WUTC DOCKET: UE-200900 UG-200901 UE-200894
EXHIBIT: PADS-19
ADMIT ☑ W/D ☐ REJECT ☐

BEFORE THE WASHINGTON

UTILITIES & TRANSPORTATION COMMISSION

WASHINGTON UTILITIES AND TRANSPORTATION COMMISSION,

Complainant,

v.

AVISTA CORPORATION d/b/a AVISTA UTILITIES,

Respondent.

DOCKET NOS. UE-200900 and UG-200901 (*Consolidated*)

PAUL J. ALVAREZ AND DENNIS STEPHENS

ON BEHALF OF THE
WASHINGTON STATE OFFICE OF THE ATTORNEY GENERAL
PUBLIC COUNSEL UNIT

EXHIBIT PADS-19

Presentation to CIGRE by Dan Martin and T. Saha "Power Transformer Failure Survey and Modeling Reliability – Update and Looking Ahead"

April 21, 2021

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POWER TRANSFORMER FAILURE SURVEY AND MODELLING RELIABILITY – UPDATE AND LOOKING AHEAD

Dr. Dan Martin & Prof. T. Saha

CIGRE AP A2 Open day 22/8/17

Powerlink Queensland, Virginia, QLD

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Outline

- Analysis of condition monitoring data up to 10 years old from vegetable oil filled transformers.
- Update on power transformer failure survey.
- Using condition instead of age in failure.
- Combining failure statistics with life determination models for paper insulation.
- Future of research with the Australasian Transformer Innovation Centre.

DEIS FEATURE ARTICLE

Condition Monitoring of Vegetable Oil Insulation in In-Service Power Transformers: Some Data Spanning 10 Years

Key words: transformer, insulation, oil insulation, condition monitoring

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Data for 17 fault-free vegetable oil–filled power transformers, in service for up to 10 years, are presented and analyzed. No significant changes in the properties of the oil during service were found.

Introduction

Power transformers are expected to operate for several decades [1]. The insulating oil of a power transformer can be replaced if it becomes too degraded. However, it is obviously financially preferable to a utility that the insulating oil last as long as practically possible.

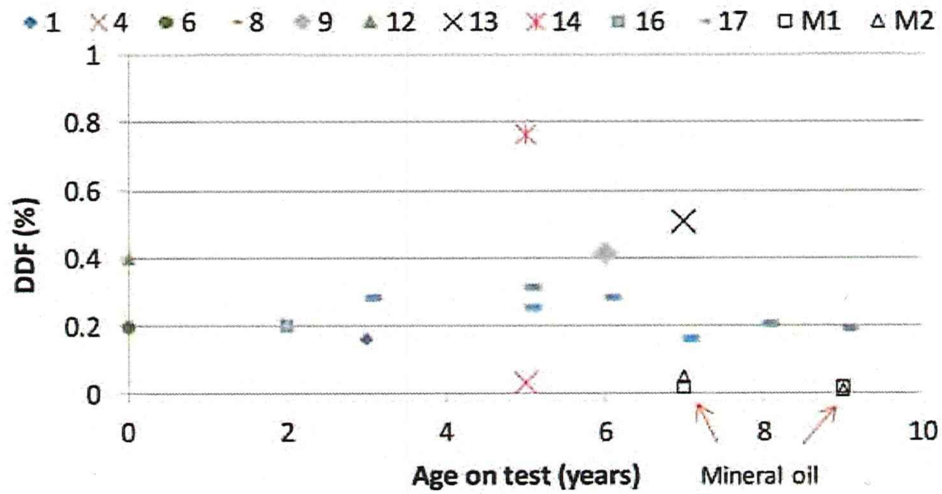
Vegetable oils were among some of the earliest types of dielectric liquid, e.g., a team led by George Westinghouse used caster and linseed oils from the late 1880s onward [2]. However, a disadvantage was that the vegetable oils readily oxidized, and so mineral oils were adopted. In the mid to late 1990s there was renewed interest in vegetable oil–based dielectrics, to which antioxidants had been added [3]. Subsequently, vegetable oil–based transformer oils became commercially available. Initially, they were used only in smaller distribution transformers. However, as the electrical industry became more confident, they began to be used in ever larger power transformers from the early 2000s.

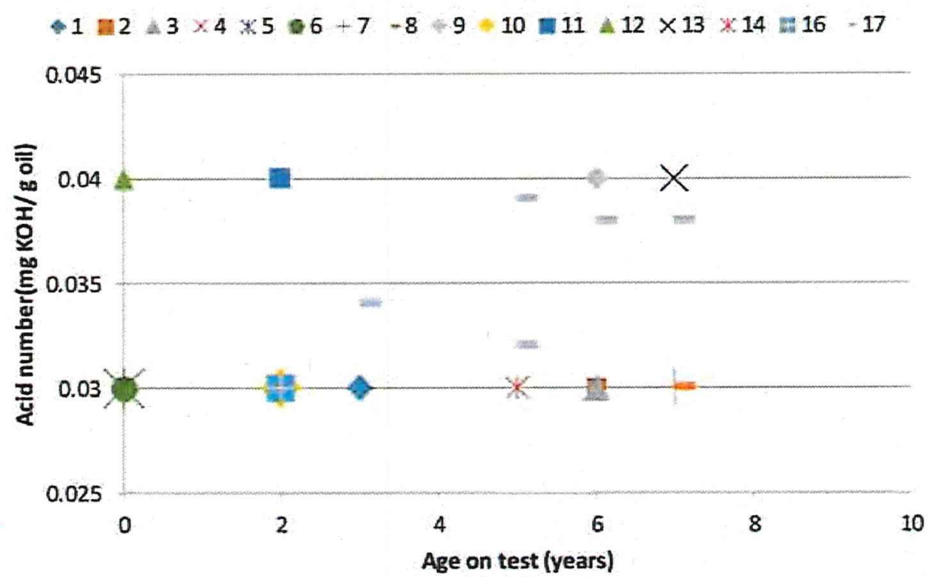
A topic of high interest to utilities is the behavior of vegetable oil–based dielectrics in the field. Although laboratory-based investigations have been performed over several years, there is

Table 1. Specifications of the 17 transformers filled with Envirotemp FR3

Transformer	Rated voltage (kV)	Rated power (MVA)	Year of manufacture	Cooling type[1]
1	33/11	5/8	2008	KNAF
2	33/11	5/8	2007	KNAF
3	33/11	5/8	2007	KNAF
4	33/11	5/8	2009	KNAF
5	66/11	20	2014	KNAN
6	66/11	20	2014	KNAN
7	33/11	5/8	2007	KNAF
8	33/11	5/8	2007	KNAF
9	33/11	5/8	2006	KNAF
10	33/11	5/8	2010	KNAF
11	33/11	5/8	2010	KNAF
12	132/11	30	2013	KNAN
13	33/11	10/16	2005	KNAF
14	33/11	10/16	2007	KNAF
15	33/11	5/8	2008	KNAF
16	33/11	5/8	2011	KNAF
17	132/33	45/90	2006	KNAF

[1]K indicates that the oil had a high fire point (>300°C); N indicates that it flowed naturally around the transformer tank, i.e., was not pumped; and AN and AF indicate, respectively, that air flowed naturally over the radiator bank or was forced with fans.





