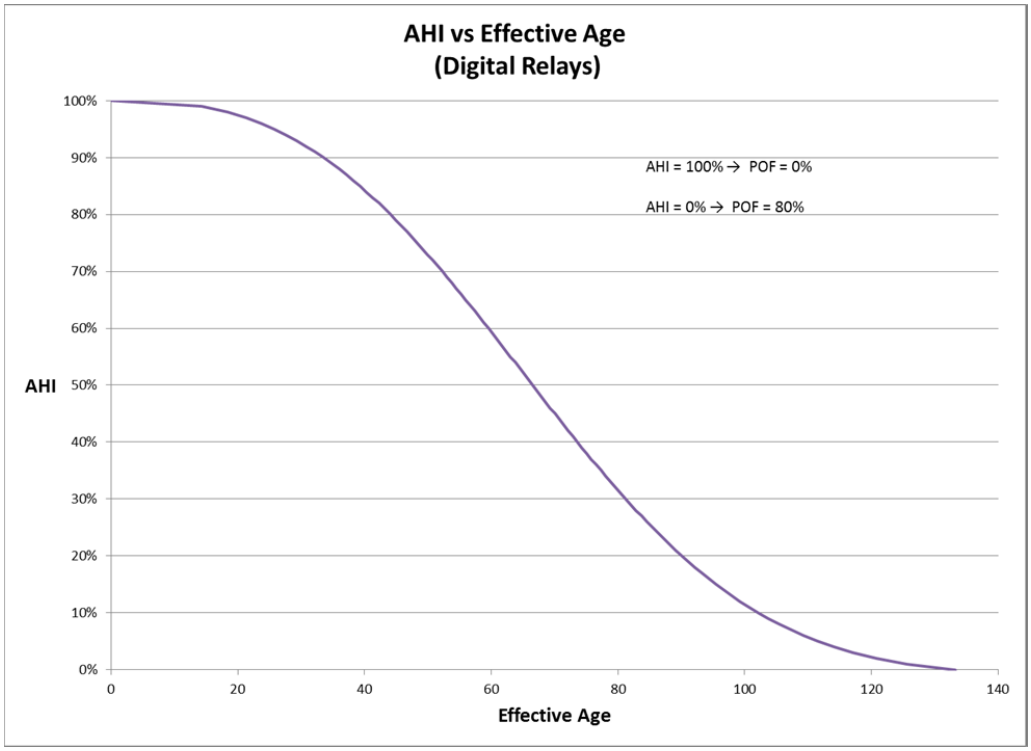

Figure 13-7 AHI vs Effective Age (Digital Relays)

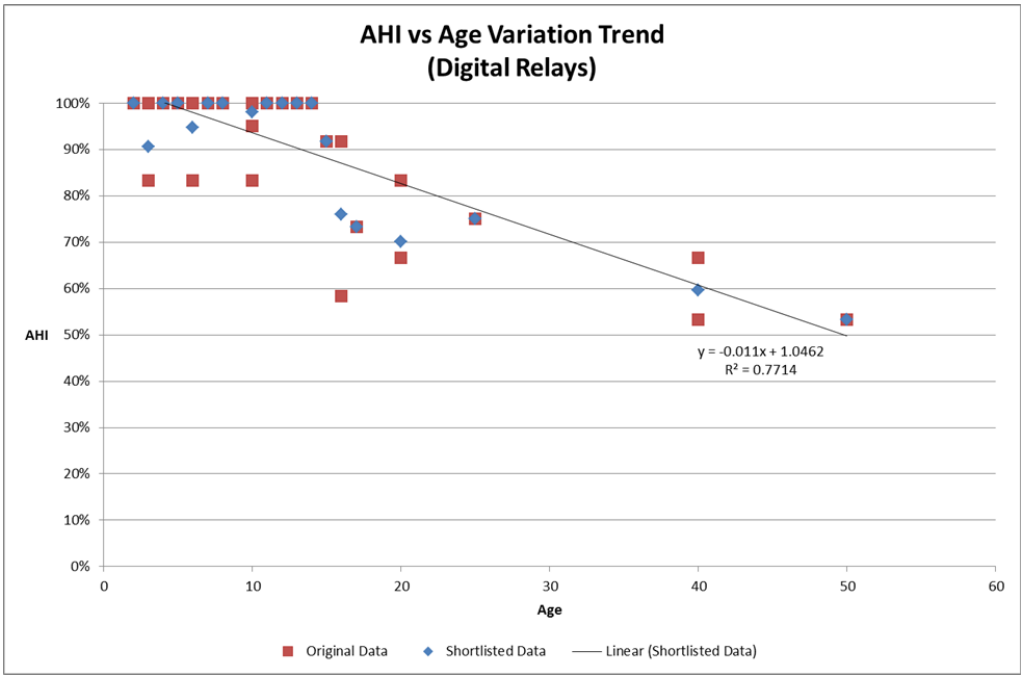

Figure 13-8 AHI vs Age Variation Trend (Digital Relays)

