

What do you see in a 'probability' plot?

Sometimes data is trying to tell you something ... if you want to listen



WORKBOOK

Presented by

Dr Chris Jackson

Reliability engineer



Copyright © 2022 Christopher Jackson

All rights reserved. No part of this publication may be reproduced, distributed or transmitted in any form or by any means, including photocopying or other electronic or mechanical methods without the prior written permission of the author (Christopher Jackson), except as permitted under Section 107 or 108 of the 1976 United States Copyright Act and certain other non-commercial uses permitted by copyright law.

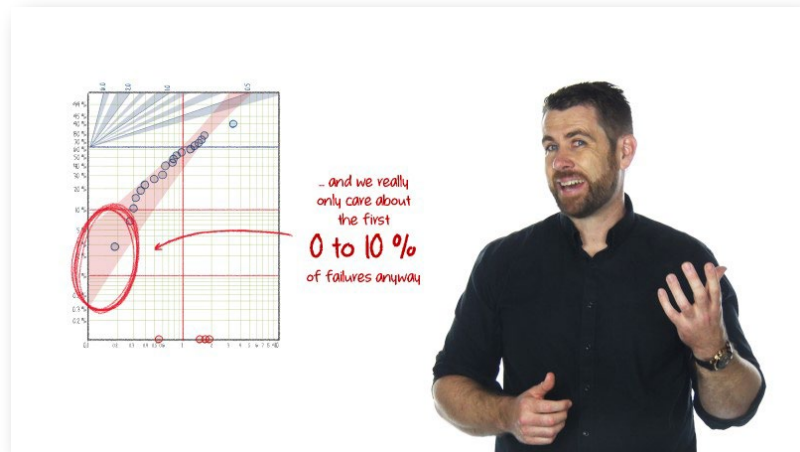
For permission requests, write to Christopher Jackson using the details on the following pages.

Limit of Liability/Disclaimer of Warranty: While the author has used his best efforts in preparing this document, he makes no representations or warranties with respect to the accuracy or completeness of the contents of this document and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. The author shall not be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

Who is your teacher? ... Dr Chris Jackson

Dr Jackson holds a Ph.D. and MSc in Reliability Engineering from the University of Maryland's Center of Risk and Reliability. He also holds a BE in Mechanical Engineering, a Masters of Military Science from the Australian National University (ANU) and has substantial experience in the field of leadership, management, risk, reliability and maintainability. He is a Certified Reliability Engineer (CRE) through the American Society of Quality (ASQ) and a Chartered Professional Engineer (CPEng) through Engineers Australia.

Dr Jackson is the cofounder of IS4 online learning, was the inaugural director of the University of California, Los Angeles (UCLA's) Center of Reliability and Resilience Engineering and the founder of its Center for the Safety and Reliability of Autonomous Systems (SARAS). He has had an extensive career as a Senior Reliability Engineer in the Australian Defence Force, and is the Director of Acuitas Reliability Pty Ltd.



He has supported many complex and material systems develop their reliability performance and assisted in providing reliability management frameworks that support business outcomes (that is, make more money). He has been a reliability management consultant to many companies across industries ranging from medical devices to small satellites. He has also led initiatives in complementary fields such as systems engineering and performance-based management frameworks (PBMFs). He is the author of two reliability engineering books, co-author of another, and has authored several journal articles and conference papers.

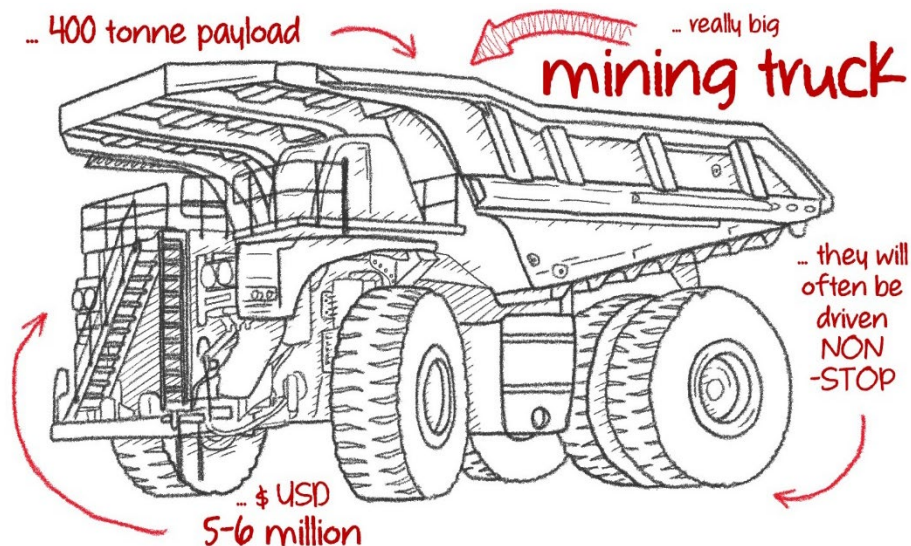
What do you see in a 'probability' plot

FULL DISCLAIMER!

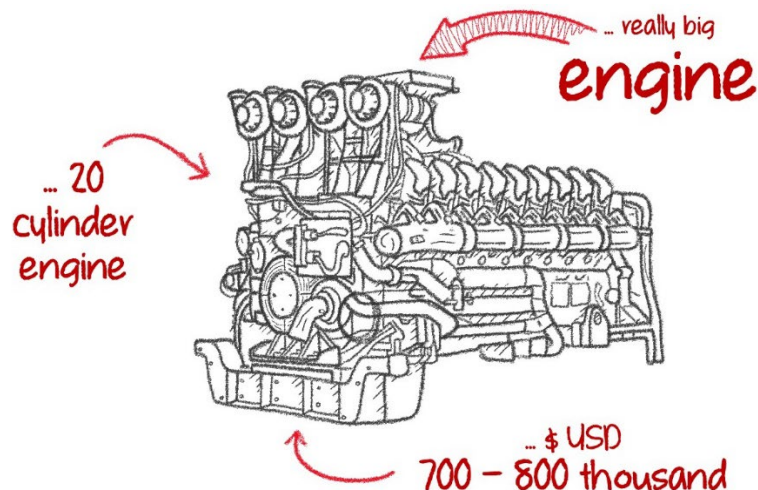
This webinar is not going to teach you every aspect of Weibull probability plotting ... or what a Weibull distribution is. You need to complete one of our other courses to learn about that. However, even if you only have a basic understanding of the underlying concepts involved, you will get something out of this webinar!

... let's look at a real-world problem ...

Have a look at the really, really, really big mining truck below.



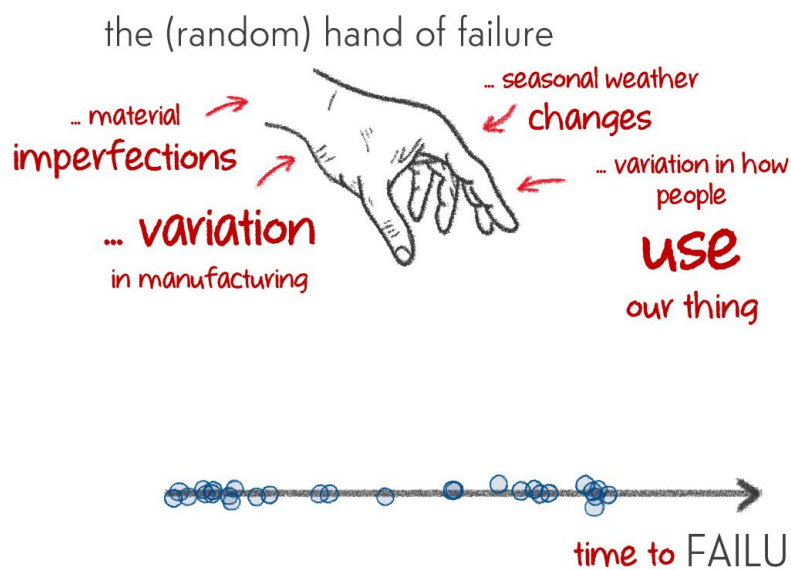
It is obviously very important for these trucks to be working as close to 'all the time' as possible. And one of the most important elements of this truck is its engine.



To keep the truck running, we need to support the reliability of the engine. Sometimes data already exists and is waiting for us to 'use' it. And one of the ways we can use it is to start with Weibull analysis.