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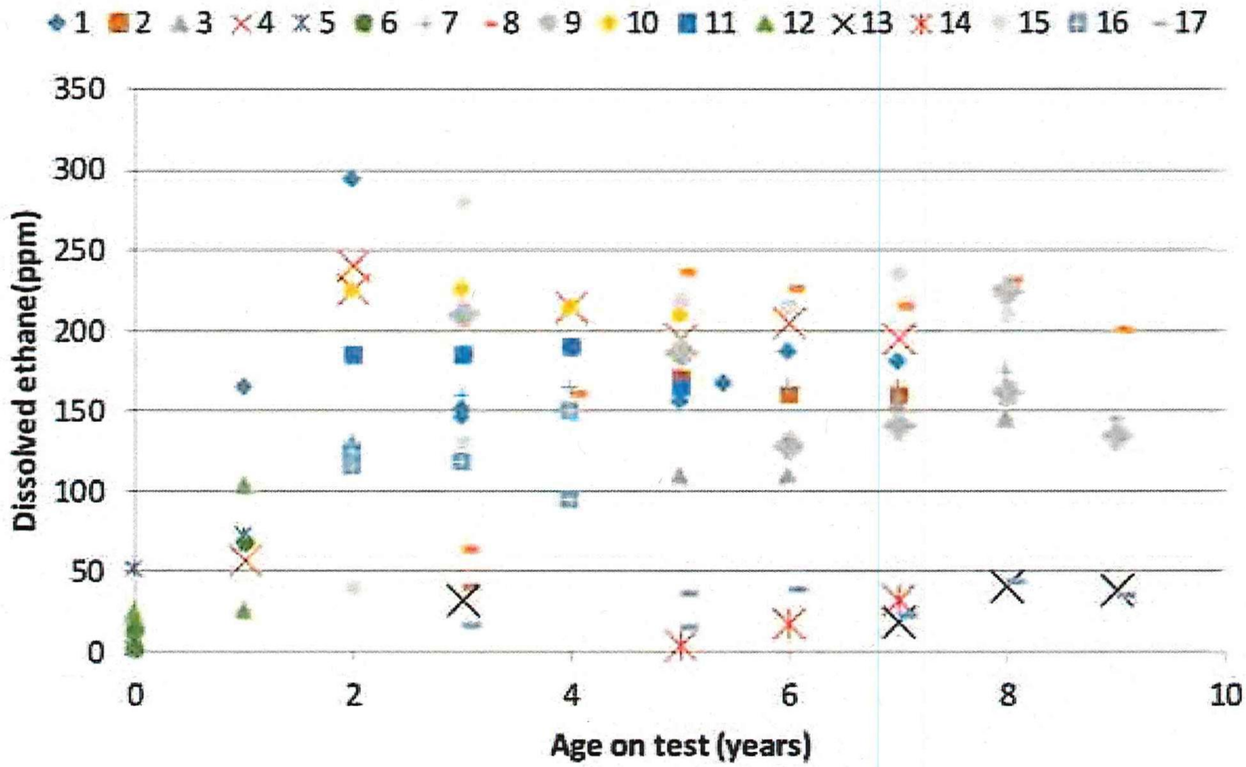
Spread of ethane



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2016 Australian Power Transformer Survey Update

- As part of UQ's research agenda looked at how to determine the optimal point when to replace a power transformer.
- Future survival is probabilistic when no obvious failure path is present.
- Last survey performed by Petersen & Austin in the late 90s.
- Industry resurveyed – last count utilities operating 98% of the 6,000 power transformers in Australia responded with data on failures, retirements and operating units.

DEFINITIONS: Failure is when the transformer was scrapped after the fault (non-repairable), catastrophic failure is when either an explosion or fire occurred.

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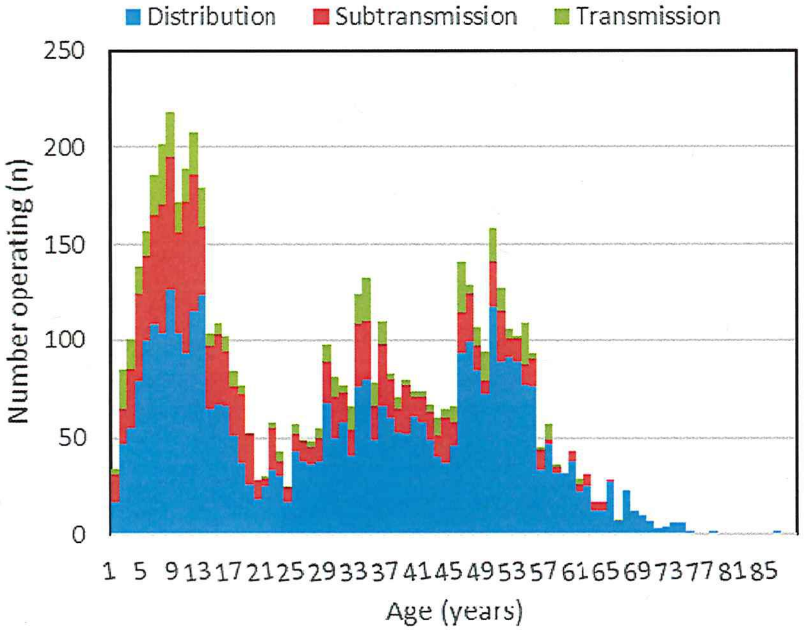
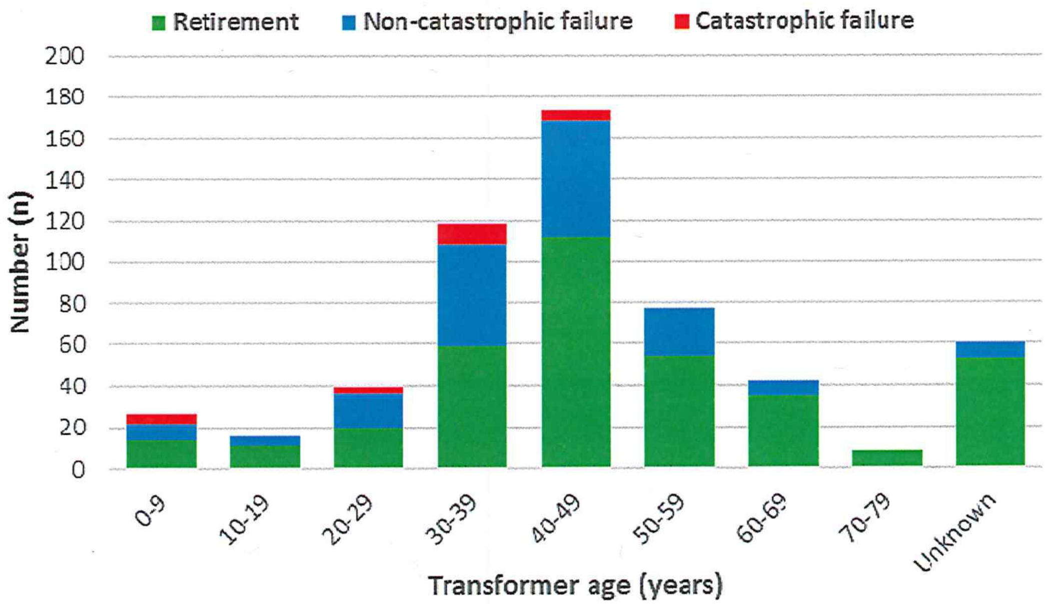
Data collection





Distribution is ≤ 66 kV AT LEAST 1 MVA, subtransmission is 110 & 132 kV, transmission is ≥ 220 kV

All utilities in Australia surveyed for data (Horizon power does not seem to operate any).

No data sourced from DNSP Ausnet (although info provided from TNSP).

6,057 power transformers by utilities, 5,921 covered by this survey, 199 failures, 387 retirements.

Data truncated from 2000 onward (81,000 transformer years).

