UNIVERSITY OF TORONTO

C-MORE Centre for Maintenance Optimization & Reliability Engineering

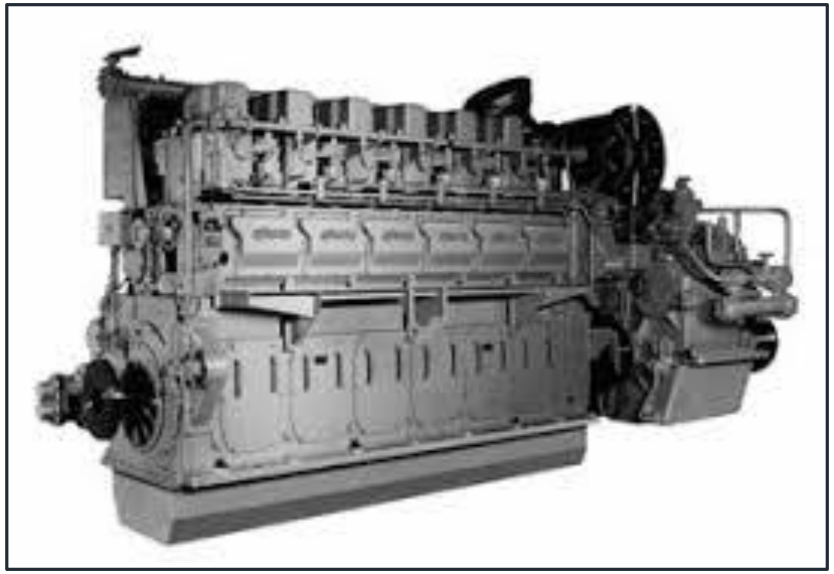
University of Toronto | Department of Mechanical and Industrial Engineering

# PROPULSION DIESEL ENGINE RELIABILITY MODELLING

# Context



- 15 City-class frigates in operation since 1990s
- Propulsion system: Diesel Engine generating and 2 gas turbines working in a CODOG arrangement
- Object of study: Propulsion Diesel Engine (PDE)
- Work orders generated based on corrective actions & schedules preventive maintenance actions periodically
- Purchase of replacement parts triggered by work orders
- Oil & coolant conditioning inspections done every 30 days
- Oil & coolant data analyzed by a third party while maintenance decisions are made by the Fleet Maintenance Facility (FMF)



**A Pielstick Propulsion Diesel Engine**

# Problem Background



- Objective: To develop a reliability model to predict engine failure with the use of a Weibull Proportional Hazards Model & Transition Probability Modelling
- Input: Event History & Inspection Data
- Design of optimal maintenance policy taking into account costs associated with average failure & preventive maintenance actions
- Available Data:
  - Work Order data (from Nov 2012 to Mar 2019 )
  - Fluid Inspection data (ranging from Dec 2012 to Jan 2019)
  - Month-wise Engine odometer running hours data
  - Cost of replacement parts corresponding to each order

# Data clean-up: Work Orders



- Work orders generated for all replacement actions concerning engine, such as failed bulbs that are not critical to engine working
- No direct one-to-one correspondence between work orders & failures
- Different classes of work orders:
  - Corrective action
  - Preventive Maintenance
  - 3rd party overhaul

- Part cost was a metric that could potentially be used to classify events
- Part replacement costs associated with only corrective action orders while Preventive Maintenance (PM) orders do not have costs associated
- If PM orders require parts, “dummy” corrective maintenance action orders generated for part procurement
- So, classification of Engine Failure & Suspension events was not straightforward

# Characterization of failures

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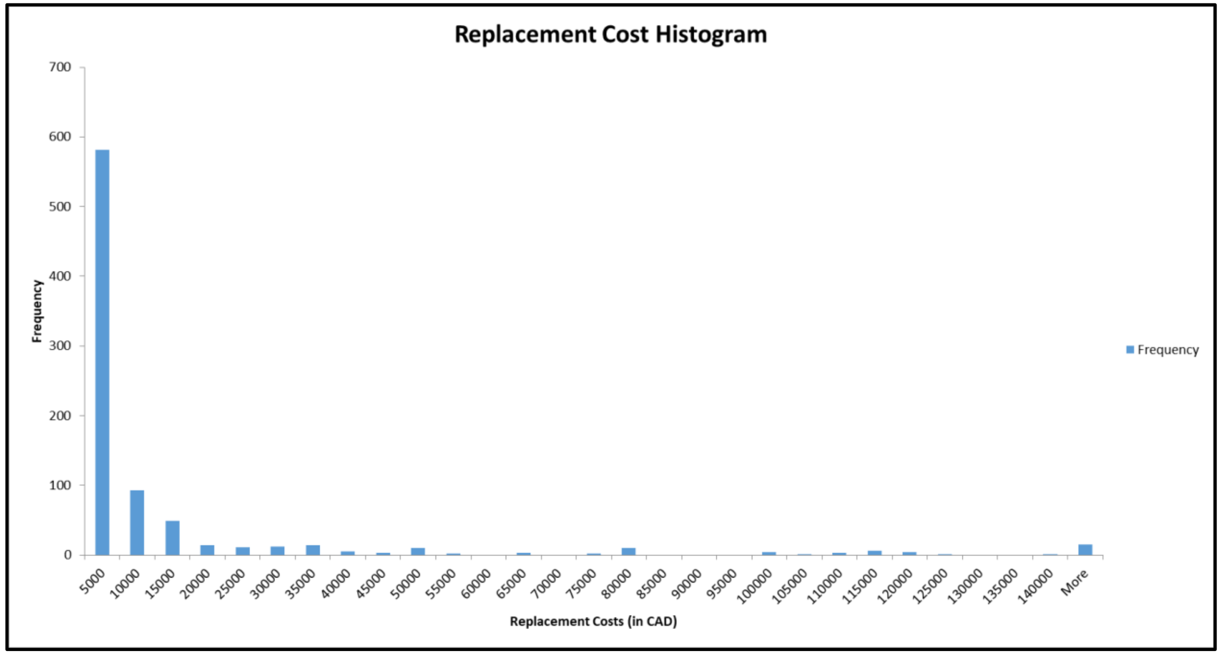
- Costs associated with corrective actions analyzed using a Histogram
- Most number of orders fell into the 0-5000 bin
- Engine failure corrective actions generally associated with relatively expensive part replacement costs
- In consultation with client, 10000 CAD was established as the threshold beyond which failures were significant and considered to be engine failures
- Since PM orders do not have costs associated, 12K/15K/24K preventive maintenance actions that brought the engine back to "good as new" are significant to analysis