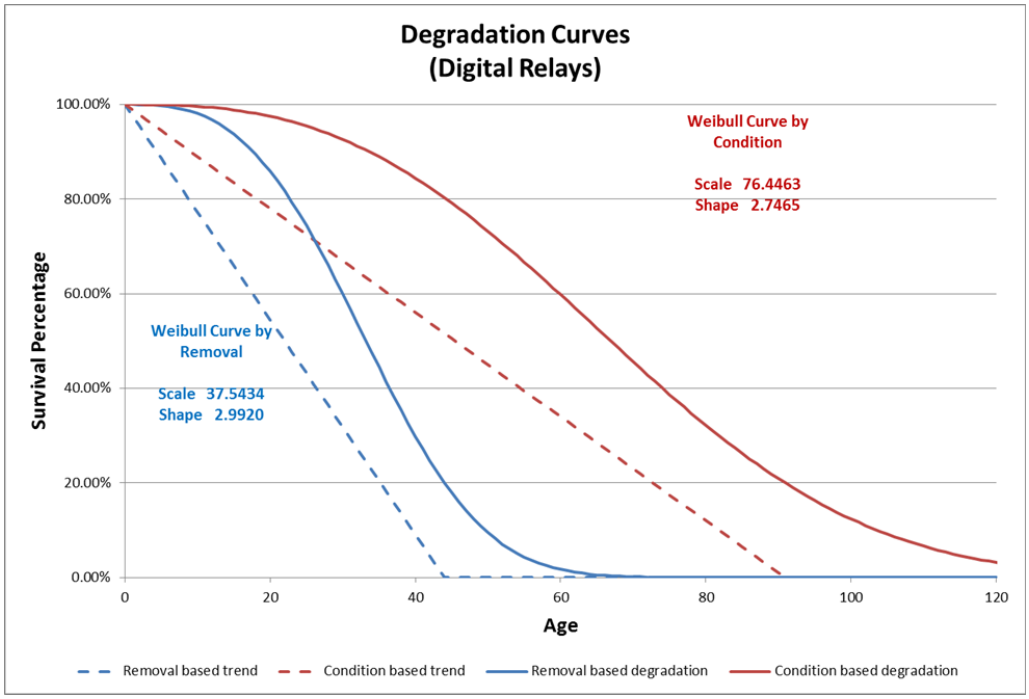

Figure 13-9 Removal Based vs Condition Based Degradation Curves (Digital Relays)

14. STEEL STRUCTURES

14.1. Removal Size and Population size

This asset group addresses the overhead line steel structures in MH transmission system.

For this asset category, there are no available removal records from MH.

There is no further sub-categorization by capacity, make, or location.

14.2. Developed Removal Based Degradation Curves

Due to above reasons, there is no curve developed based on MH data. CIGRE curve is adopted for the reference of MH. The following diagrams show the series of CIGRE average degradation curves based on statistics of multiple utilities.