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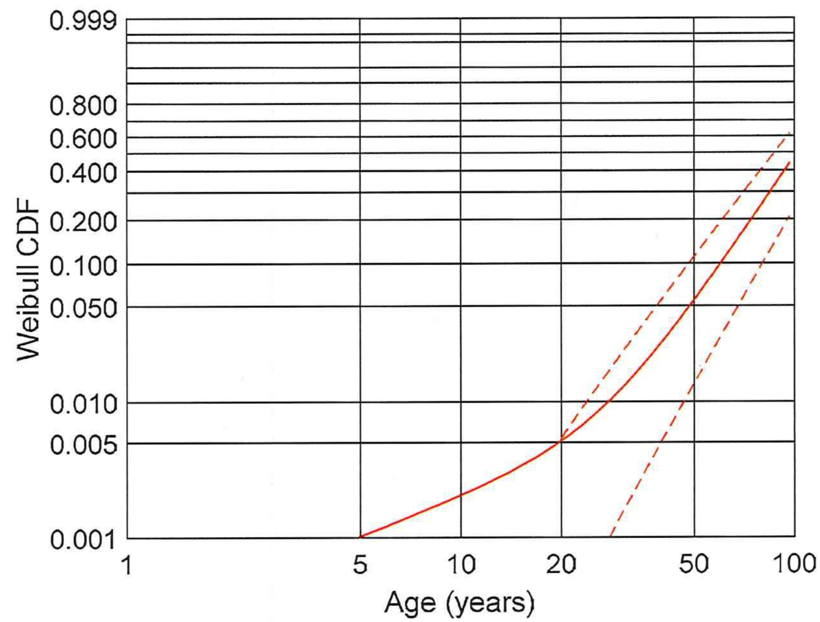
Introduction to the Weibull distribution

- Two coefficients are fitted to our failure data, then, the PoF can be calculated for any age power transformer. (Shape and scale parameters.)
- ±95% confidence intervals fitted to data to allow for variability.
- The Cumulative Distribution Function (CDF) shows the *proportion of assets which have failed by a certain year*.
- The CDF should not finish at 0.999 because not every transformer in our population has failed. Data on surviving units by the end of our observation window is required.



Failure statistics for power transformers ≤ 66 kV occurring 2000 - 2015

Fig from J. Marks thesis on Australian power transformer failures, UQ, 2016

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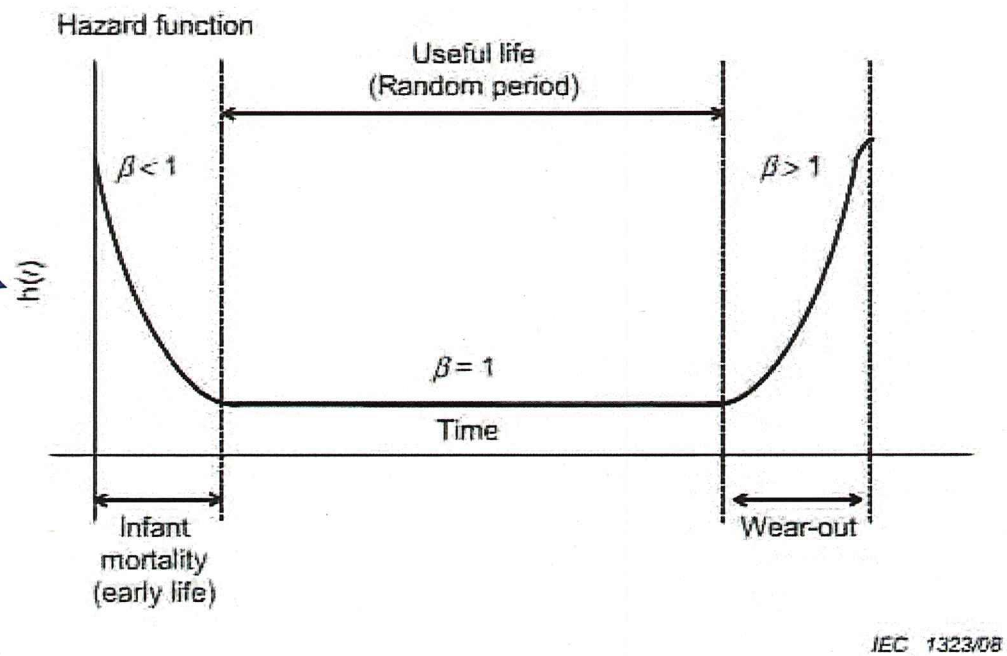
Interpretation of Weibull Curve

Hazard function (rate of failure)



β is the shape parameter of the Weibull distribution

Figure 3 from IEC 61649:2008

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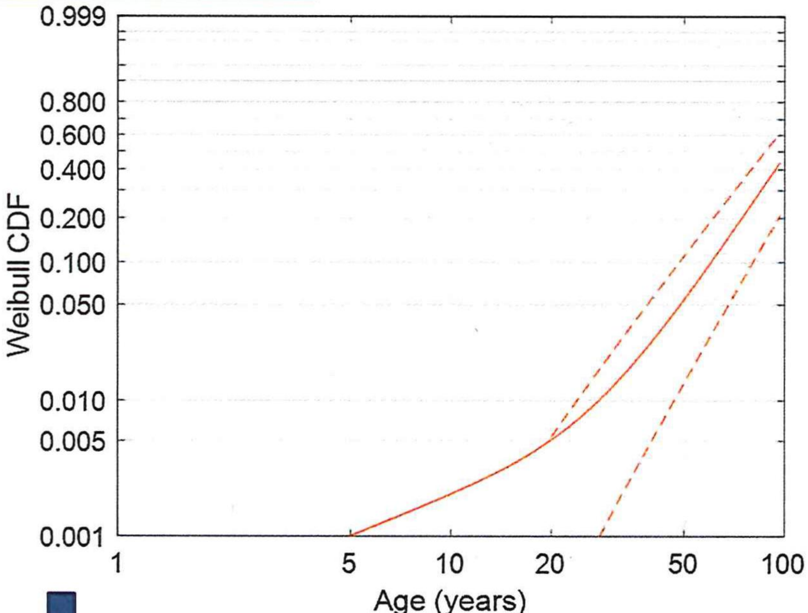
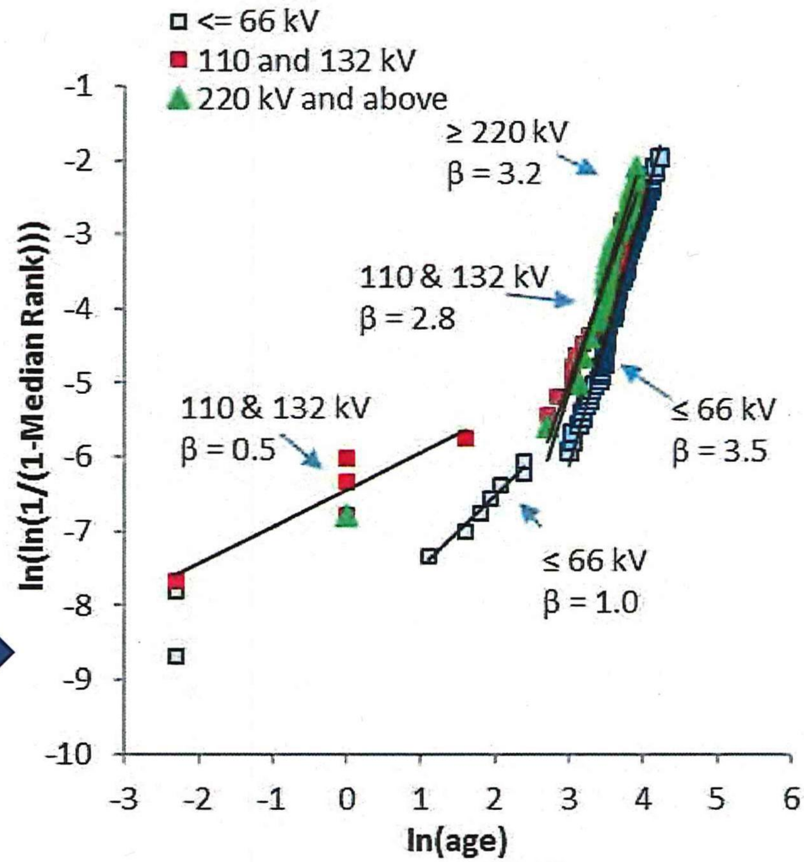
What does the Weibull Distribution tell us?