... how does RELIABILITY behave?

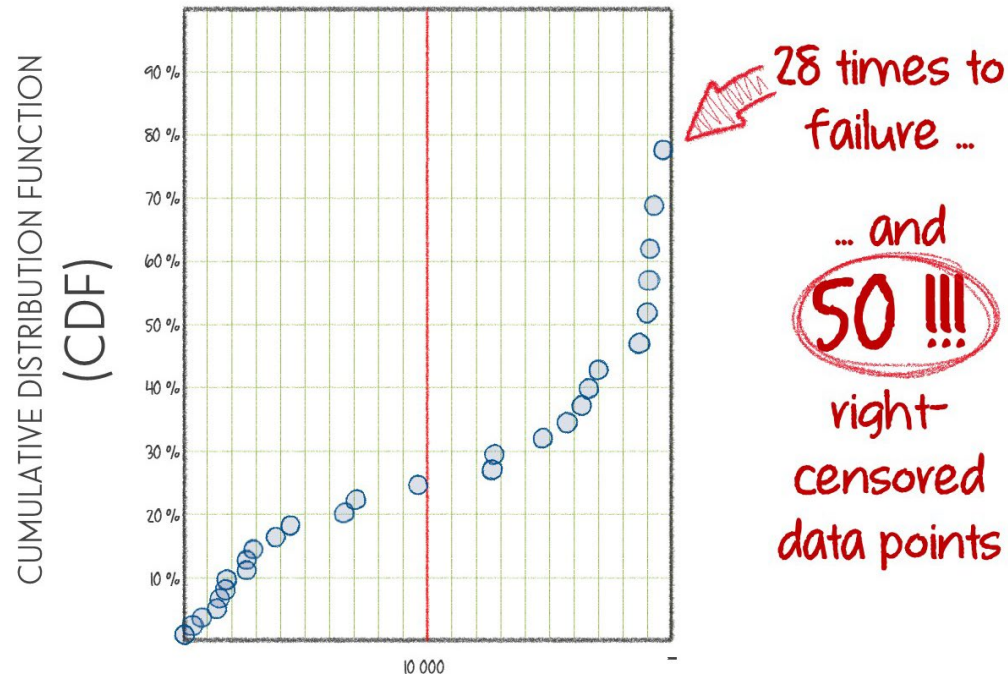
Let's look at the then 'random hand of failure.' The hand represents all the factors, uncertainties and things we cannot know with absolute precision that will mean that two, seemingly identical systems will fail in different ways at different times. It can represent all the factors from a **reliability test**, actual use, historical data or anything else where your product, system or service is allowed to operate until **failure**.



The data points above contain information. They can tell us a story – as long as we know how to 'read' the story. Where those data points fall – or the time to failure of each system that was observed – can combine to explain how our system fails, what might cause that failure, and how failure might occur in the future.

To get a better idea of what is happening, we can plot these data points on a chart where the vertical axis represented the percentage of things that have **failed**. This makes a 'smooth' line that helps us better visualize the 'nature' of **failure**.

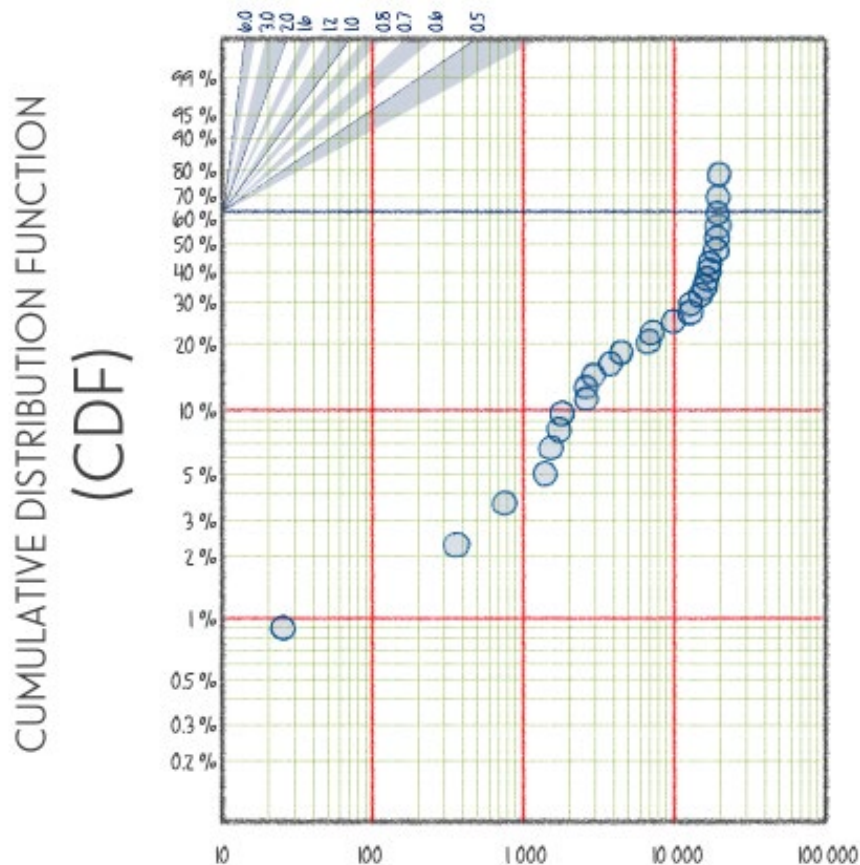
In this scenario, this approach to visualizing the data is particularly useful as we have 'censored' data. This means there are systems that are still being observed that haven't failed. This means that the effective percentage of things that have failed is affected by things that have not failed. So the chart on the previous page doesn't include the whole picture. The chart below does.



While this line is 'smooth' ... which usually means it is easier to spot patterns. The key to a lot of data analysis activities is to make a 'straight line.'

... WEIBULL plotting paper

We can manipulate the scaling of the CDF chart on the previous page a little bit to create a 'special' chart that is often referred to as **Weibull probability plotting paper**. The reason we do this is down to the fact that any data that is described by a **Weibull distribution** will create a straight line. And that straight line can be used to estimate our **Weibull distribution parameters** directly. The **TTF** data points on the previous page are shown plotted below on **Weibull probability plotting paper**.

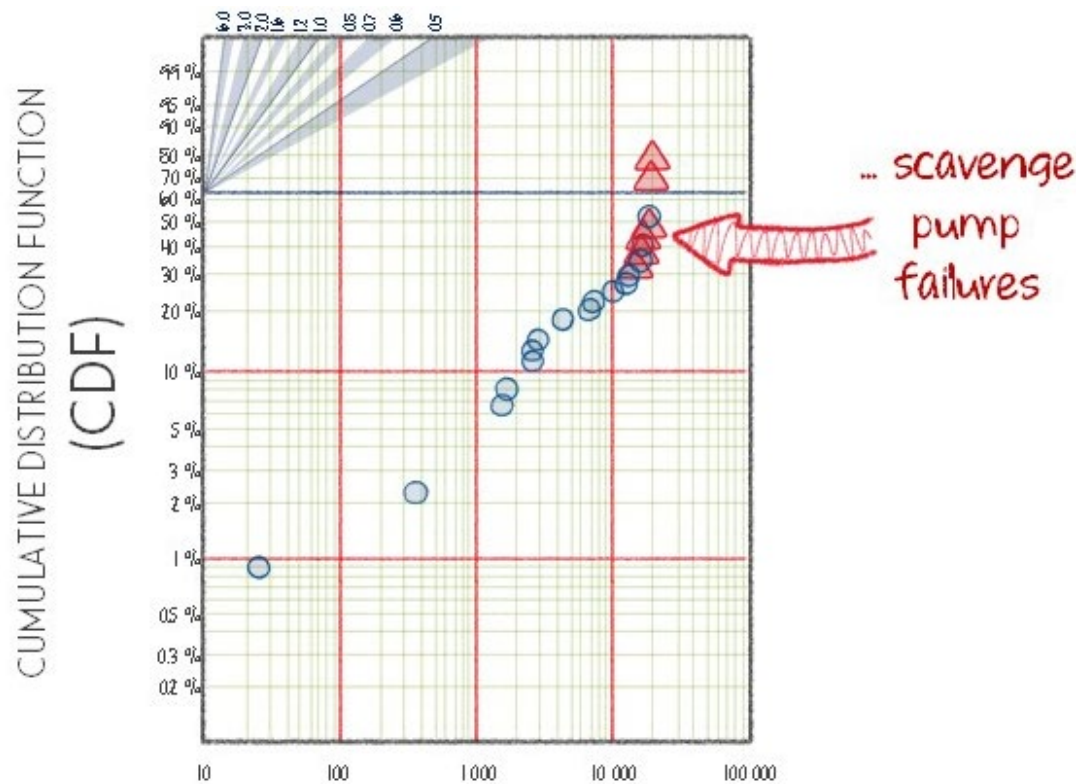


DO YOU THINK THE LINE IS STRAIGHT?