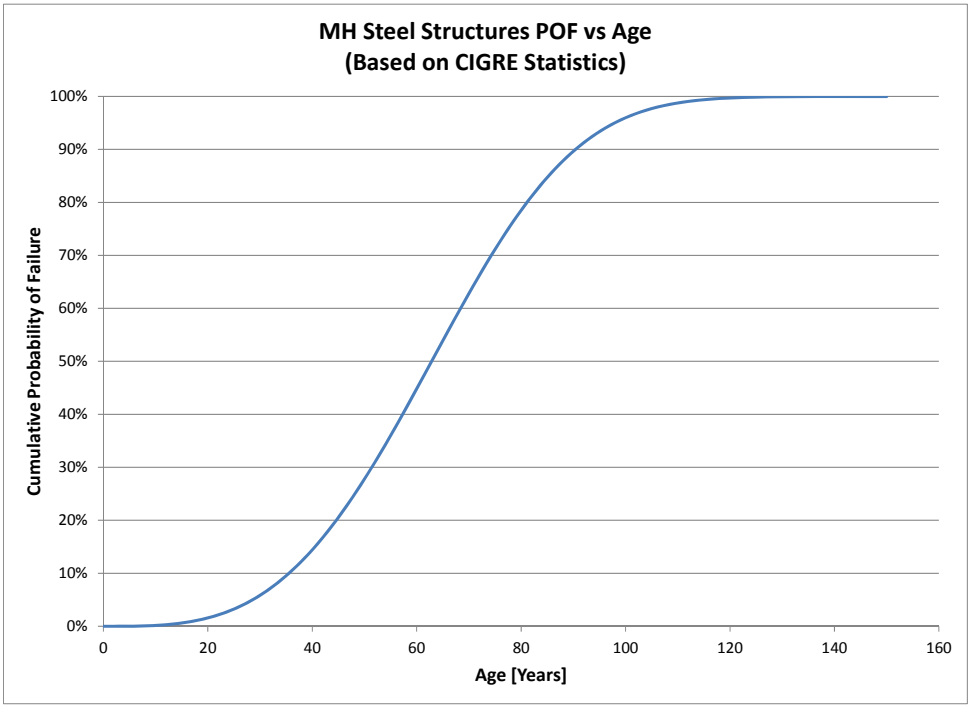

Figure 14-1 Cumulative Probability of Failure vs Age (Steel Structures)

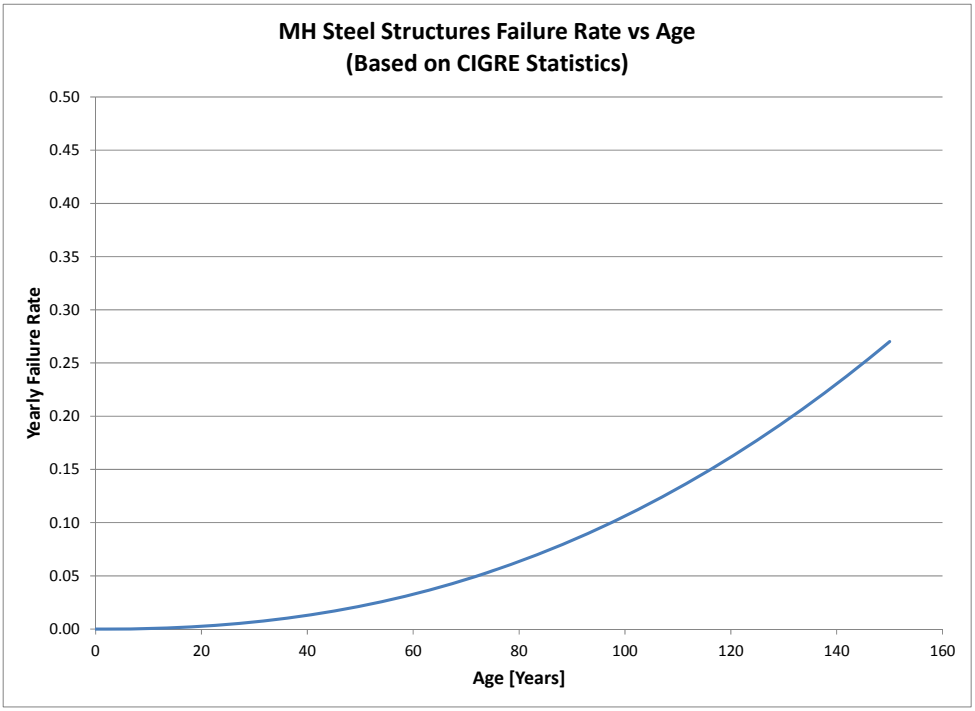

Figure 14-2 Annual Failure Rate vs Age (Steel Structures)