# EXAKT Data Prep & Analysis



- From the filtered down orders, an event history was constructed
- An order does not correspond to an event directly since:
  - they correspond to purchase orders and not maintenance events
  - multiple orders generated within a small window indicate part replacements for one failure event
- Odometer readings (month-wise) are the only source for Working Age of the PDE
- Scheduled date of completion of orders as generated for some orders was inordinately long – due to administrative issues & Mid-Life Refits
- Though ships came into operation as early as 1992, event and running hour information dates back to 2013

**Weibull analysis of Halifax class frigates**

EXAKT, Condition - Based Maintenance Software    08:38 PM Tue., Oct. 08, 2019

Weibull Distribution Goodness of Fit Test
(Based on Cox - generalized Residuals)

**Weibull (*) ()**

Summary of Events and Censoring Values

| Sample Size | Failed | Censored (Def) | Censored (Temp) | % censored |
|---|---|---|---|---|
| 69 | 27 | 42 | 0 | 60.9 |

Summary of Estimated Parameters

| Scale | Shape |
|---|---|
| 15739.4 | 0.549538 |

Summary of Goodness of Fit Test

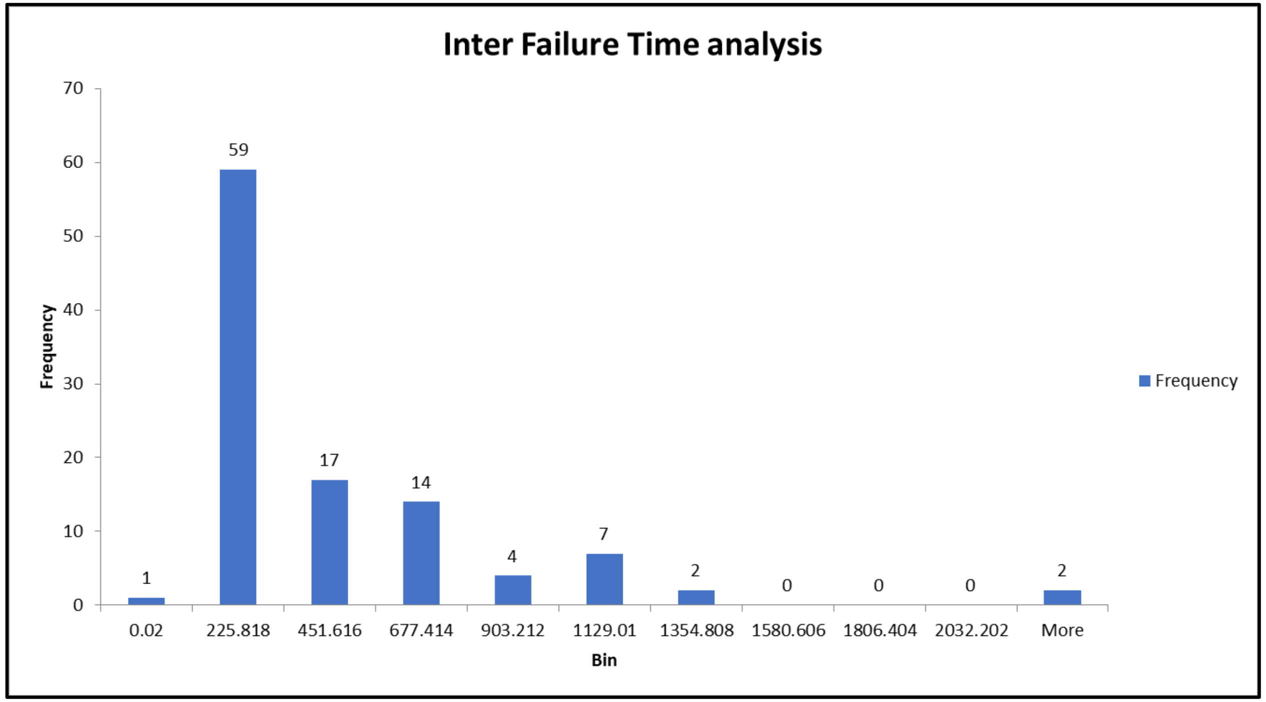
| Test | Observed Value | p - Value | PHM Fits Data |
|---|---|---|---|
| Kolmogorov - Smirnov | 0.235725 | 0.000729629 | Rejected (*) |