... or in other words, the DATA IS DESCRIBED BY THE WEIBULL DISTRIBUTION?

... but what might be DRIVING failure?

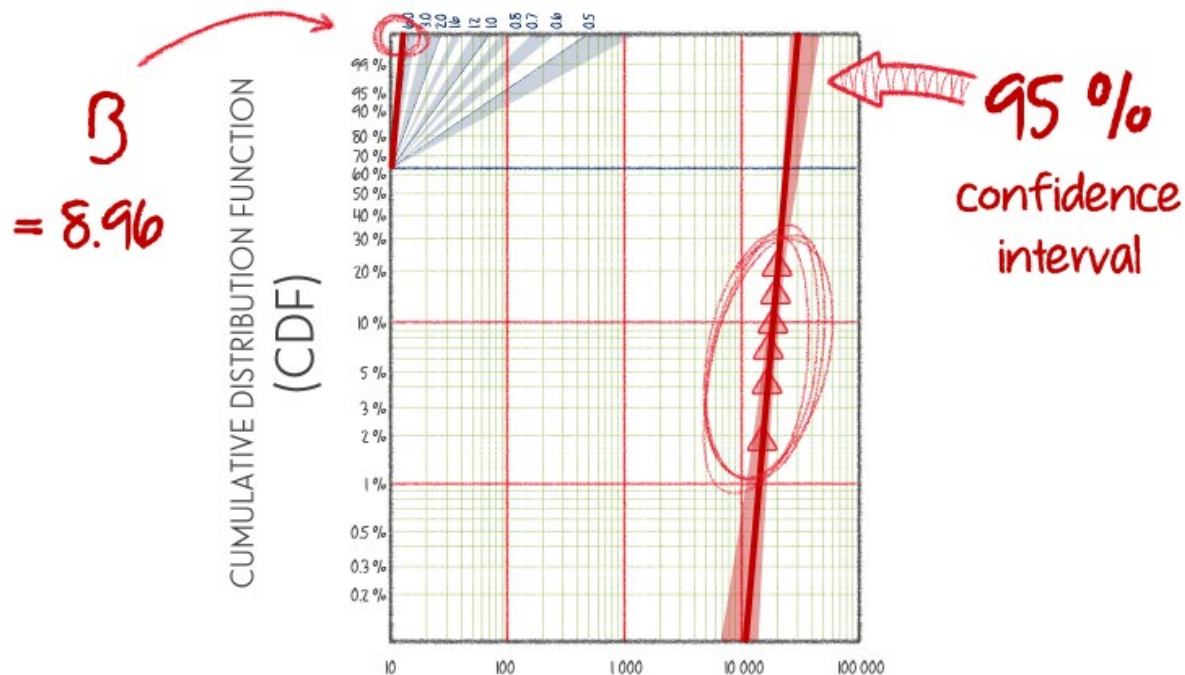
If we have time to failure data, we might have a little more information. For example, of the 28 failure points below, 6 of them were caused by the scavenge pump.



WHAT DOES THIS TELL US ... IF ANYTHING?

Note that these failures appear at the 'end' of the data.

What we can do to learn more is to ONLY plot the scavenge pump failures. We still need to think of all the other data points, but now they become 'censored' from the perspective of the scavenge pump. If the system failed due to (for example) the 'bottom end' failing, this implies that the scavenge pump was still working at that time. This gives us the following Weibull plot (with 95 % confidence intervals on the line of best fit).



For this particular plot, the line of best fit has a slope of 8.96. This corresponds with the ' β ' or shape parameter of the Weibull distribution that best fits the data.

DO YOU THINK THE LINE THE DATA TRACES OUT IS STRAIGHT?

**... or in other words, the (SCAVENGE PUMP)
DATA IS DESCRIBED BY THE WEIBULL DISTRIBUTION?**

The slope of this line tells us a lot. If the slope is greater than one (1), it implies that the system is ...

... *WEARING OUT* or *ACCUMULATING DAMAGE* ...

There are many failure mechanisms that wear out. This includes ...

(1) *fatigue*

(2) *creep*

(3) *diffusion*

(4) *wear*

(5) *corrosion*

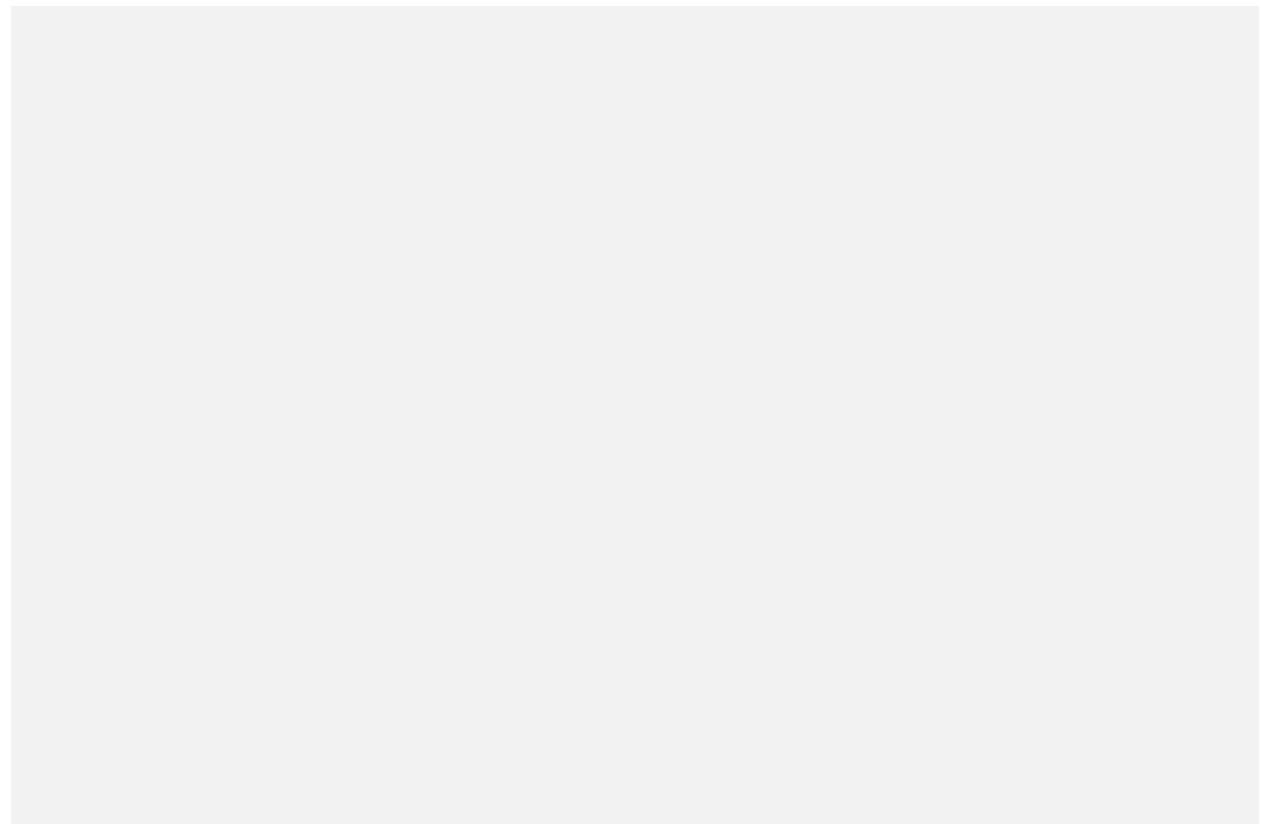
(6) *oxidation*

(7) *lubricant contamination*

... and plenty of others.

Knowing this is very useful.

WHAT CAN WE DO TO MITIGATE OR PREVENT FAILURE MECHANISMS LIKE THIS?