Median rank is the y-axis plotted
As ln(ln(1/1-y-value))



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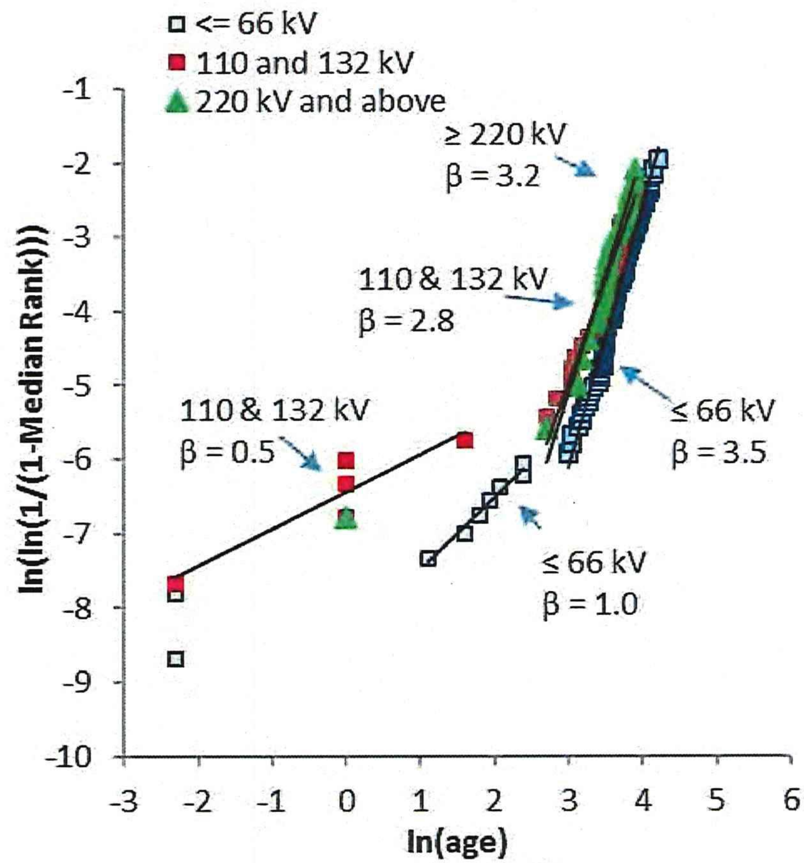
What does the Weibull Distribution tell us II?

Two distributions present for the lower voltage populations.

Age-related failures begin at around 20 years (end of useful life).

Why? Need to analyse individual failure modes.



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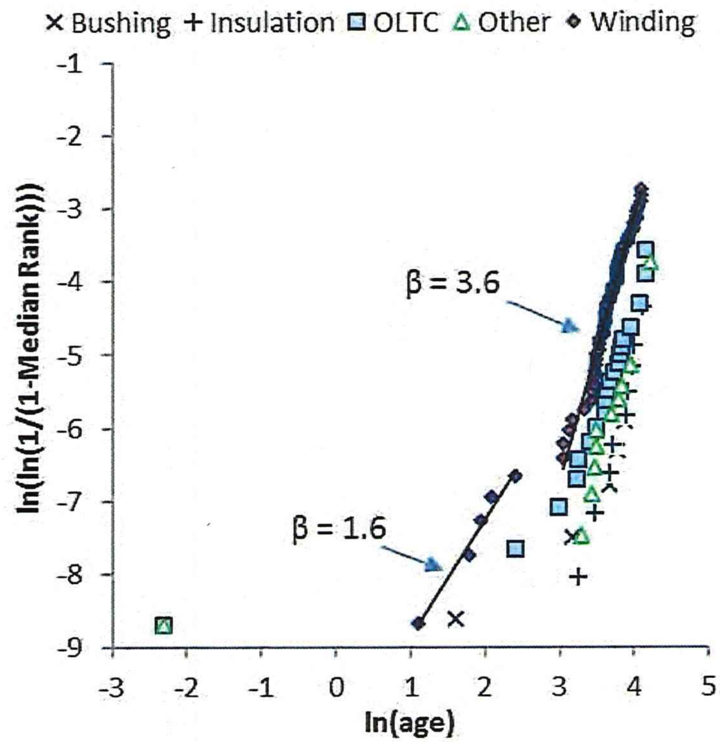
Analysis of Failure Data I

≤ 66 kV transformers:

Winding is predominant mode of fail.

There is a transition between ln(2) 7 years & (3) 20 years.

High beta (3.6) indicative of wearing out.



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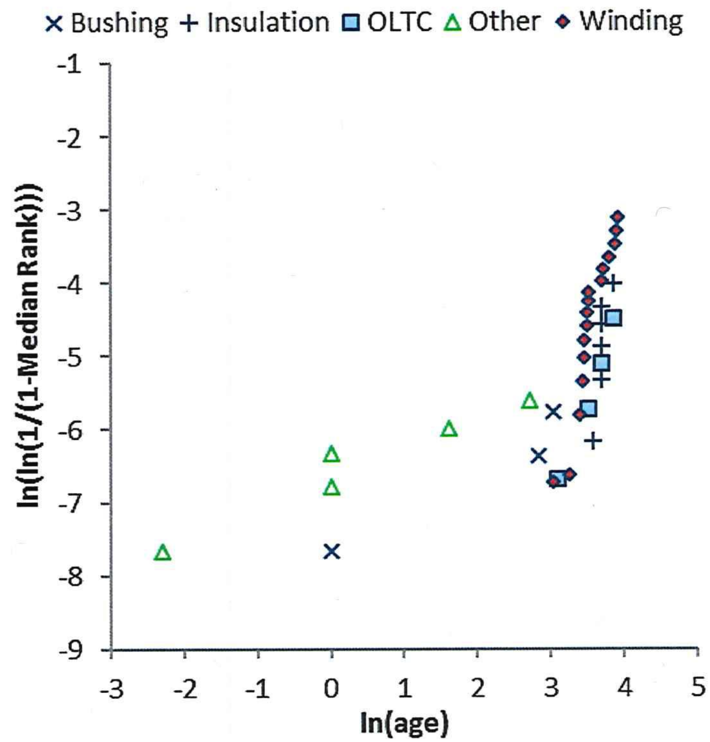
Analysis of Failure Data II

110 & 132 kV transformers:

Mostly 'other' failures early on.

Some bushing failures.

Winding failures begin to predominate.