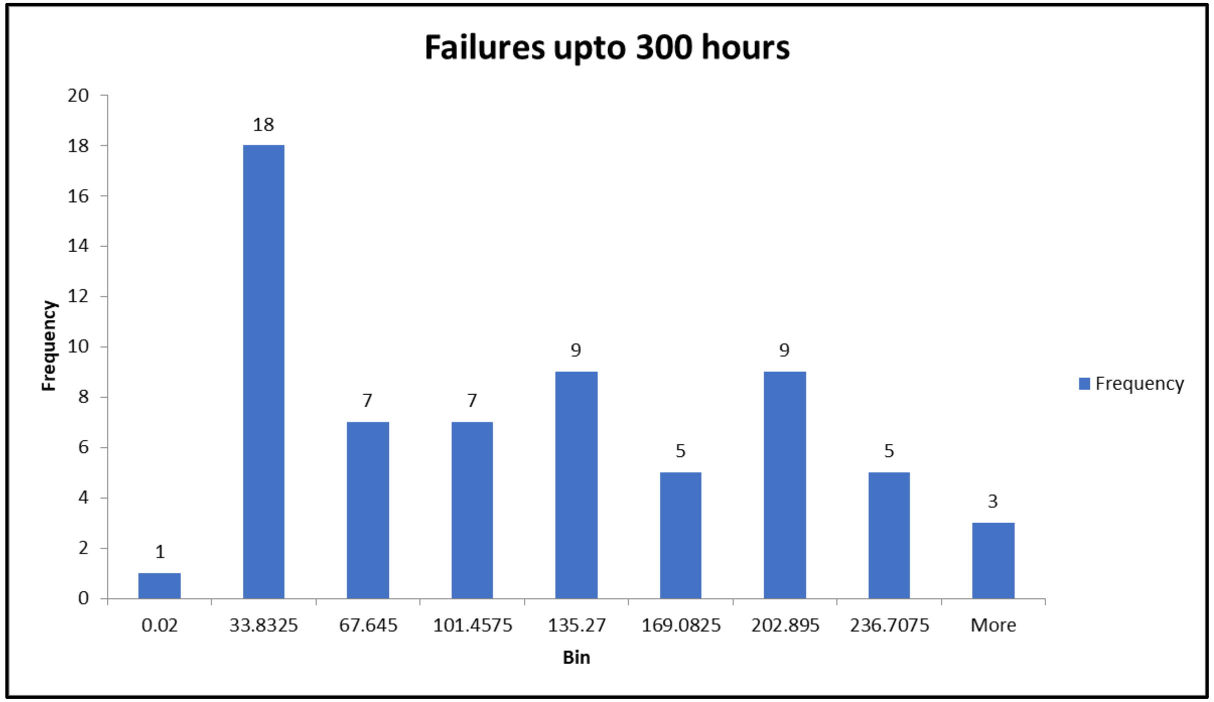
(*) based on 5% significance level

Weibull fit rejected; meaningless shape factor encountered

# Inter-failure Time Analysis





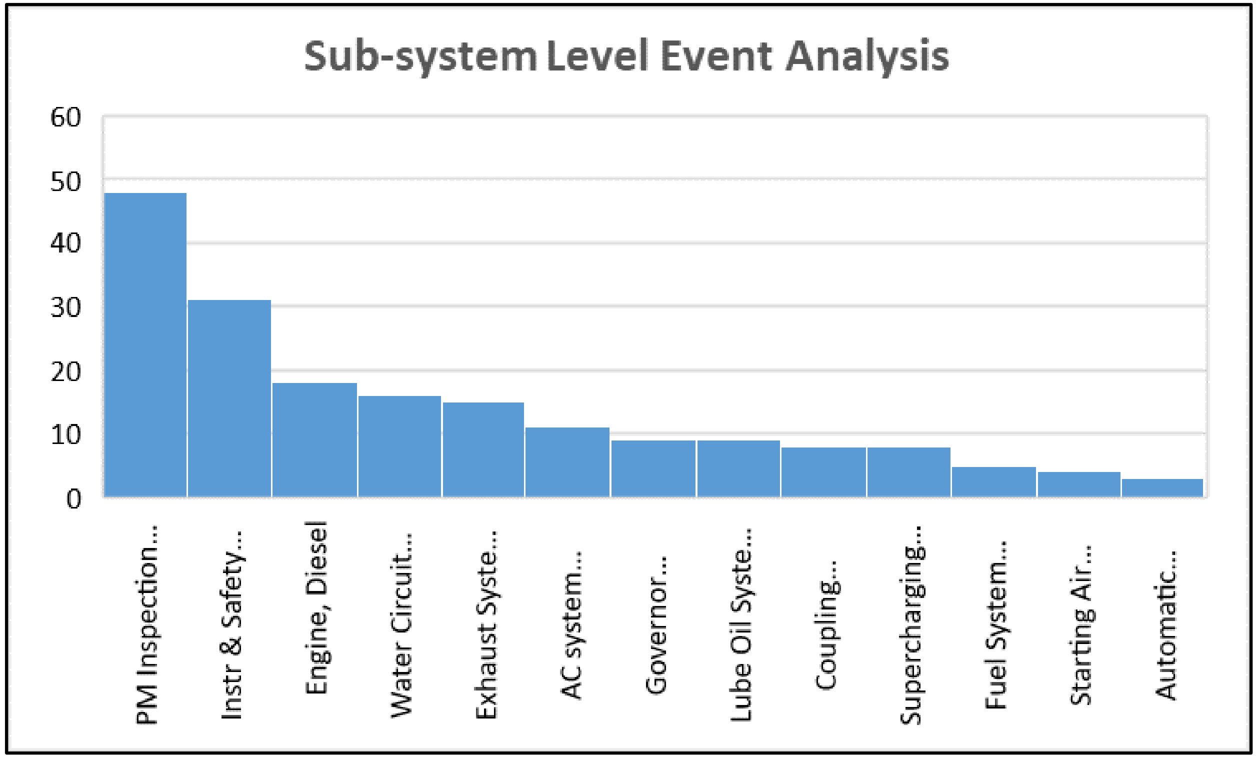




- Distribution follows a ski-slope shape – uncharacteristic of reliability study of similar assets
- 59 IFTs fell into < 225 hours bin, necessitating a dive into this bucket
- 19 events with inter-failure times less than 33 hours, i.e, most of these failures were not even an entire day apart