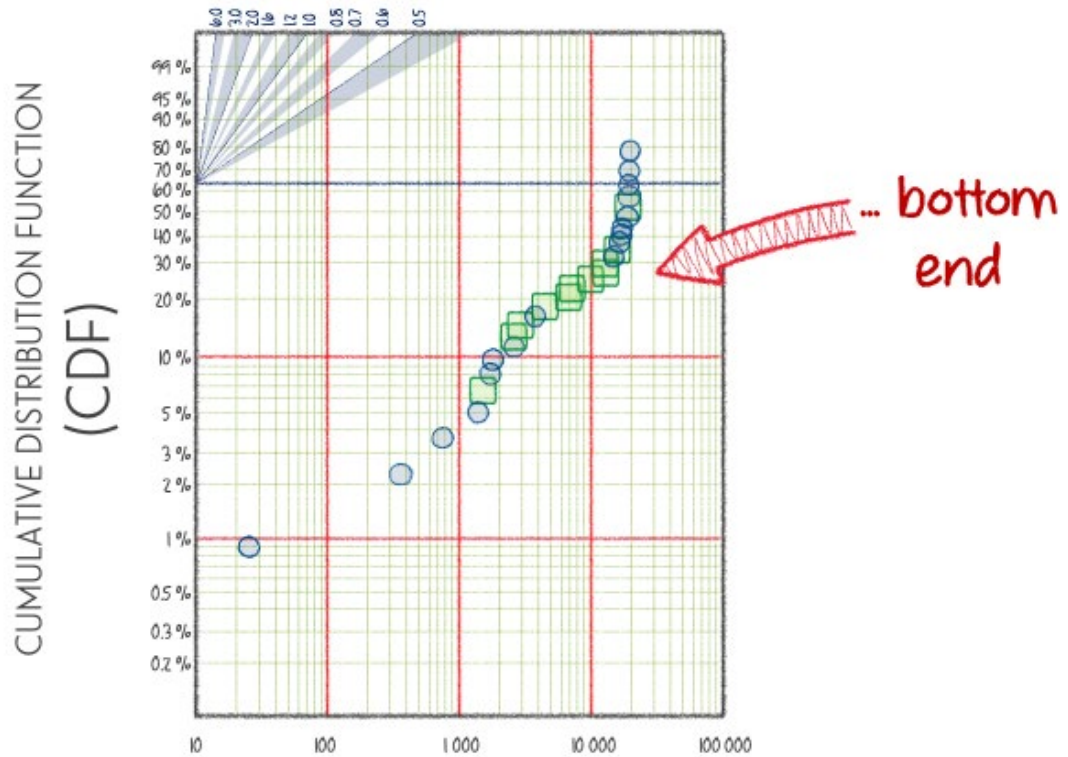
The many things we can consider to deal with these sorts of failures include ...

- (1) CONDITION BASED MAINTENANCE (CBM) where we monitor the status of the damage in our system until it gets to a point where we 'trigger' maintenance to stop it progressing further or removing the damage entirely*
- (2) PREVENTIVE MAINTENANCE (PM) where we conduct maintenance that removes damage based on intervals of usage*
- (3) define the SERVICE LIFE of our system based on wear-out failure mechanisms that are so severe or encompassing that maintenance is not an option*
- (4) defining the WARRANTY PERIOD or WARRANTY RELIABILITY based on our understanding of the wear-out characteristics of the system to support our business model*
- (5) identifying which failure mechanism dominates wear-out which become the VITAL FEW weak points we focus on.*

WHAT WOULD YOU RECOMMEND FOR THE SCAVENGE PUMP?

... but what might be DRIVING failure ... #2?

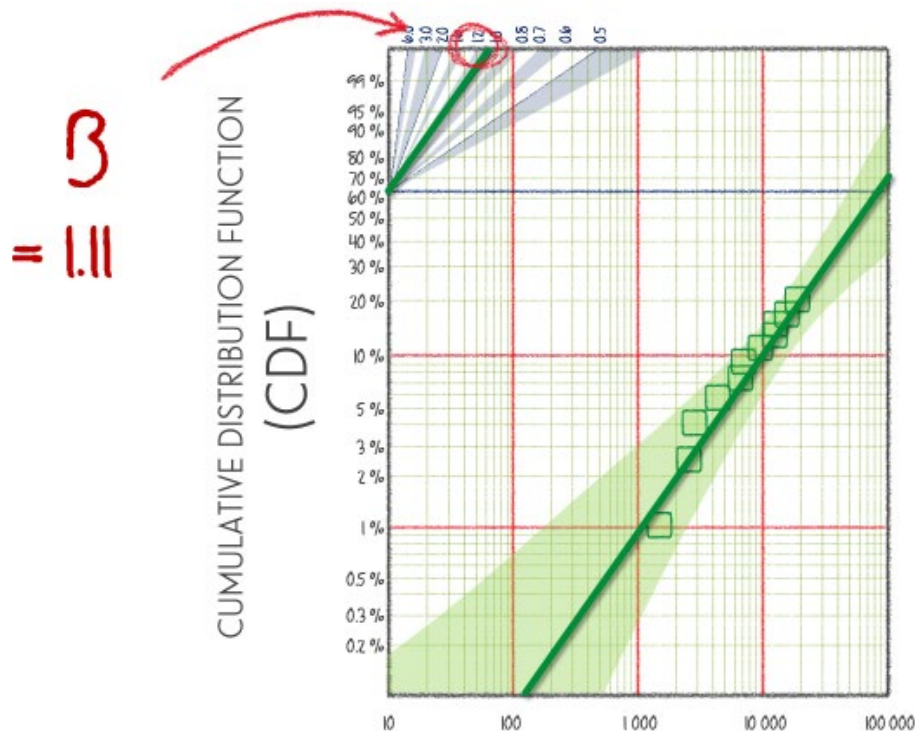
Of the 28 failure points below, 11 of them were caused by the bottom end.



WHAT DOES THIS TELL US ... IF ANYTHING?

Note that these failures appear in the 'middle' of the data.

We can do the same thing we did with our scavenge pump with the bottom end and create a Weibull plot (with 95 % confidence intervals on the line of best fit) specific to the bottom end failure points.



For this particular plot, the line of best fit has a slope of 1.11. Remember, this corresponds with the ' β ' or shape parameter of the Weibull distribution that best fits the data.

DO YOU THINK THE LINE THE DATA TRACES OUT IS STRAIGHT?

... or in other words, the (BOTTOM END)
DATA IS DESCRIBED BY THE WEIBULL DISTRIBUTION?

If the slope is approximately equal to one (1), it implies that the system is failing with a ...

... *CONSTANT HAZARD RATE* ...

This means that it doesn't matter how old or young a surviving system is, it will have the same likelihood of failure. There are many failure mechanisms that have a constant rate. This includes ...

(1) CATASTROPHIC ENVIRONMENTAL STRESSES that occur randomly with respect to the age of the system and will cause instant failure ... like lightning, tsunamis, spikes or debris on roads and many others