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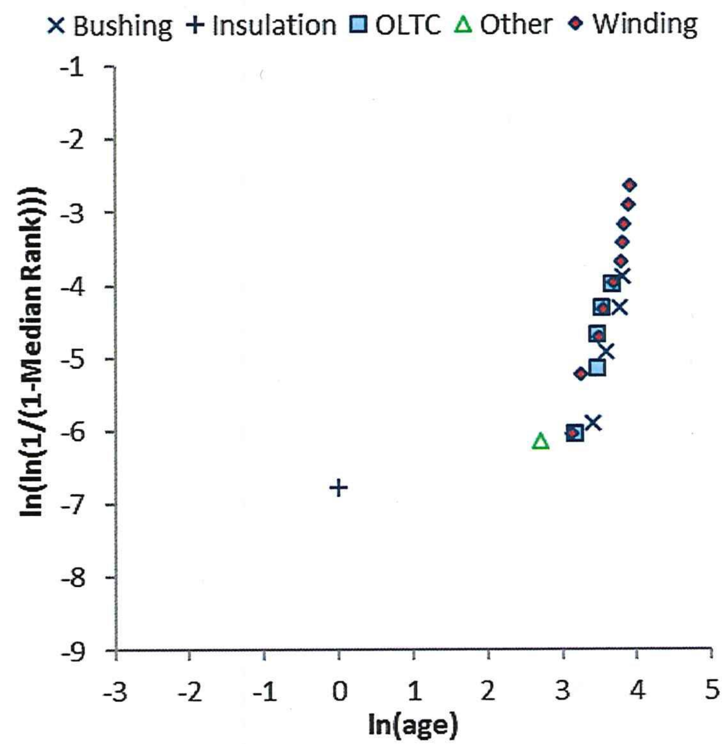
Analysis of Failure Data III

≥ 220 kV transformers:

Absence of early or random failure modes.



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And what about the Retirements?

- Problem using retirements is that the transformer has not actually failed.
- However:
  - A transformer withdrawn due to being in a poor condition can be considered as a potential failure.

"A potential failure is an identifiable physical condition which indicates a functional failure is imminent" – page 19, F. S. Nowlan et al, Reliability-centered maintenance, http://www.barringer1.com/mil_files/AD-A066579.pdf

  - A transformer retired due to network augmentation activities might not meet this definition if part of the whole network were being upgraded.
  - A plot of survival (1-failure) can be plotted, where the transformers neither failing or being retired are analysed.

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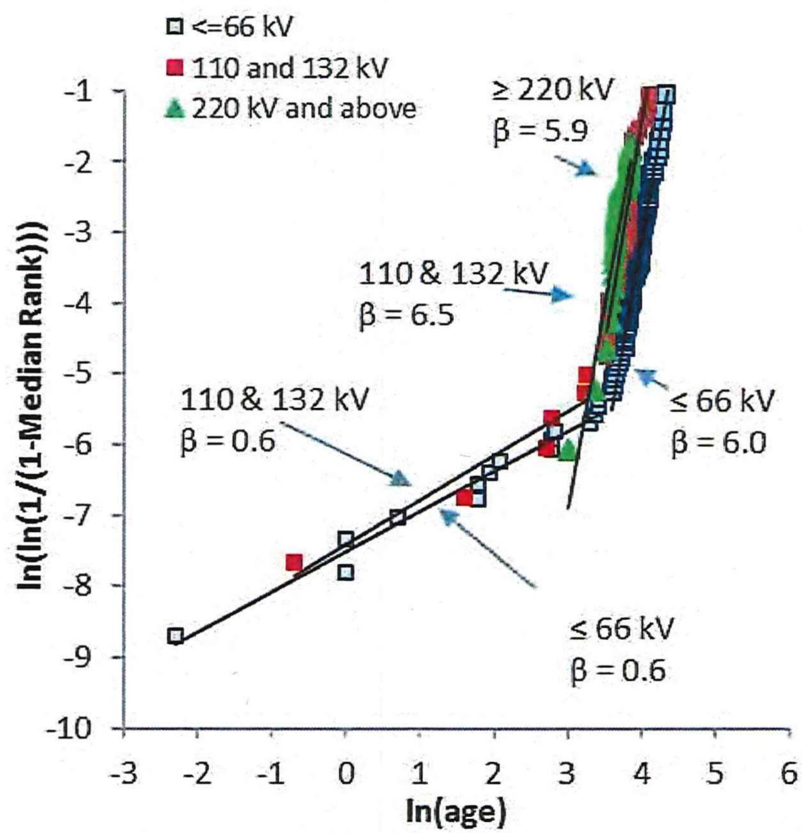
Retirements

Weibull distributions for retirements due to poor condition.



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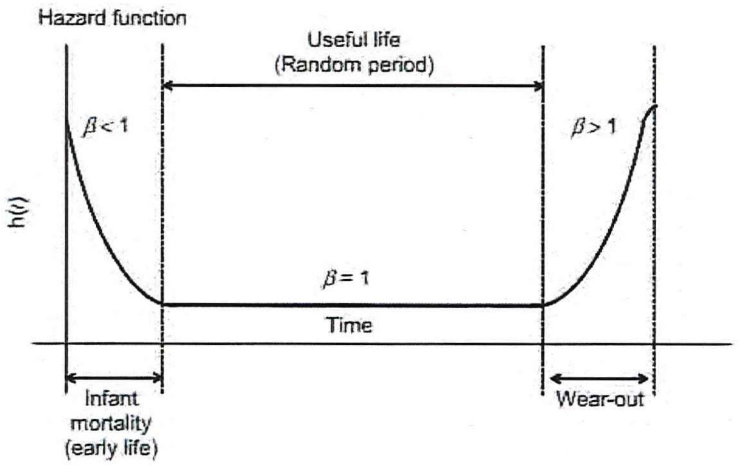
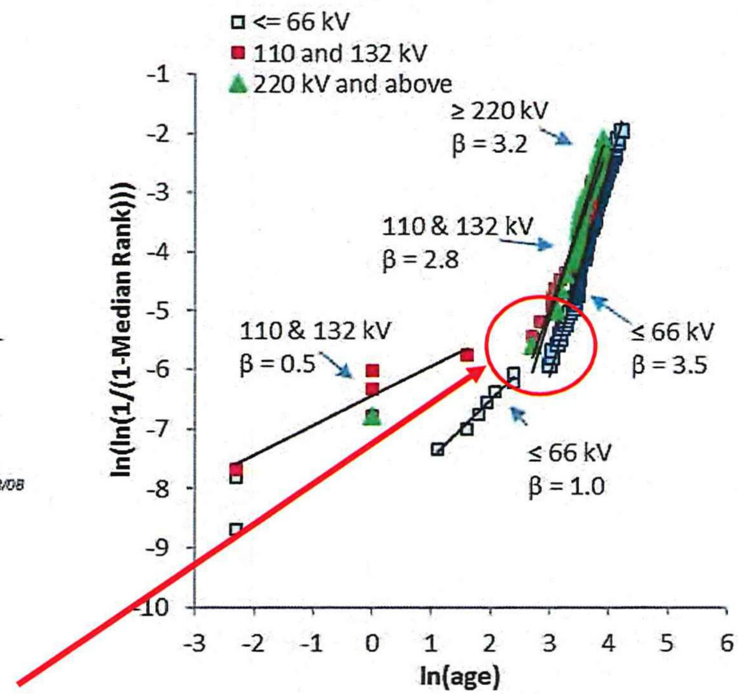
Determining Useful life





Looking at when the age-related failure h(t) = early failure h(t)
(not looking at first point in age-failures distribution)
≤ 66 kV = 15 years, 110 & 132 = 10 years, ≥ 220 kV = 15 years