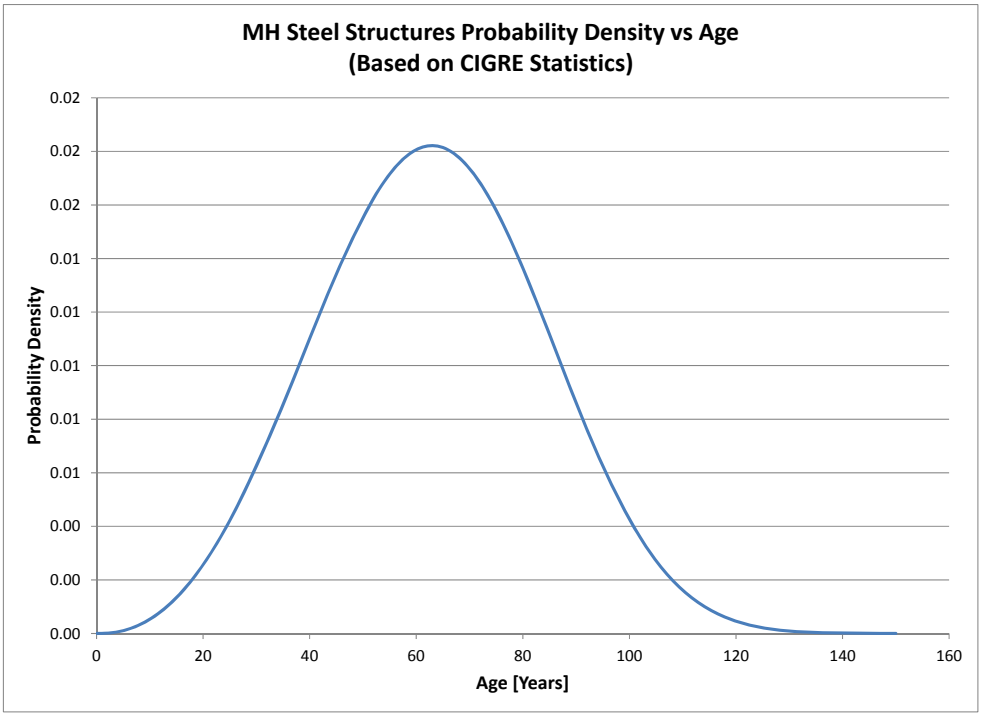

Figure 14-3 Failure Density Curve (Steel Structures)

14.3. Comparison of MH Curve with Industry Curves

As there is no MH data based curve or curves from other utilities, the following diagram shows the CIGRE curve range.

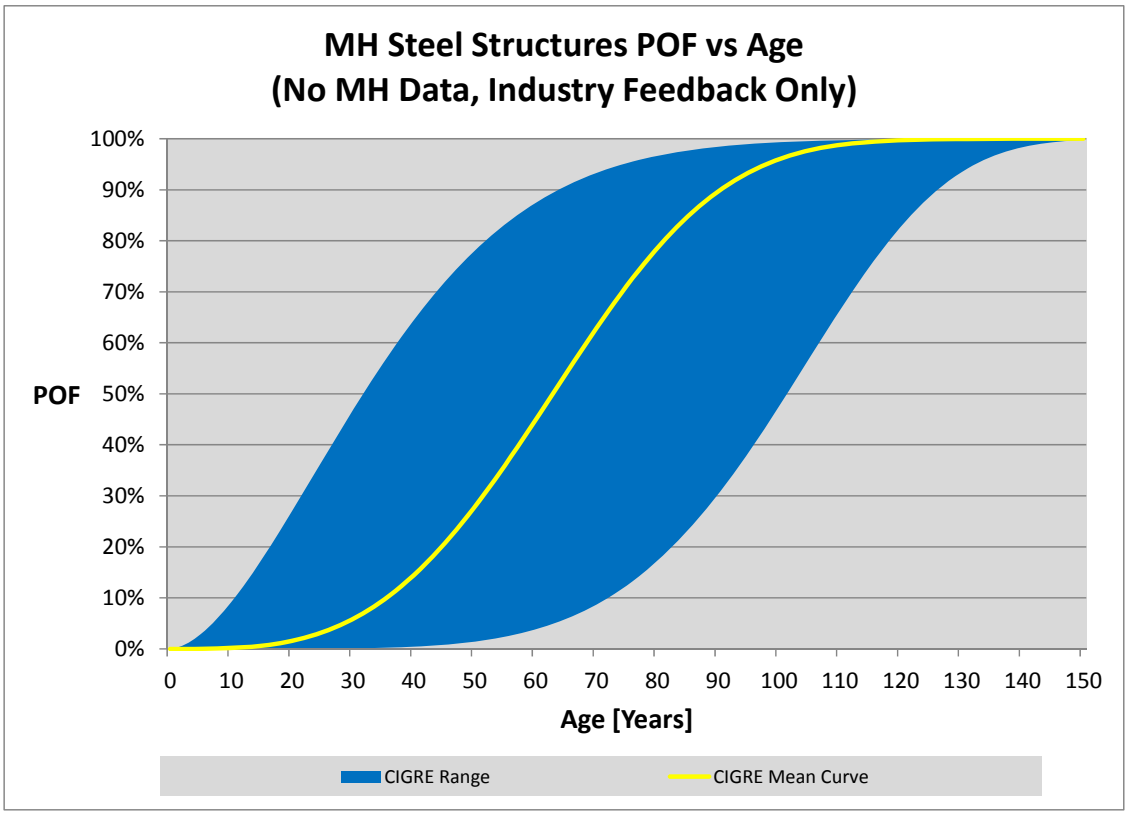

Figure 14-4 CIGRE Curve Range (Steel Structures)