(2) HUMAN ERRORS that also occur randomly with respect to the age of the system

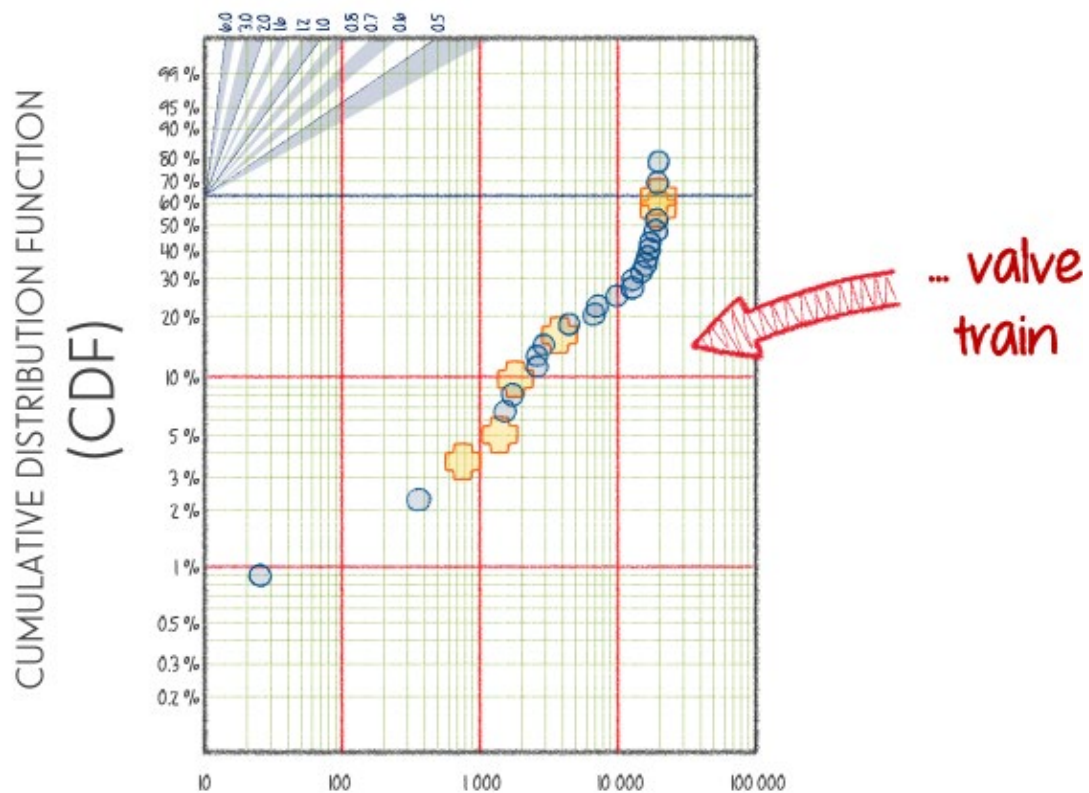
(3) ACCIDENTS for the same reasons above.

For the bottom end in question, a root cause analysis (RCA) was conducted which confirmed (after the analysis) that contaminants in the lubrication were randomly critically damaging the engine.

WHAT CAN WE DO TO MITIGATE OR PREVENT FAILURE MECHANISMS LIKE THIS?

... but what might be DRIVING failure ... #3?

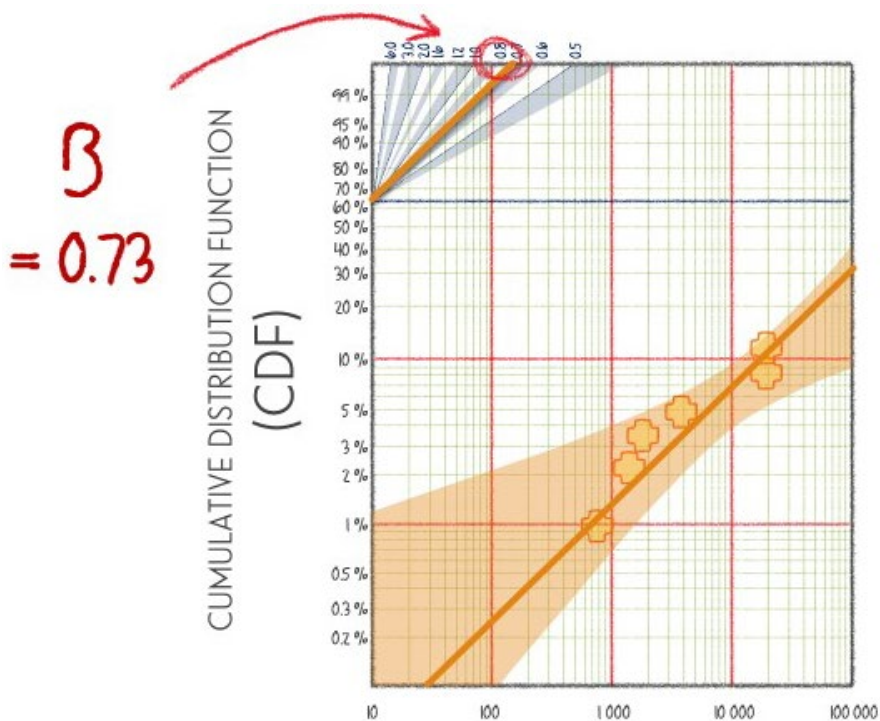
Of the 28 failure points below, 6 of them were caused by the valve train.



HAT DOES THIS TELL US ... IF ANYTHING?

Note that these failures appear in the 'throughout' the data.

We can now create another Weibull plot based on the valve train failure data below.



For this particular plot, the line of best fit has a slope of 0.73. Remember, this corresponds with the ' β ' or shape parameter of the Weibull distribution that best fits the data.

DO YOU THINK THE LINE THE DATA TRACES OUT IS STRAIGHT?

... or in other words, the (VALVE TRAIN)
DATA IS DESCRIBED BY THE WEIBULL DISTRIBUTION?

If the slope is approximately less to one (1), it implies that the system is ...

... *WEARING-IN or experiencing INFANT MORTALITY* ...

This typically means that there is a subpopulation of systems that are not 'perfect' ... or at least 'within specifications.' Another term is defective. We usually think of things like ...

(1) interfaces issues

(2) assembly or installation error

(3) software bugs

(4) manufacturing defects

(5) damage during transit

... and lots of other things that lead to a subpopulation of defective systems or components.

For the valve train in question, a root cause analysis (RCA) was conducted which confirmed (after the analysis) that failures were caused by an installation issue.

WHAT CAN WE DO TO MITIGATE OR PREVENT FAILURE MECHANISMS LIKE THIS?

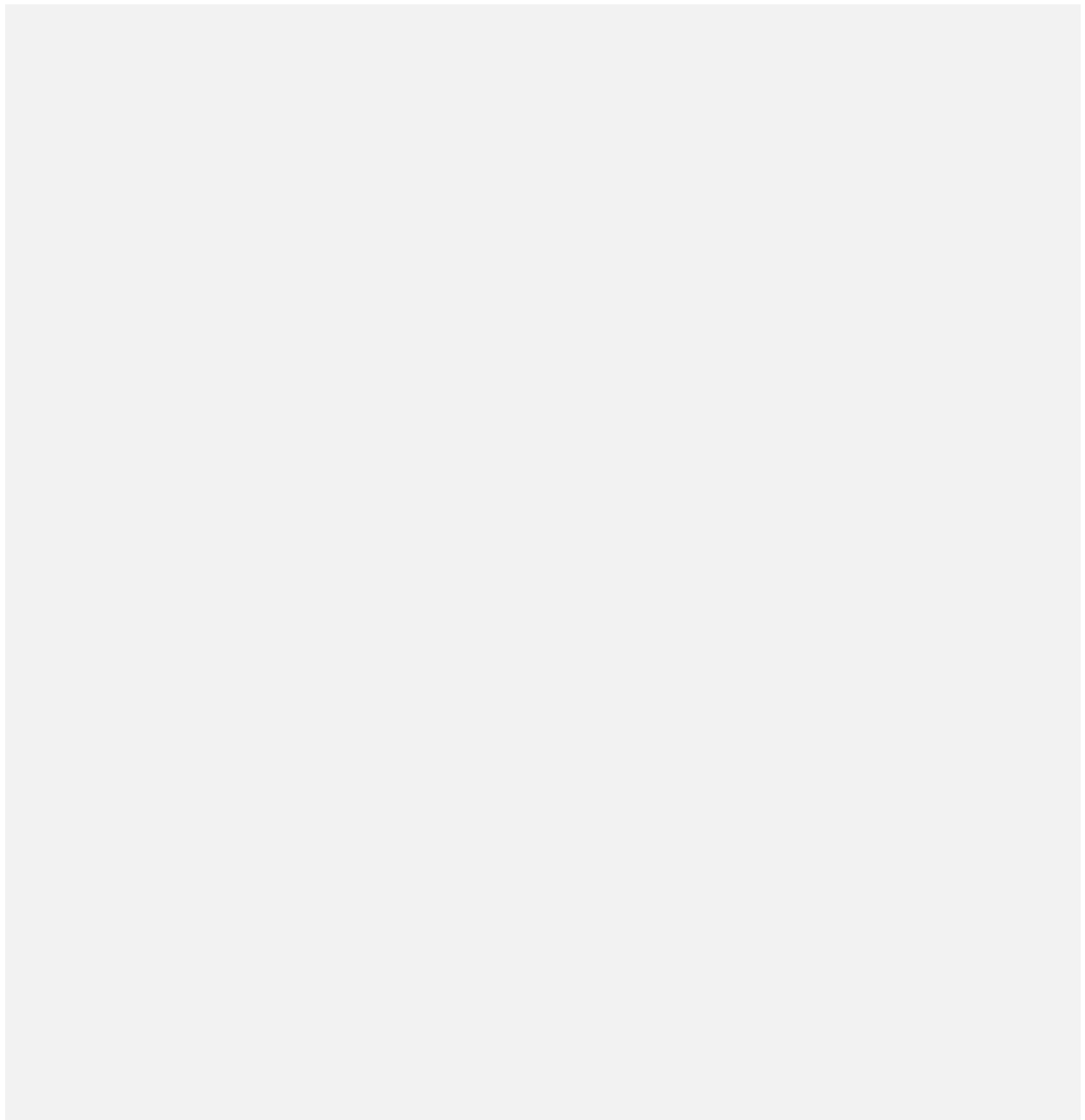
The many things we can consider to deal with these sorts of failures include ...