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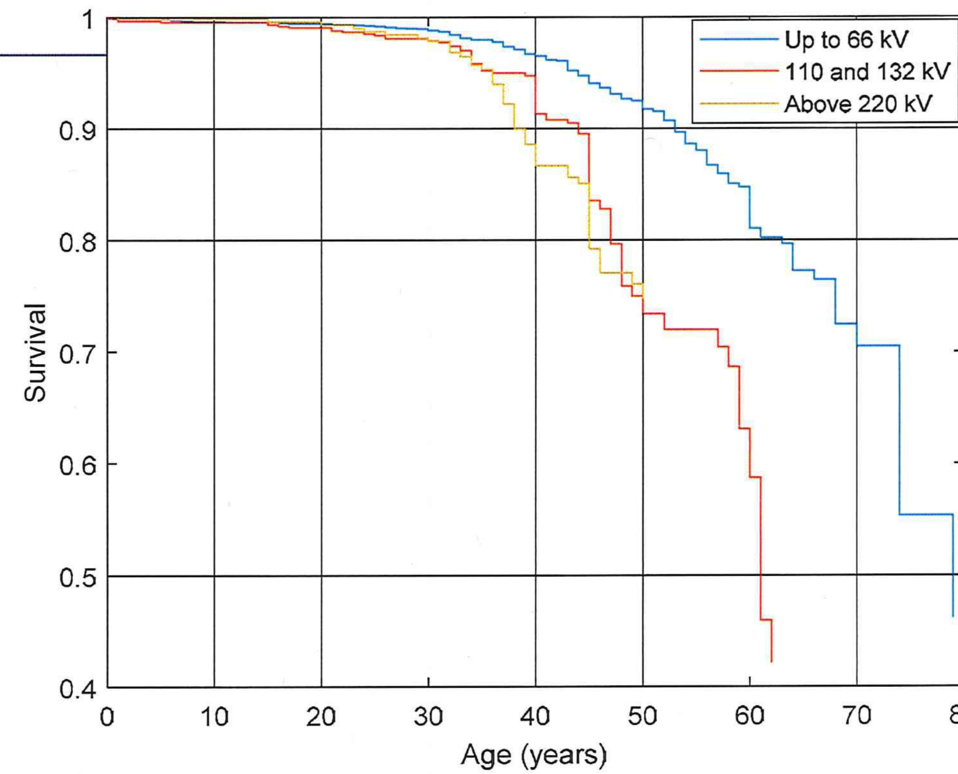
Nonparametric Survival

The average life (survival = 0.5) is:

79 years for distribution.

61 for subtransmission.

Most transmission transformers have been retired due to network augmentation. There have been insufficient failures & retirements to see the average life. (However, Weibull distribution can be used to estimate it – 58 years within bounds 55 and 68 years.)



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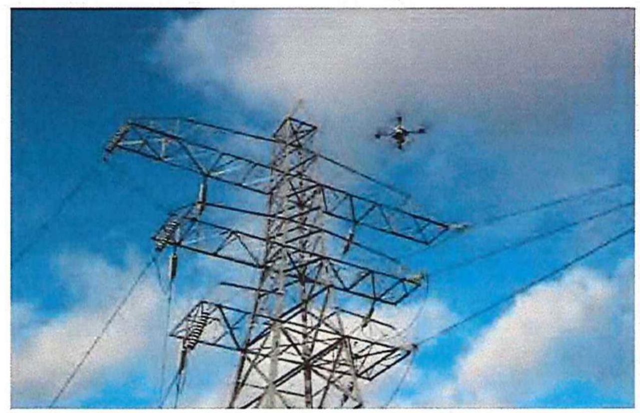
Using Health Instead of Age

- Comparing number of failures expected using this method to the number of failures actually recorded.
- Worked with Ausgrid to evaluate method.

DNO COMMON NETWORK ASSET INDICES METHODOLOGY

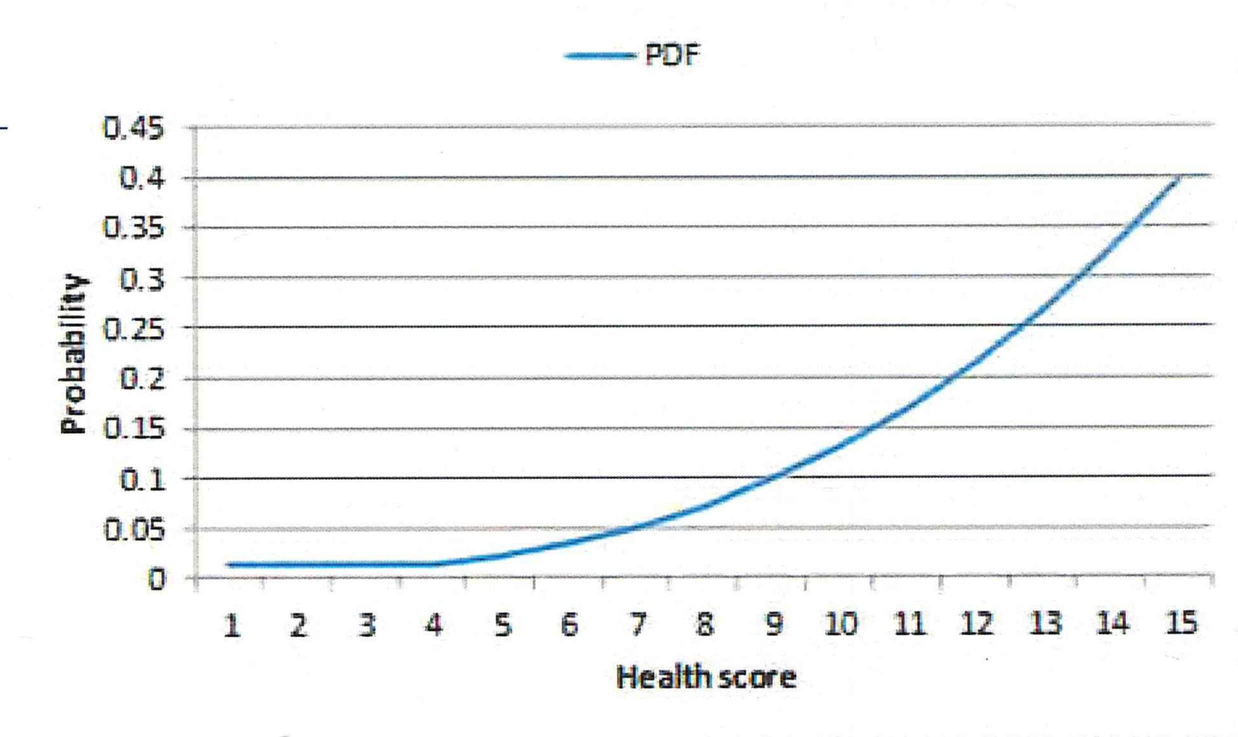


01/07/2015 | Health & Criticality - Draft Version 3

A common framework of definitions, principles and calculation methodologies, adopted across all GB Distribution Network Operators, for the assessment, forecasting and regulatory reporting of Asset Risk.