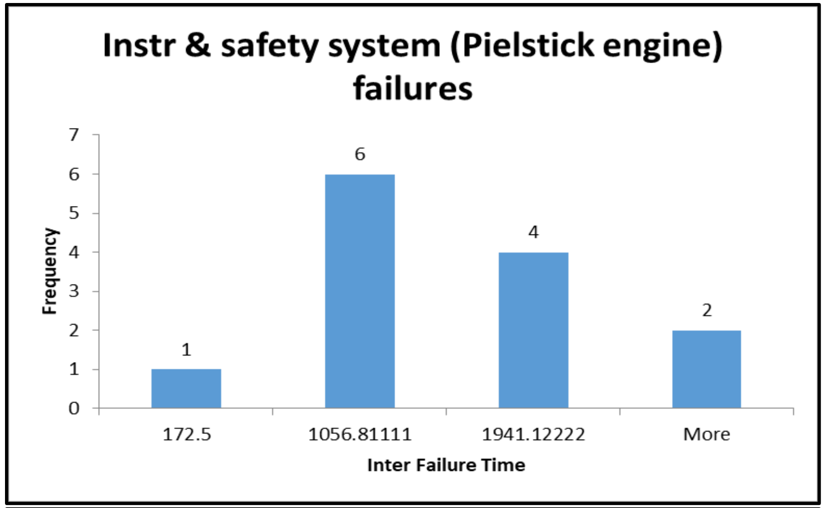
# Sub-system level Analysis

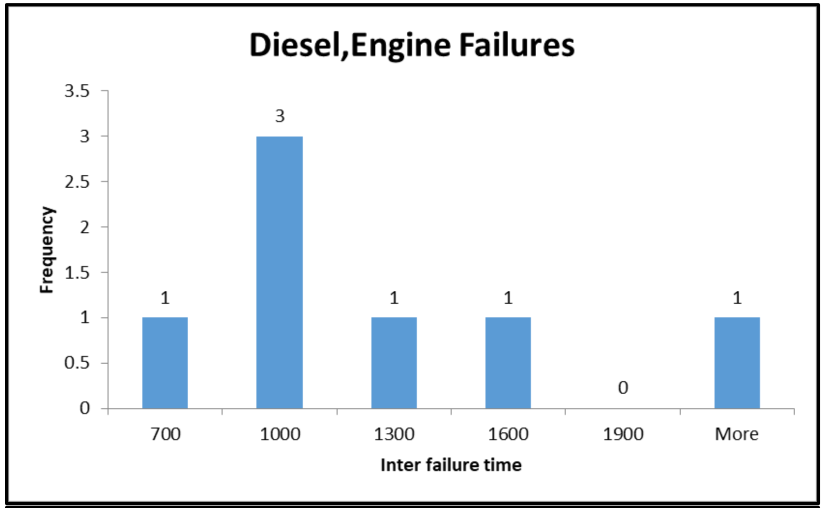


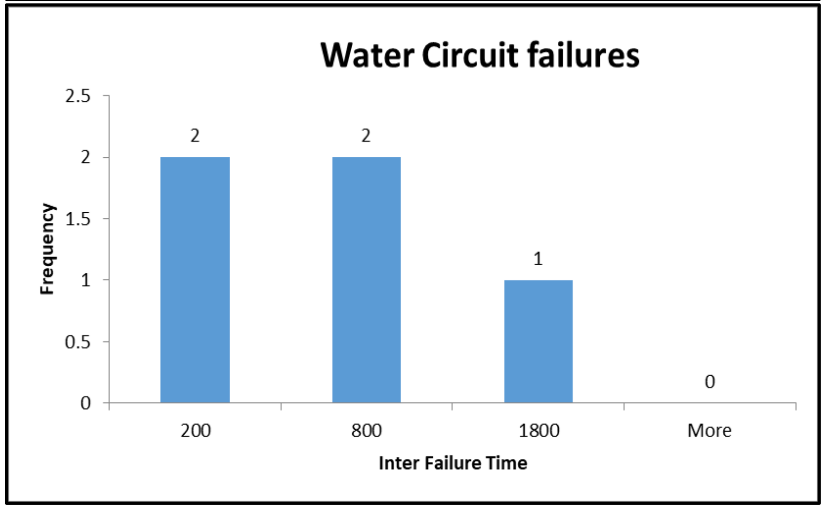
- Closer look at IFTs less than 33 hrs
- In one case two consecutive failures that were just 4 hours apart
- Was confirmed that they were different failures that belonged to independent subsystems (freshwater system, exhaust system & cylinder heads)
- Subsystem level histogram was plotted
- Instrument & Safety System failures, Engine, Diesel failures, Water circuit failures & exhaust system failures were chosen for further analysis

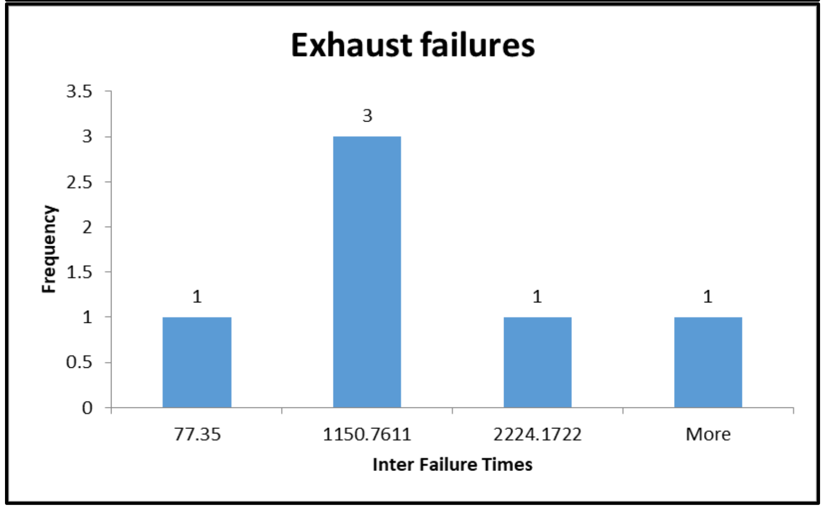


# Drilling down to failure modes




- Analysis of each failure mode by itself shows independent frequency distributions exhibit expected reliability characteristics
- **Inference:** Analyze each failure mode independently to model the behaviour of the whole PDE