(1) activities that improve MANUFACTURING QUALITY like STATISTICAL PROCESS CONTROL (SPC) or SCREENING.

(2) TRAINING that helps teach installers and manufacturers how minimize defects

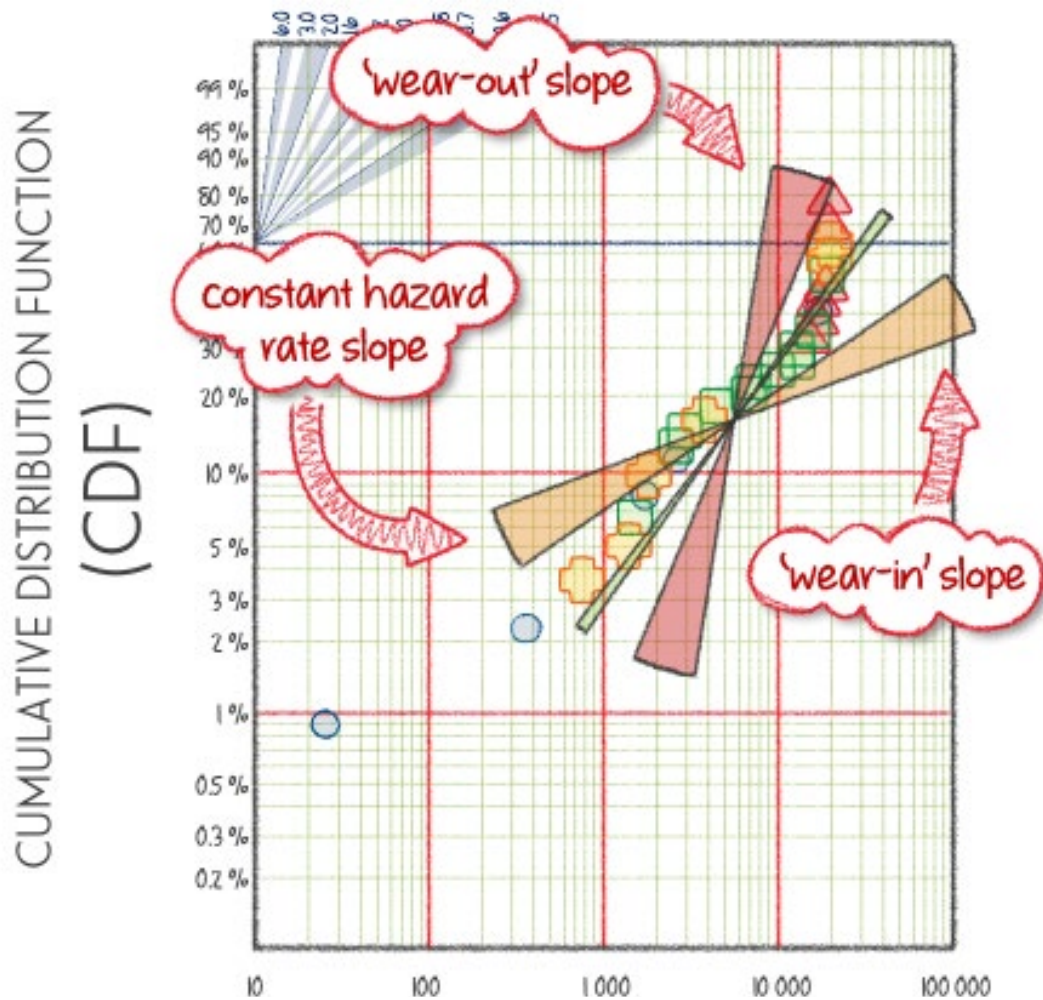
(3) BURN-IN that involves testing to try and stimulated 'early' failures before systems or components are used, meaning those that pass the test are less likely to be defective?

WHAT WOULD YOU RECOMMEND FOR THE VALVE TRAIN?

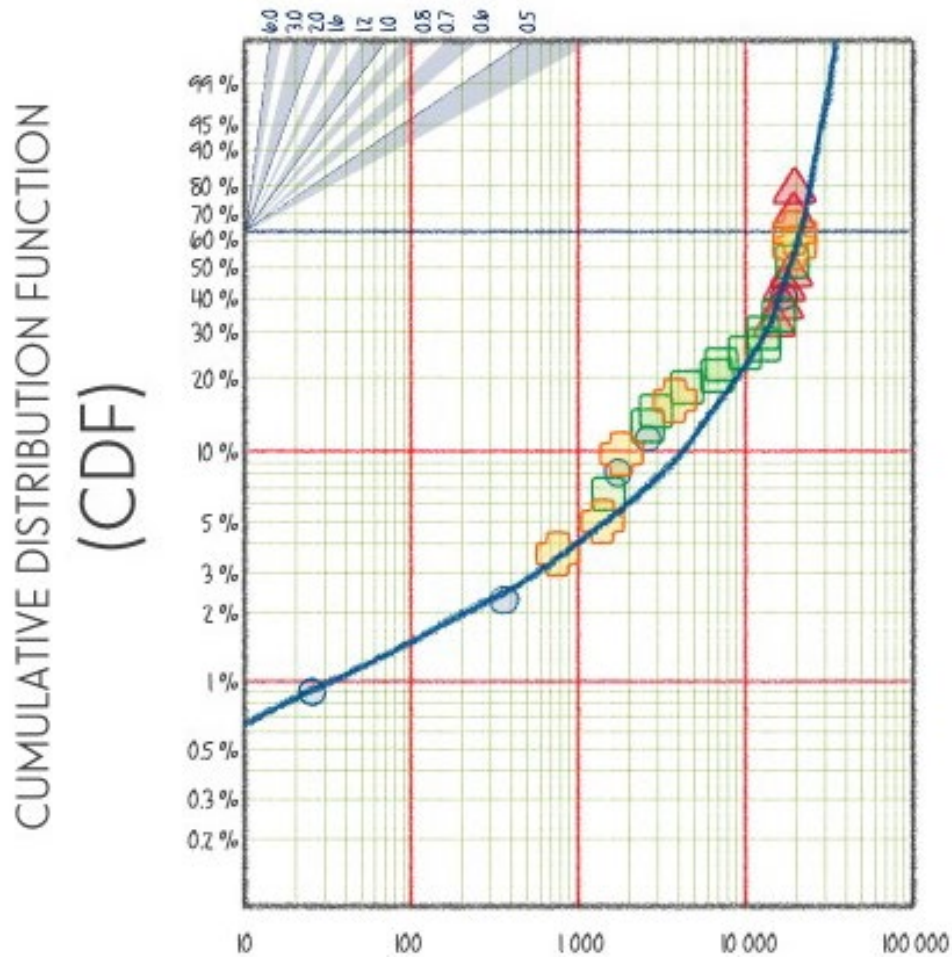


... so let's go back to the start

We can see hints of the previous analyses in the overall system Weibull plot. The slopes of typical 'wear-out,' 'wear-in' and 'constant hazard rate' failure mechanisms are illustrated below.



And if we draw a 'non-straight line of best fit' we can see the following (admittedly rough) trend.