The University of Queensland
Australia

DNO method



Health score H is a function of nameplate age adjusted for condition, environment, usage etc.

$$PoF = k\left(1 + CH + \frac{CH^2}{2!} + \frac{CH^3}{3!}\right)$$

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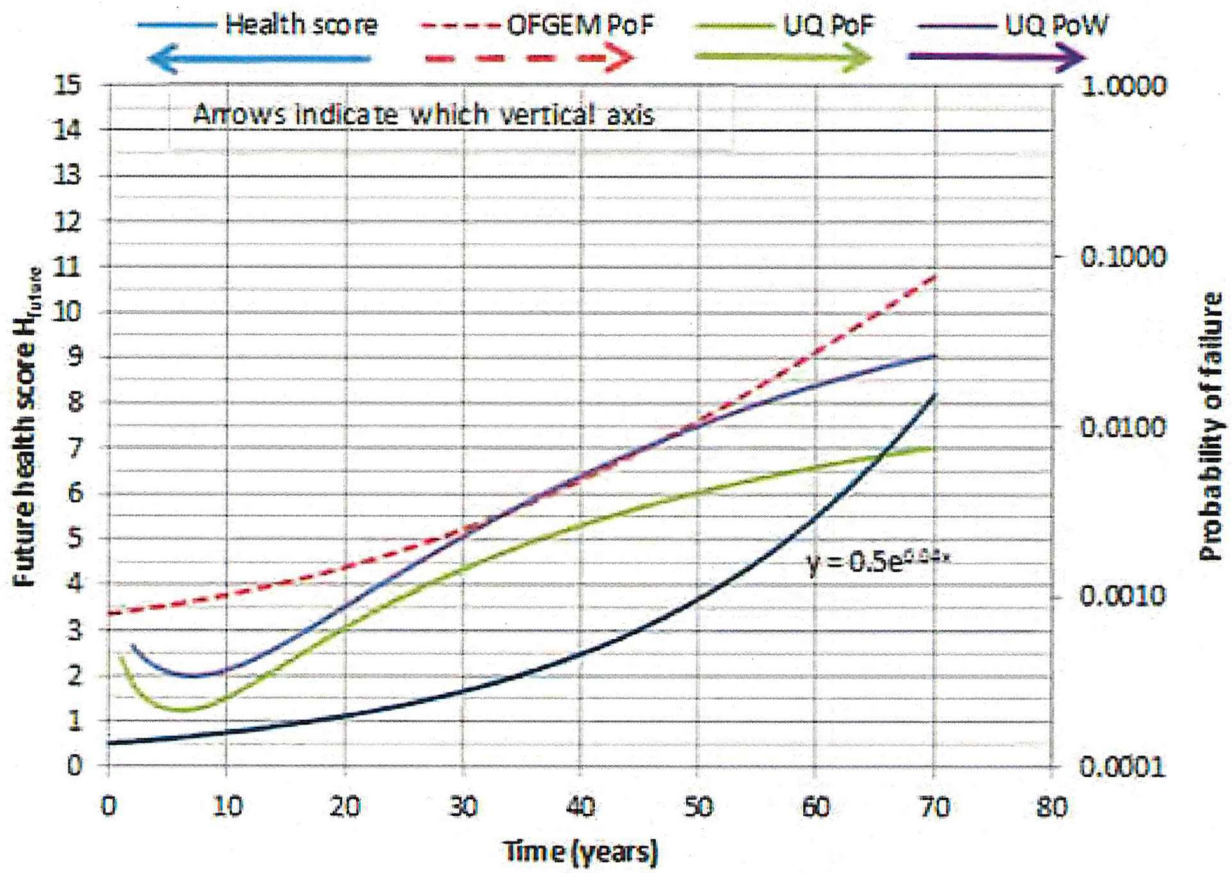
Comparing DNO method to UQ



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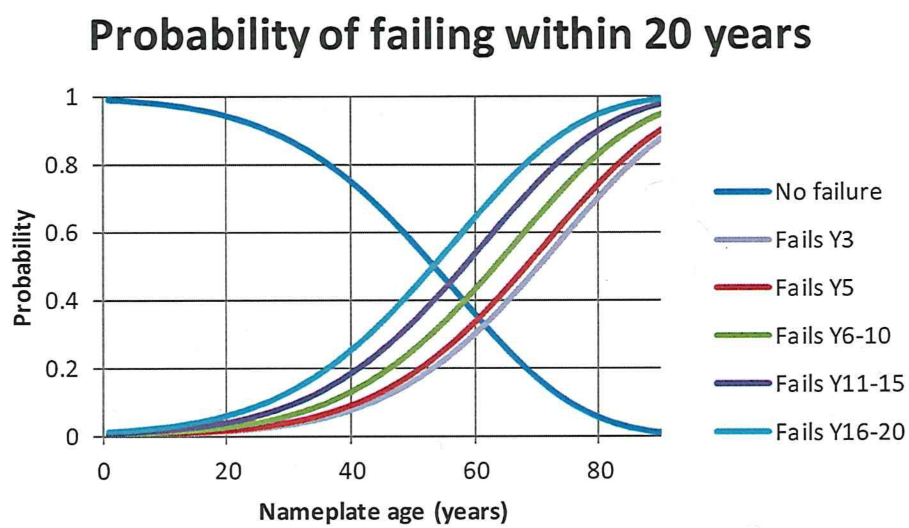
Also looking at establishing probabilistically likely state of a particular transformer after time



Currently based on age, ideally we want this based on condition.

50/50 chance of survival/failure at crossover points.

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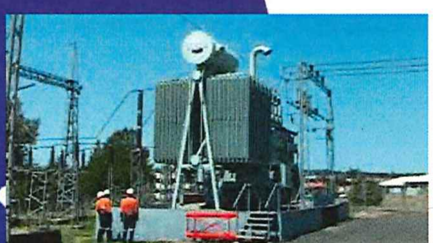
Combining with 2013 – 2014 UQ project to estimate remaining life of paper insulation

Motivation and background

Existing IEC and IEEE models only use temperature to determine the life expectancy of paper insulation.

Water and oxygen also degrade paper (models exist)

In this project we set out to accurately measure water.



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Tracking life remaining in real time

$$\frac{1}{DP_{ageing\ period}} - \frac{1}{DP_{start}} = A \times ageing\ period \times e^{\frac{-E_a}{RT}}$$

We can rearrange this equation to calculate the fall in DP over a given time period from now until the near future(e.g. 5, 30 or 60 minutes).
The temperature is the hotspot.

$$DP_{ageing\ period} = \frac{1}{A \times t_n \times e^{\left(\frac{-E_a}{RT}\right)} + {}^{1}/_{DP_{now}}}$$

The DP continues to fall over successive time-blocks.

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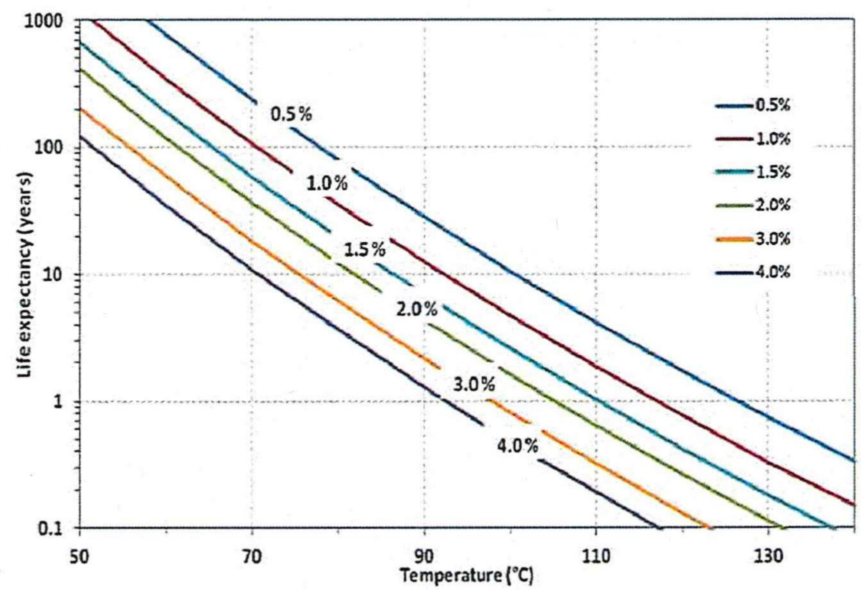
Life lost

Life lost can also be expressed as a number between 1 (DP=1000) and 0 (DP=200), beneficial because the fall in DP is not linear.

$$LL_n = \frac{t_n}{\frac{\left(\frac{1}{200} - \frac{1}{1000}\right)}{A} \times e^{\frac{E_a}{RT}}}$$



This is the duration at that temperature divided by the estimated life at the temperature.