# Failure mode-wise Weibull Analysis

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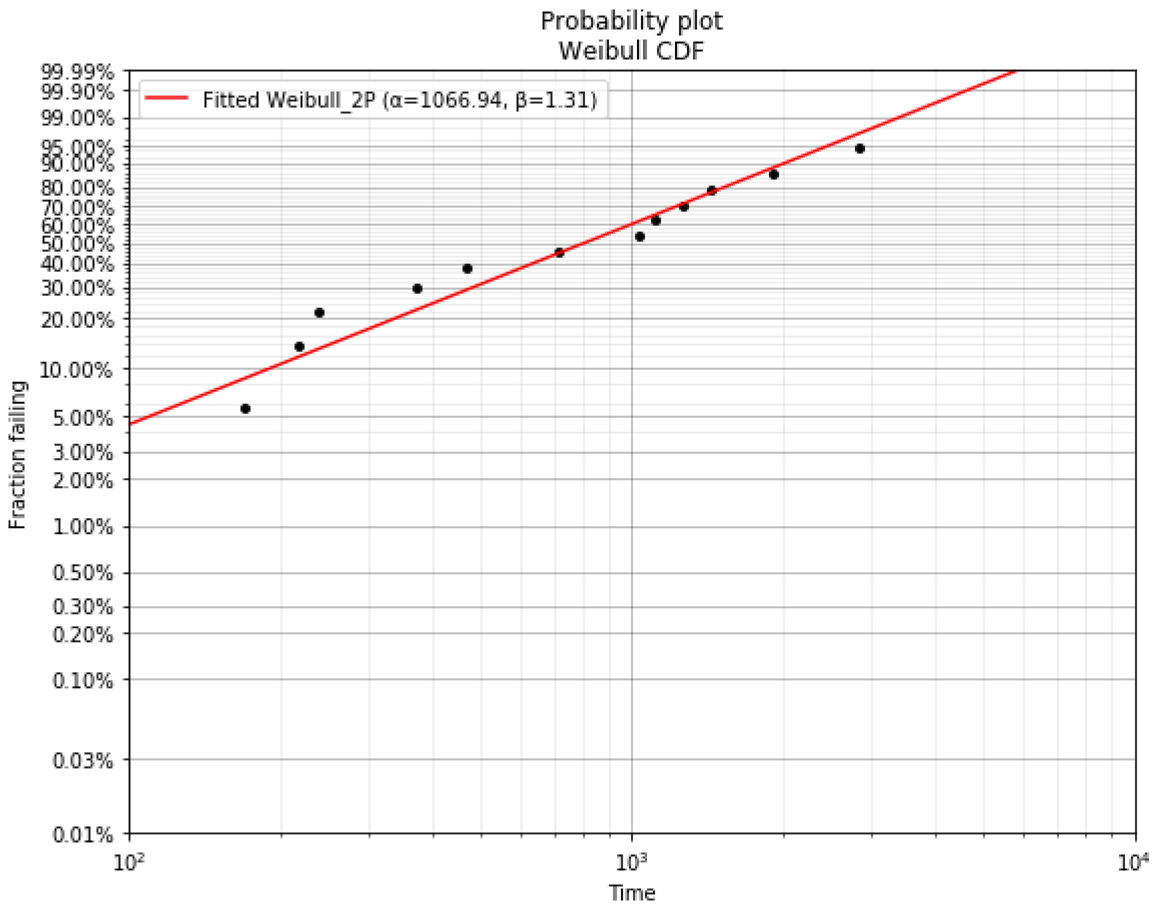