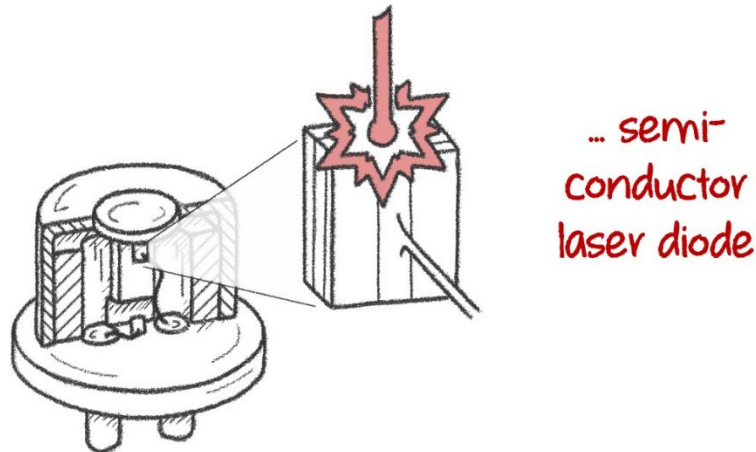


This is a basic 'bell curve.' The shallow slope at the start indicates 'wear-in.' The steeper slope at the end indicates 'wear-out.' And the bit in between shows 'constant hazard rate' failures.

SO YOU DON'T NEED TO DO DETAILED WEIBULL ANALYSIS TO IDENTIFY THESE TYPES OF FAILURES!

... but let's look at a SIMPLE COMPONENT (which is very different)

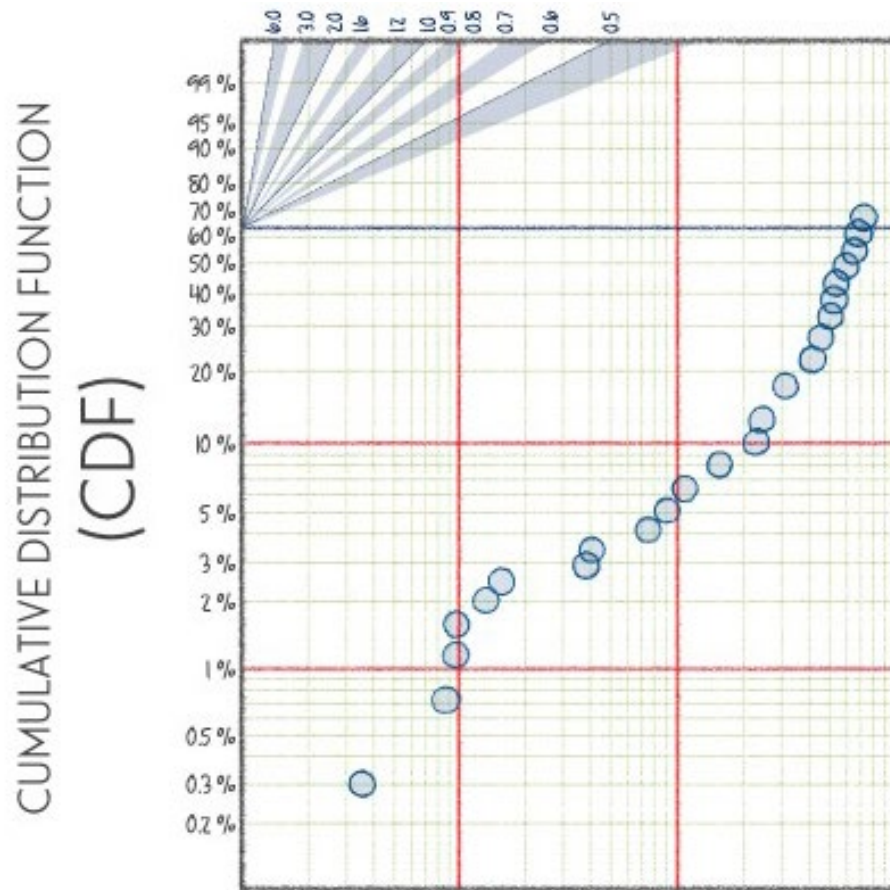
We are constantly told that 'infant mortality' or 'wear-in' has a decreasing hazard rate. And this is often true ... especially for systems with lots of different failure mechanisms. But this is not always the case ... especially for simple systems like laser diodes.



The element in the image above is a semiconductor that is not based on silicon. Instead, it is based on gallium aluminium arsenide (AlGaAs). This becomes a Light Emitting Diode (LED). There are mirrors on the surface of the semi-conductor to create a laser cavity. The laser is then emitted out the 'side' of the semiconductor in a controllable way.

This is a very simple system. But it is very challenging to manufacture in a defect free way. The AlGaAs semiconductor needs to be created in a way that ideally involves a perfect crystalline structure. Of course, this is never possible. So manufacturing techniques are all about as making the crystalline structure as 'perfect as possible.' So even the 'best' approaches to manufacturing will never guarantee defect free components.

Below is a Weibull plot of a laser diode times to failure.

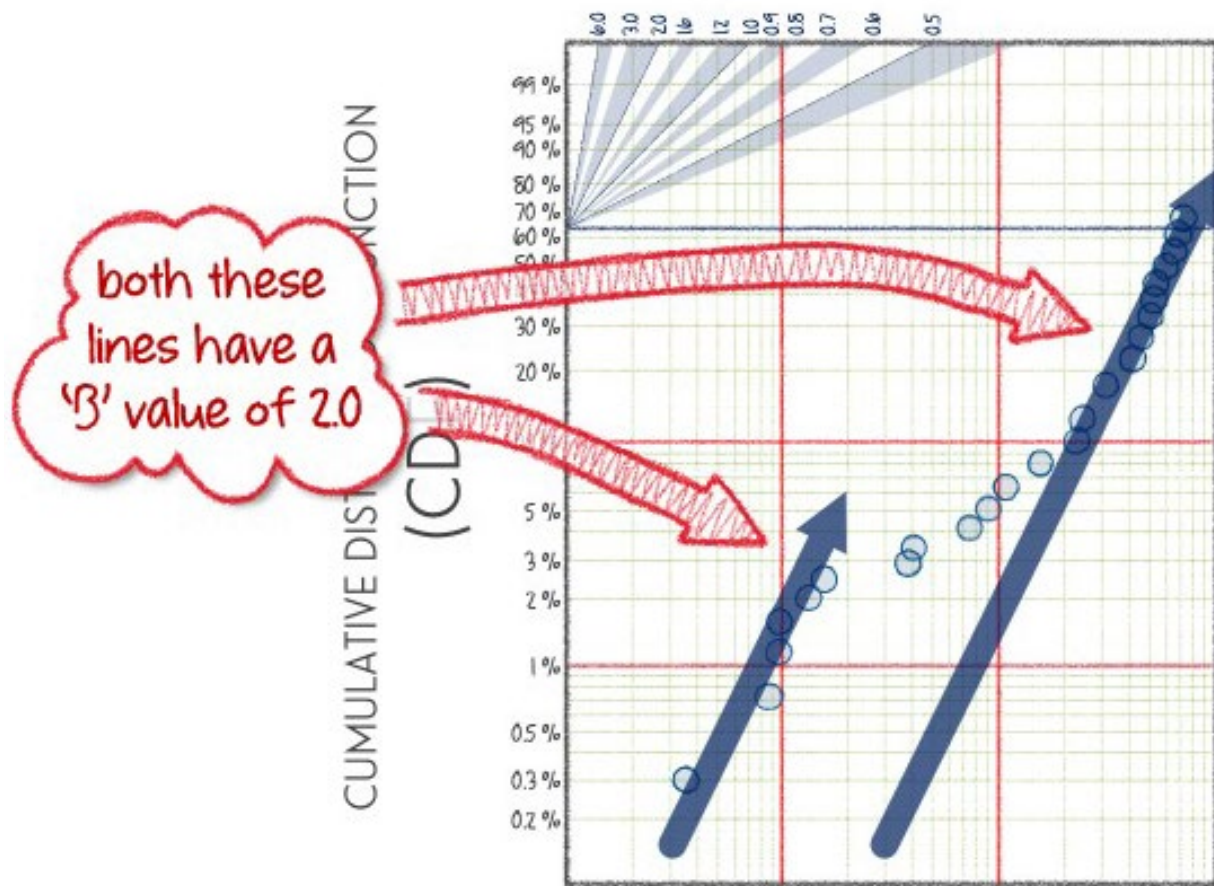


And we can work out straight away from this plot the nature of failure. We can tell that because the line of 'best fit' is steeper than the dotted line, the **shape parameter** (β) is greater than 1 AND our product, system or service is wearing out.

DO YOU THINK THE LINE IS STRAIGHT?