14.4. Link AHI to Condition Based Failure Rate

Due to lack of data, no study was conducted on this asset category to link its AHI to failure rate. MH is recommended to conduct an AHI study for this asset group in the future. For the purpose of long term investment planning using the existing data, MH could use the CIGRE mean failure curves and link them to AHI by assuming AHI = 100% - POF. This would be a conservative approximation and requires calibration based on the AHI results.

This page is intentionally left blank.

15. STEEL STRUCTURE FOOTING – PIPE MAT

15.1. Removal Size and Population size

This asset group addresses the steel structure footings (PIPE Mat installation) in MH transmission system.

For this asset category, there are 41 available removal records. They cover the units that were removed during the period of 2003 – 2013. Note that the removal data were only considered from transmission line RC60.

The root causes for the removals include:

- Unit condition

In this case, there is no exiting age profile incorporated in developing asset degradation curve.

There is no further sub-categorization by make or family.

15.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

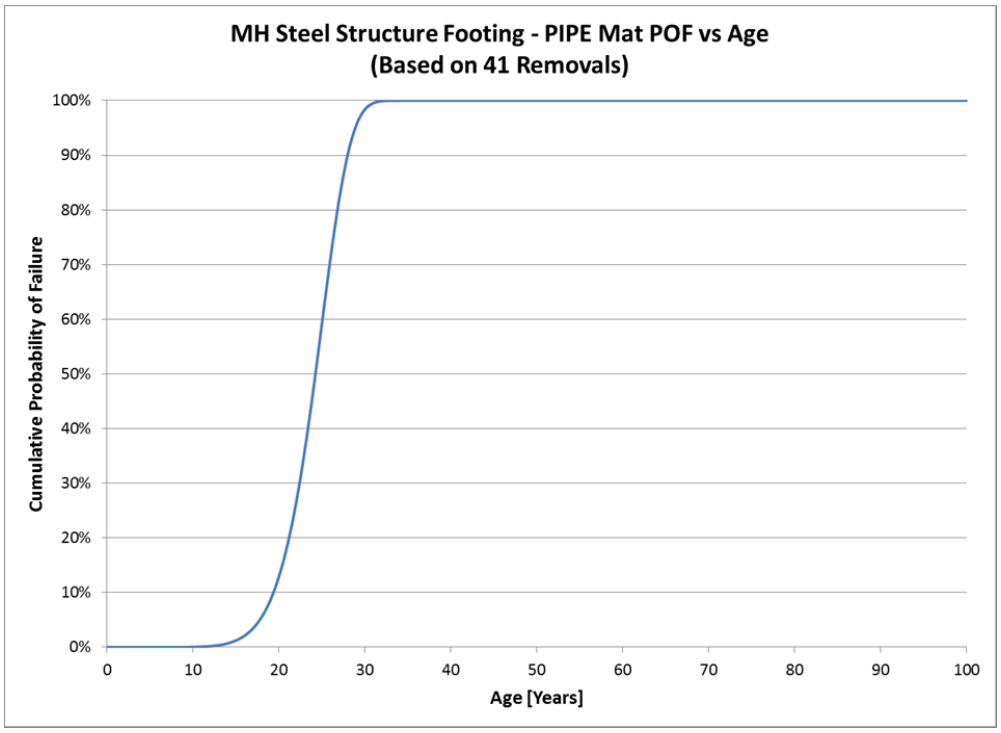

Figure 15-1 Cumulative Probability of Failure vs Age (Steel Structure Footing – PIPE Mat)