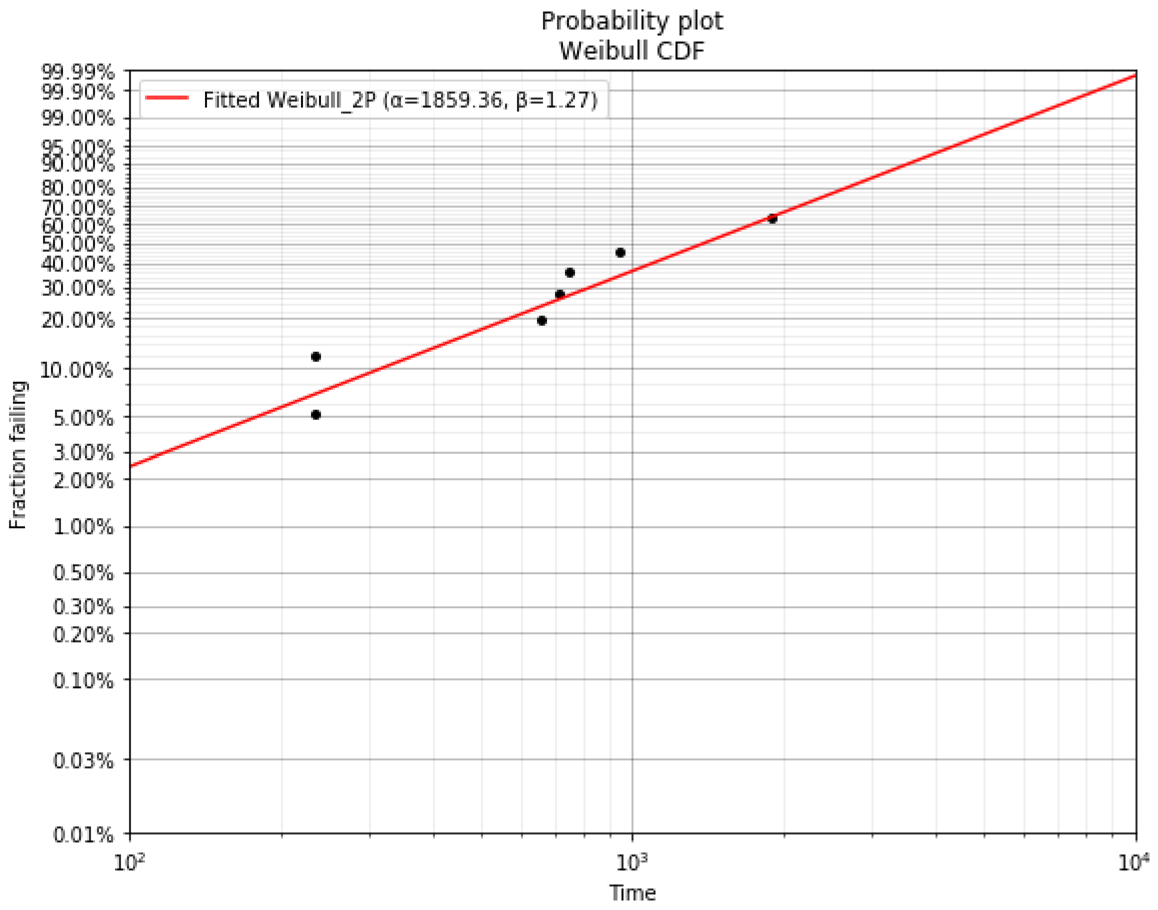
**Instrumentation & Safety System failure mode**