... or in other words, the DATA IS DESCRIBED BY THE WEIBULL DISTRIBUTION?

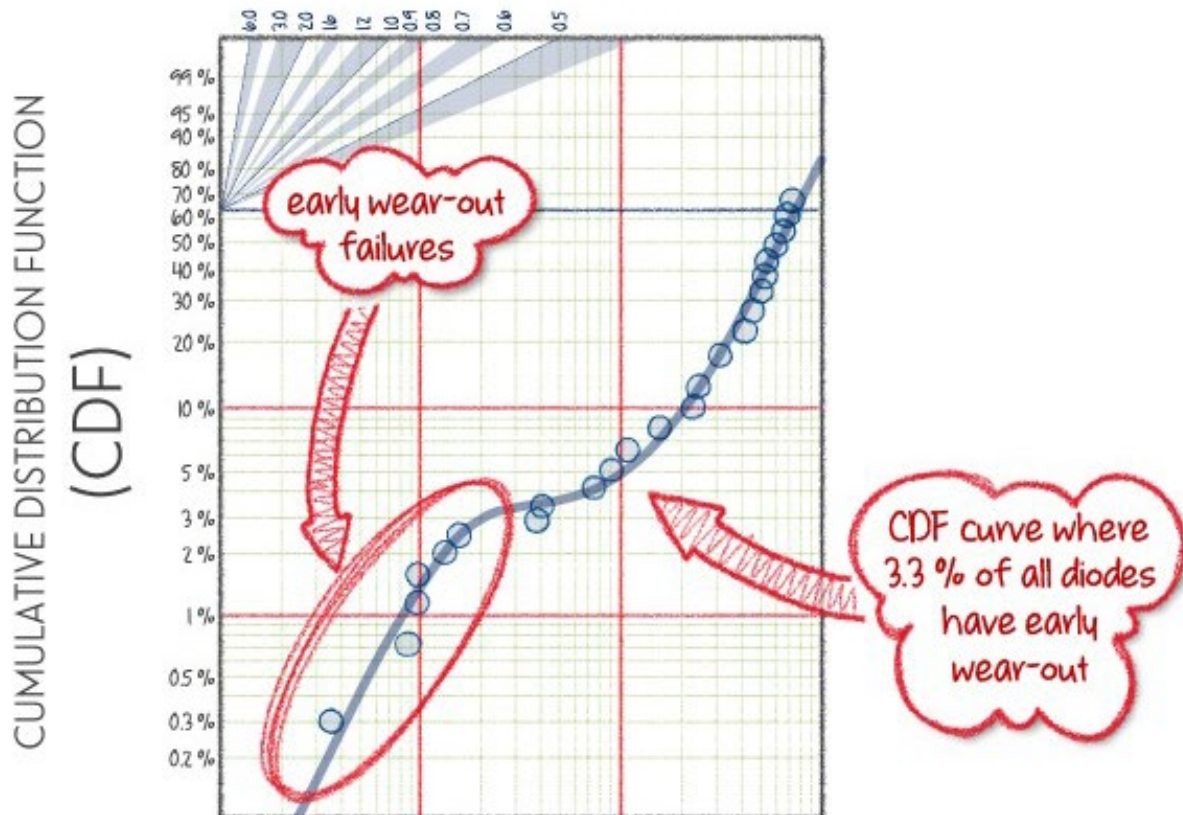
A lot of Weibull analyses would 'stop here.' But there is more information if you look for it. For example, look what happens when we add two lines that have a slope (β) of 2.0.



WHAT DOES THIS TELL US ... IF ANYTHING?

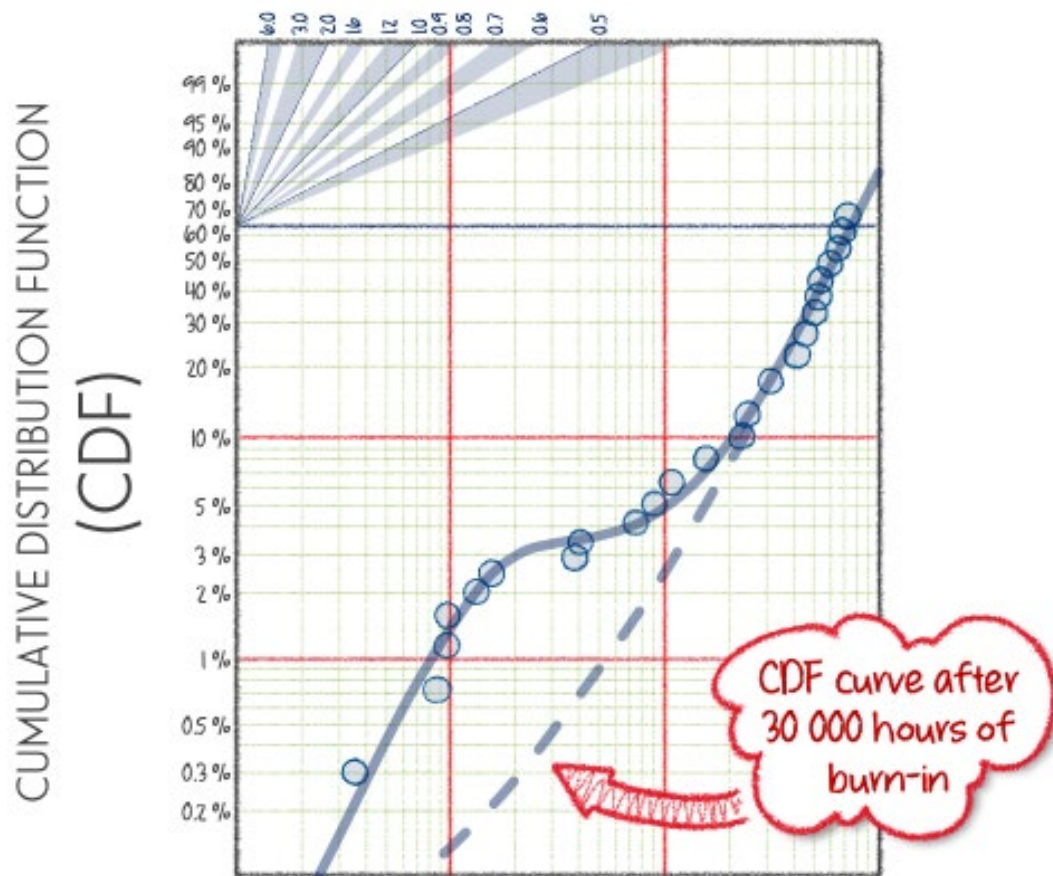
With the help of the lines on the previous page, we can see that there is likely a case of what we call 'early wear-out.' This is caused by a specific defect that tends to be the only defect that will be present ... if any. So as opposed to lots of different types of wear-in failure mechanisms, there is only one. And this will usually create a wear-out phenomenon early, which disappears when the defective components have all prematurely worn out.

For example, if we create a system reliability model where the early wear-out only applies to 3.3 % of the entire population, we get the CDF curve. As you can see, this is a very good fit.



WHAT WOULD YOU RECOMMEND FOR THE LASER DIODE?

This is still a 'wear-in' or 'infant mortality' phenomenon. So all the potential responses above could apply (such as SPC to minimize manufacturing defects). However, if we can't (for whatever reason) improve the quality of the laser diodes, we can investigate burn-in. With the model above, we can deduce the following effect on reliability caused by a 30 000 burn-in period.



A burn-in of 30 000 hours is very long. For example, there are 8 766 in a single year. But burn-in can be accelerated in a controlled way where we might (for example) increase the temperature to create a burn-in test that is equivalent to 30 000 hours in a much shorter period.

...but it is all about the VITAL FEW

If we go back to the engine of the mining truck, 82 % of failures were caused by just three components. So being able to focus on the reliability characteristics of components is very important to have the biggest impact on reliability.

With the laser diode, virtually all the early failures (which are the most important) are caused by early wear-out. So that is what you need to focus on.

And that is where Weibull analysis can be very important. Not only can it help you characterize how reliability 'happens,' it can help you work out the VITAL FEW elements of your system that drive failure. This includes the nature of failure (wear-in, constant hazard rate and wear-out), if early wear-out exists, the likely fraction of the population which is defective, and what can happen if you conduct burn-in.

So don't ever settle with a 'straight line' if it is not the best fit. If there are other things going on, a Weibull plot will probably show it!