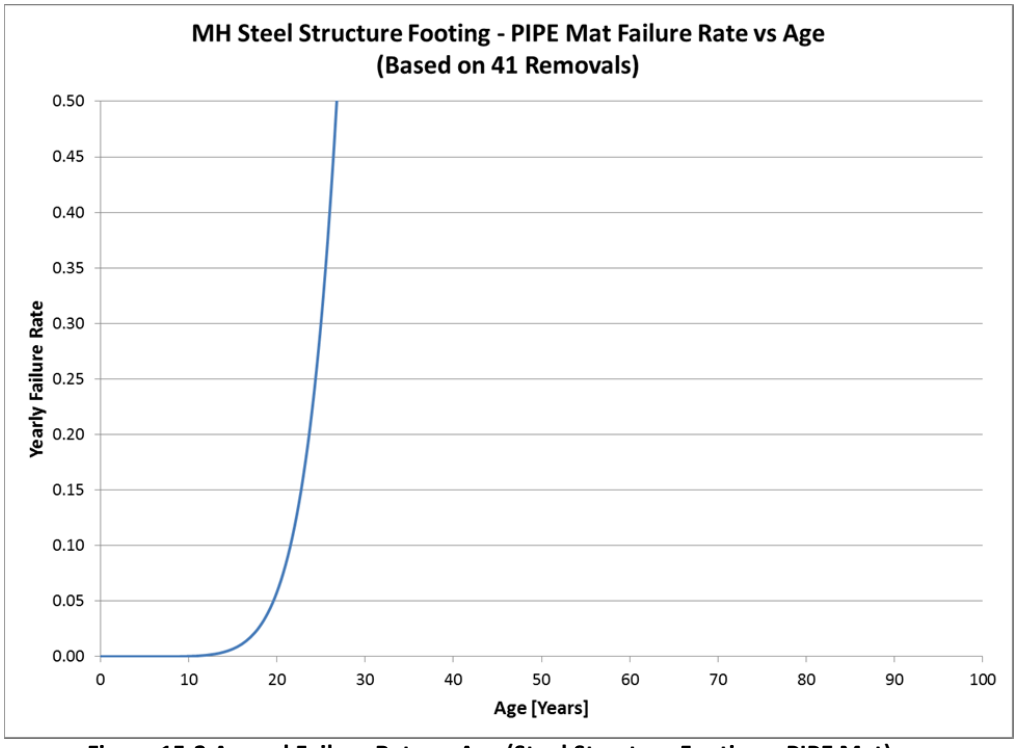

Figure 15-2 Annual Failure Rate vs Age (Steel Structure Footing – PIPE Mat)

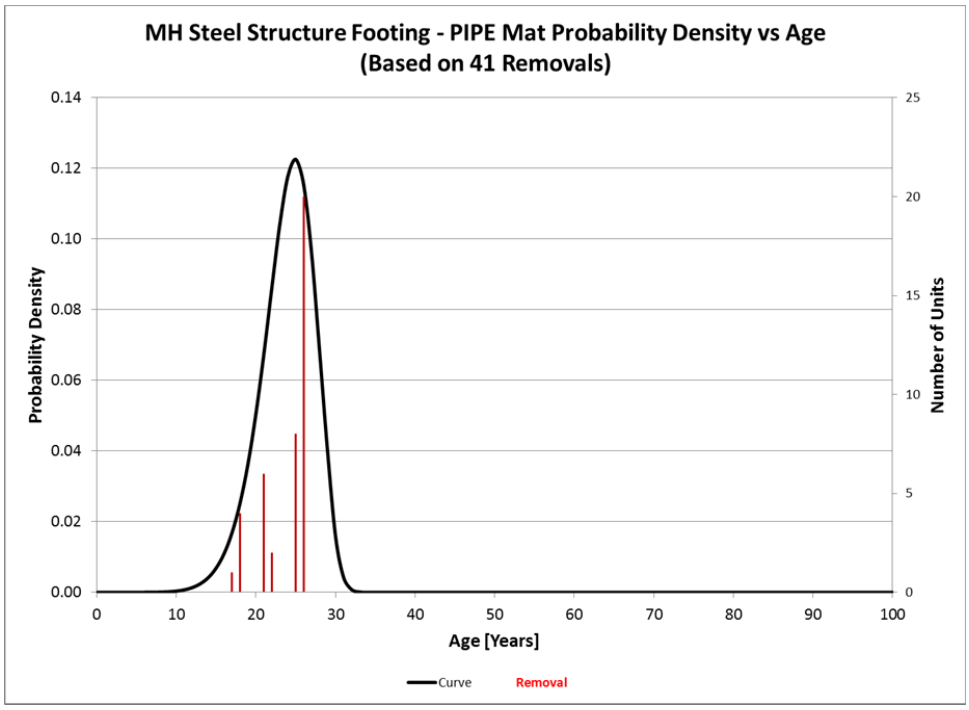

Figure 15-3 Failure Density Curve and Age Profile (Steel Structure Footing – PIPE Mat)

15.3. Comparison of MH Curve with Industry Curves

There are no industry practice curves for comparison with MH curves.