Obviously, total life lost is:

$$\sum LL_n$$

Figure from Lelekakis, Martin, and Wijaya , "Ageing Rate of Paper Insulation used in Power Transformers: Part 2: oil/paper system with medium and high oxygen concentration", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 19, Iss. 6, pp. 2009 – 2017, Nov 2012.

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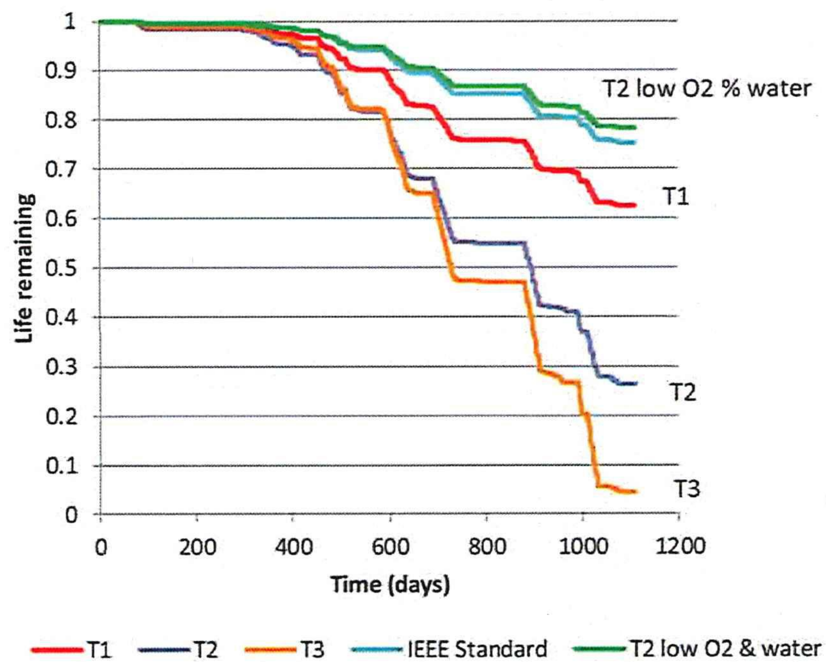
REMAINING LIFE



In order to determine the time until DP=200 need to estimate the average temperature that the transformer will operate at.
This can be determined from historic data, or a temperature by estimated from load information.

D. Martin, Y. Cui, C. Ekanayake, H. Ma, and T. Saha, "An Updated Model to Determine the Life Remaining of Transformer Insulation", IEEE Transactions on Power Delivery, Vol. 30, Iss. 1, pp. 395 – 402, 2015.

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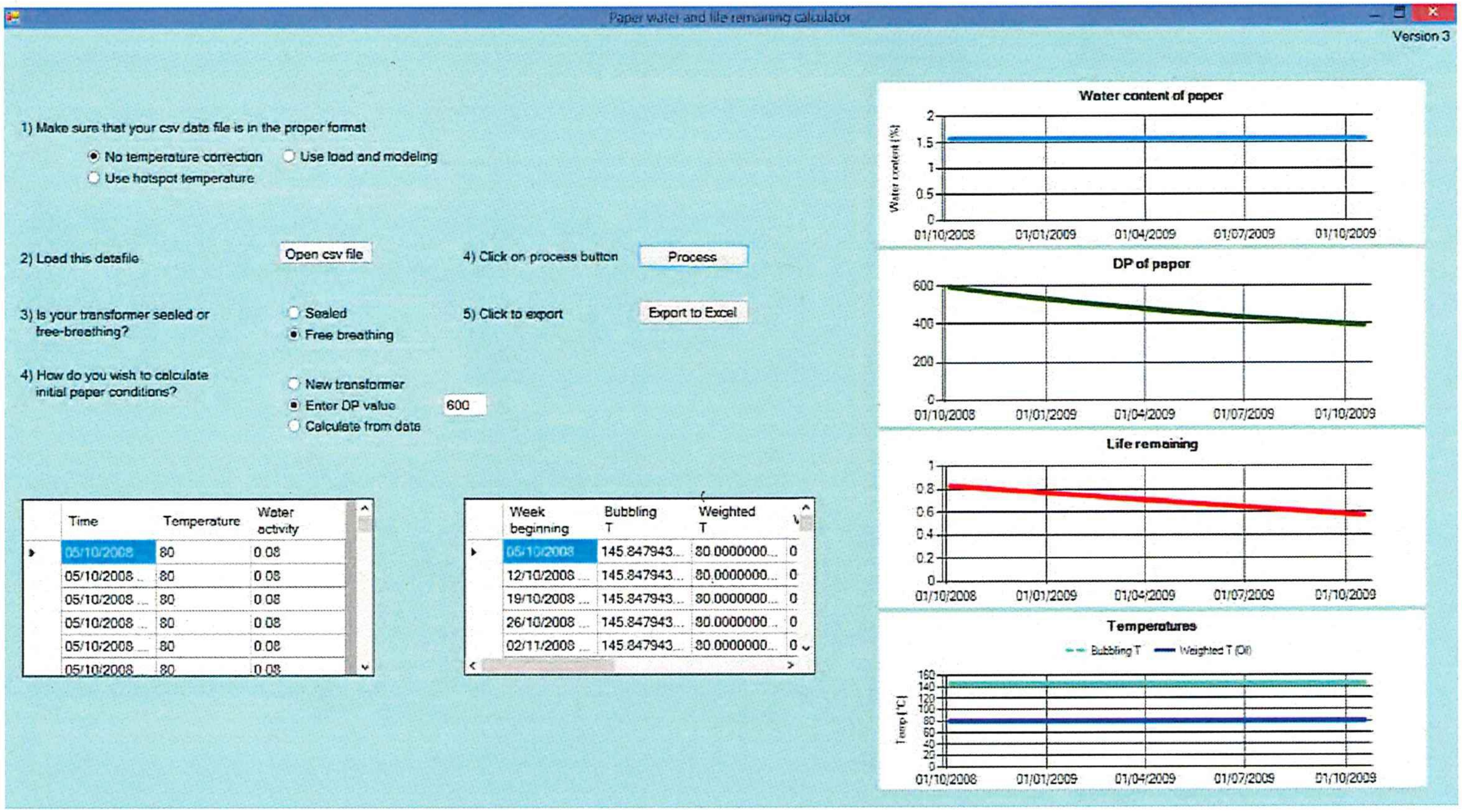
Integration into probabilistic modelling tool



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Future work

Set up algorithms on partner utility's database to ascertain the probabilistic life remaining of each asset.

Develop analytics to drive maintenance, loading and replacement strategy, and implement using a utility's database.

Transformer Innovation Centre

TRANSFORMER INNOVATION CENTRE

- Test transformer is retrofilled with vegetable oil (research to help usage)

TRANSFORMER INNOVATION CENTRE

- A current project:
  - Investigate behaviour of retrofilled transformers during network contingency events, i.e. network ratings.
  - If these transformers become overloaded how long does the utility have to switch load to another substation?
  - Will look at how thermal and chemical properties of vegetable oil affect winding temperature and insulation condition.