Shape factor: 1.31, Scale Factor: 1066.94

**Diesel, Engine failure mode**

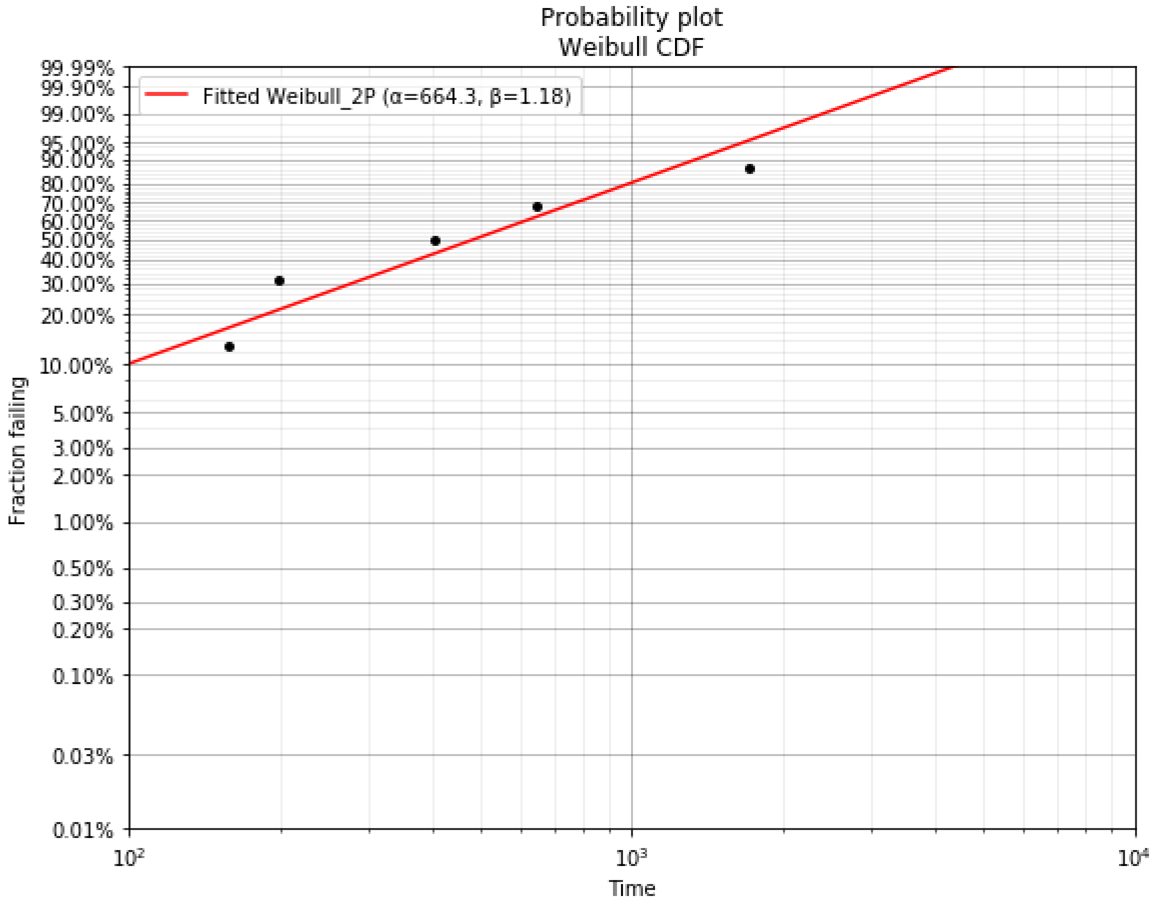



Shape factor: 1.27, Scale Factor: 1859.36

# Continued

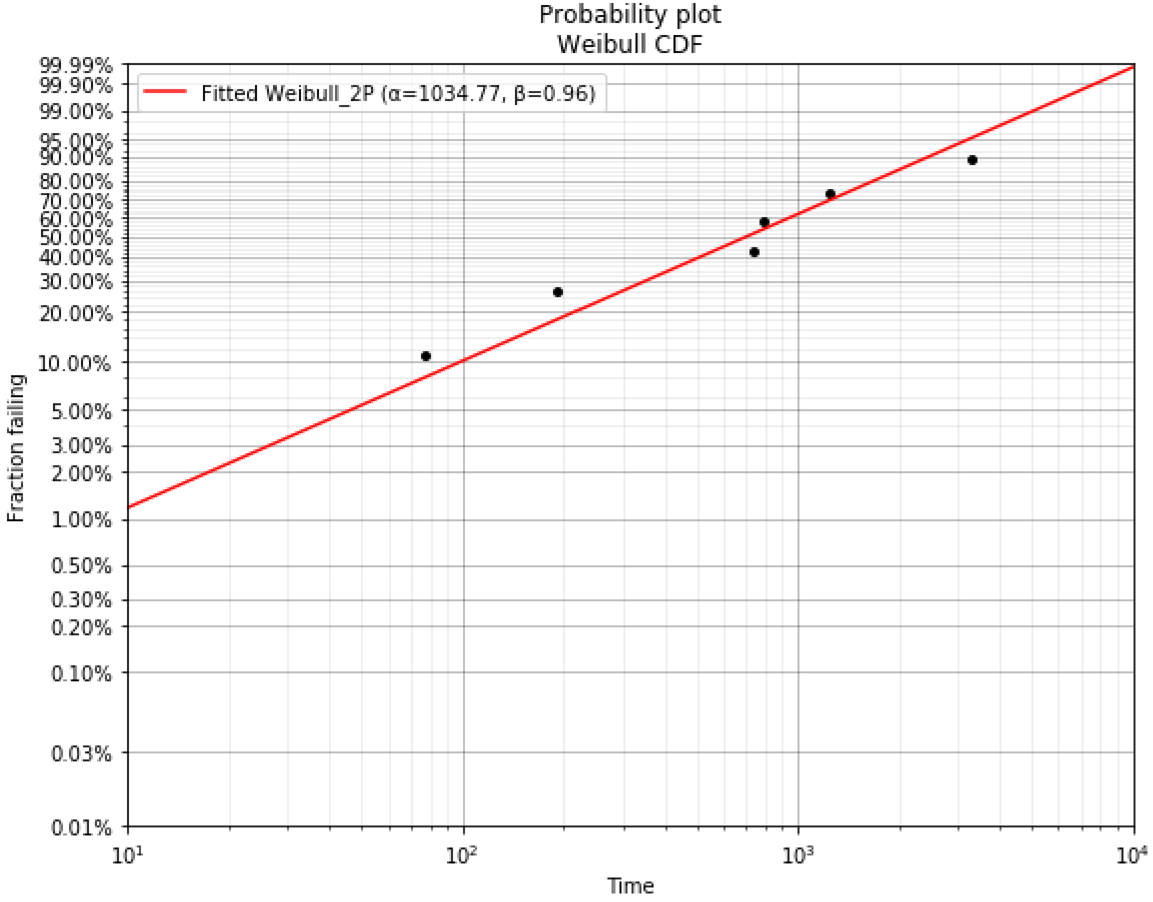


**Water Circuit failure mode**




Shape factor: 1.18, Scale Factor: 664

**Exhaust system failure mode**

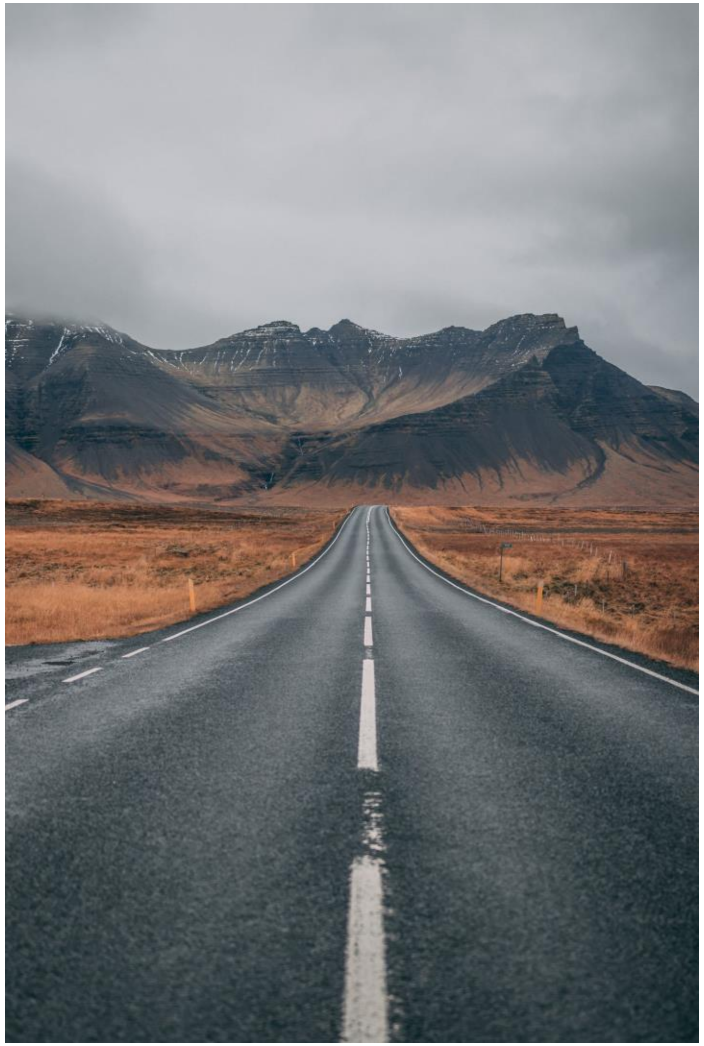



Shape factor: 0.96, Scale Factor: 1034.77

**Inference:** Weibull fit achieved & this proves hypothesis that failure modes need to be investigated separately

# Road Ahead...

- Analysis of failure modes with not more than one failure per ship
- Exploration of Marginal Analysis of independent failure modes to consolidate event data history
- Clean-up & preparation of Inspection data for covariate analysis
- Obtaining cost data for replacement and preventive maintenance activities



# Thank you!