15.4. Link AHI to Condition Based Failure Rate

Due to lack of data, no study was conducted on this asset category to link its AHI to failure rate.

This page is intentionally left blank.

16. STEEL STRUCTURE FOOTING - QUADRUPED

16.1. Removal Size and Population size

This asset group addresses the steel structure footings (quadruped installation) in MH transmission system.

For this asset category, there are 45 available removal records. They cover the units that were removed during the period of 2003 – 2014. Not that the removal data were only considered from transmission line DC1_DC2 and DC3_DC4.

The root causes for the removals include:

- Unit condition

In this case, there is no exiting age profile incorporated in developing asset degradation curve.

There is no further sub-categorization by make or family.

16.2. Developed Removal Based Degradation Curves

The following diagrams show the series of developed removal based degradation curves, as well as the age profiles of removal and existing demography.

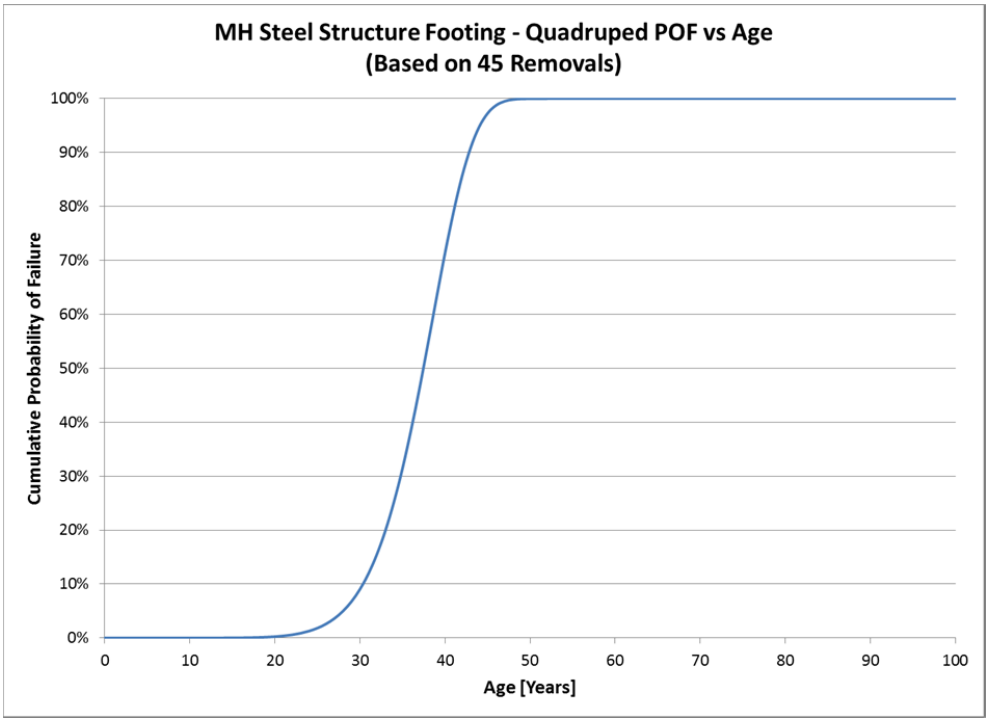

Figure 16-1 Cumulative Probability of Failure vs Age (Steel Structure Footing - Quadruped)

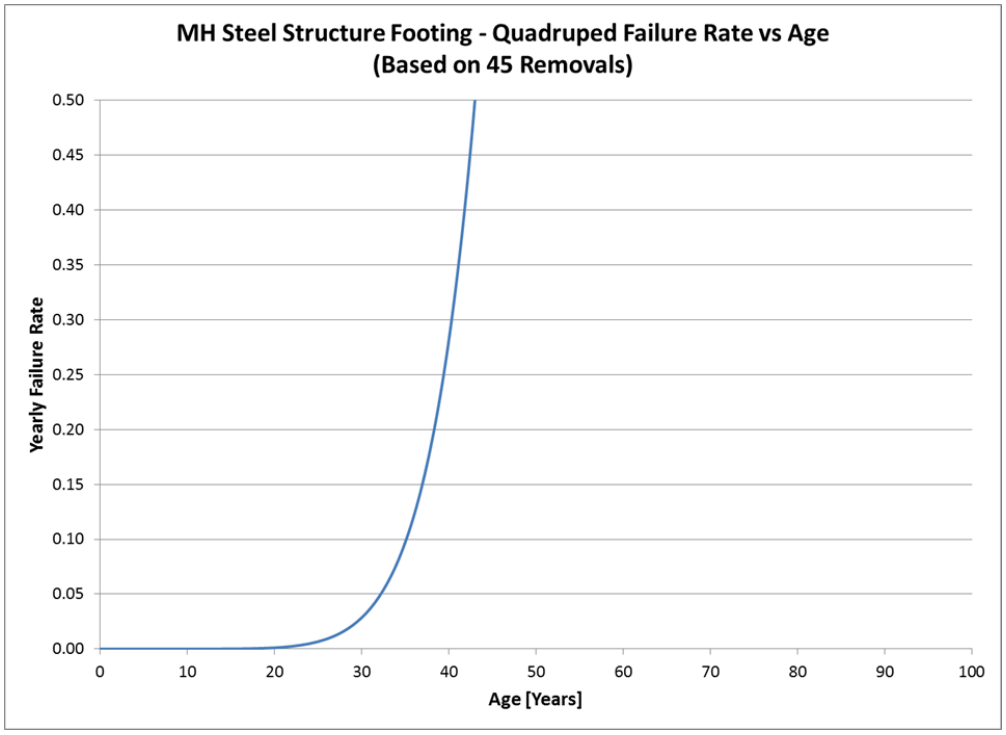

Figure 16-2 Annual Failure Rate vs Age (Steel Structure Footing - Quadruped)

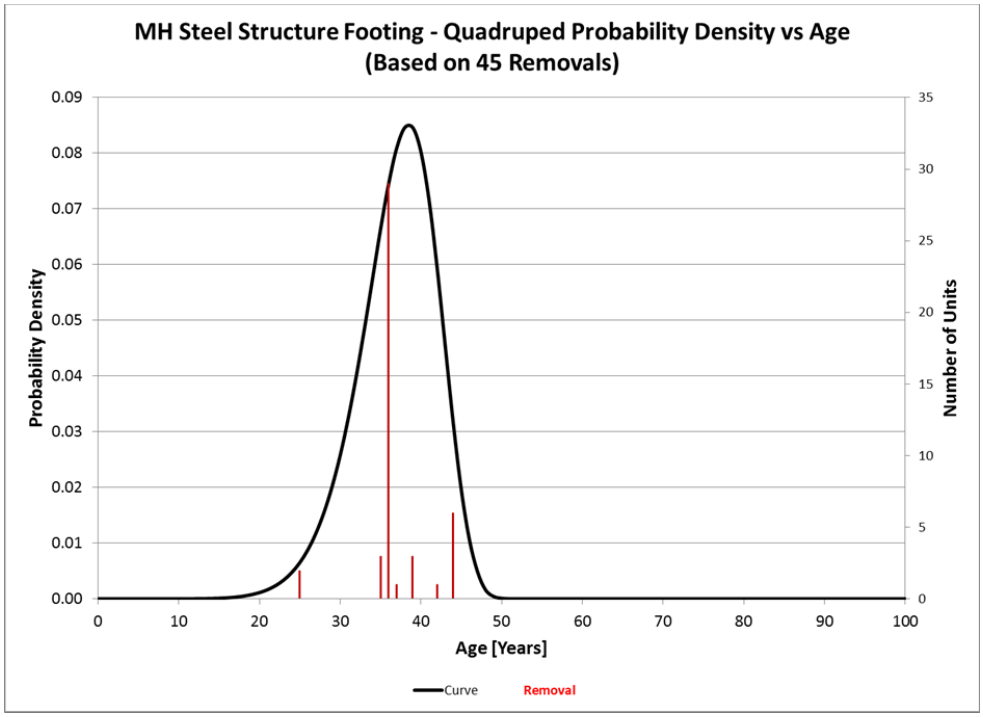

Figure 16-3 Failure Density Curve and Age Profile (Steel Structure Footing - Quadruped)

16.3. Comparison of MH Curve with Industry Curves

There are no industry practice curves for comparison with MH curves.

16.4. Link AHI to Condition Based Failure Rate

Due to lack of data, no study was conducted on this asset category to link its AHI to failure rate.