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Method for Investigating Repair/Refurbishment Effectiveness

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Introduction

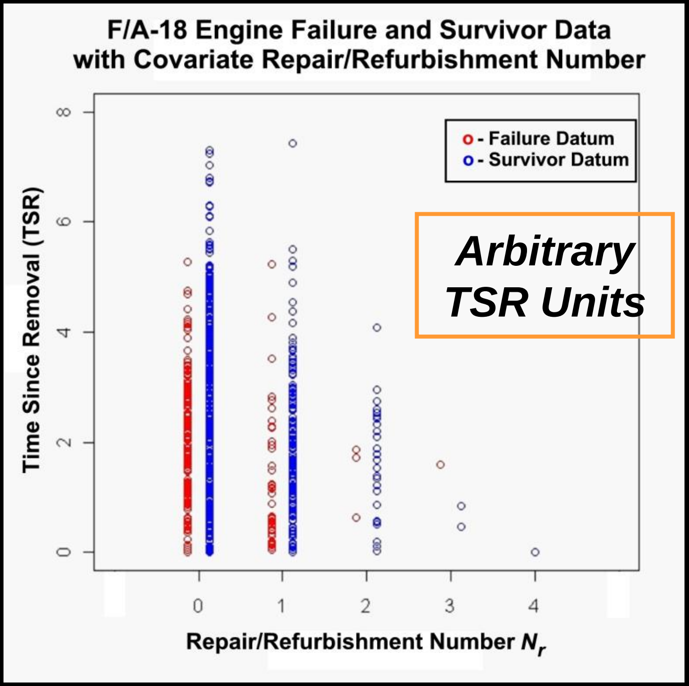
- **Modern Aerospace Systems Often Repaired when they Fail, and Returned to Service**
- **More Often, Repaired or Refurbished as Part of Preventative Maintenance and Returned to Service**
- **Questions:**
  1. ***Do the Repair/Refurbishments Improve, Degrade, or Not Alter Subsequent Reliability of the System?***
  2. ***If the Answer to Question 1 were Known, Could Preventative Maintenance Procedures be Improved?***
- **The F/A-18 E/F Super Hornet, General Electric F414 Low Bypass Gas Turbine Engine is Such a System**

The F/A-18 Engine Data

N_r	0	1	2	3	4	Totals
Failures	193	41	3	1	0	238
Survivors	421	140	29	2	1	593

N_r is the Number of Repair or Refurbishments

- N_r is Covariate to the Failure and Survivor Data
- Over 71% of Data was Survivors
- Numbers of Data Fell Off Rapidly with increasing N_r
- Fall Off of Number of Failures with increasing N_r Suggests Reliability may Improve with Repeated Repair/Refurbishment



A Novel Modeling Approach

- Modify a Standard ***Weibull*** Model to take Advantage of the Information Contained in the Associated Covariate Number of Repair/Refurbishments
  - Modification Should Provide Some ***Physical Insight*** into the Data (with the Covariate as well)
  - Modification Should Allow Improvements, Degradations, or Stable Reliability as a Function of Increasing N_r
- ***Solution:*** **Convert Weibull Parameters into Exponential Functions of N_r Introducing Four New Parameters η_0, β_0, η_c, *and* β_c**

$$\eta\left(N_r\right)=\eta_0 * e^{\eta_c * N_r};\ \beta\left(N_r\right)=\beta_0 * e^{\beta_c * N_r}$$

The Covariate Weibull Model

- **Covariate Weibull Parameters:** $\eta(N_r) = \eta_0 * e^{\eta_c * N_r}$; $\beta(N_r) = \beta_0 * e^{\beta_c * N_r}$
- **When N_r = 0, $\eta(N_r) = \eta_0$ and $\beta(N_r) = \beta_0$ - Standard Weibull**
- **When η_c = 0, *Critical Life* is Constant with Increasing N_r**
- **When β_c = 0, Failure Mode is Constant with Increasing N_r**
- **As $\eta_c \to -\infty$, $\eta(N_r) \to 0$, $\beta_c \to -\infty$, $\beta(N_r) \to 0$**
- **As $\eta_c \to \infty$, $\eta(N_r) \to \infty$, $\beta_c \to \infty$, $\beta(N_r) \to \infty$**

$\eta(N_r)$ and $\beta(N_r)$ Behave Properly!

- **The Resultant Covariate Weibull Model is Somewhat *More Complex* than the Standard Weibull Model**

$$pd(t_f \mid N_r, \eta_0, \beta_0, \eta_c, \beta_c)$$

$$= \left(\frac{\beta_0 * e^{\beta_c * N_r}}{\eta_0 * e^{\eta_c * N_r}} \right) \left(\frac{t_f}{\eta_0 * e^{\eta_c * N_r}} \right)^{\beta_0 * e^{\beta_c * N_r} - 1} e^{-\left(\frac{t_f}{\eta_0 * e^{\eta_c * N_r}} \right)^{\beta_0 * e^{\beta_c * N_r}}}$$

The Impact of the Covariate Weibull Model

- Reliability is now a Function of Time and N_r

$$R(T \mid N_r, \eta_0, \beta_0, \eta_c, \beta_c) = e^{-\left(\frac{T}{\eta_0 * e^{\eta_c * N_r}}\right)^{\beta_0 * e^{\beta_c * N_r}}}$$

- The Uncertainty Model for Reliability as a Function of Time and N_r is Related to the Joint Uncertainty Model for η_0, β_0, η_c, *and* β_c
- No Classical Method Exists to Infer Statistically from the Covariate Data the Joint Uncertainty Model for η_0, β_0, η_c, *and* β_c
- But, Conditional Methods Enable this Inference
  - Without Unnecessary Assumptions
  - Producing the Full Four Dimensional Joint Uncertainty Model for η_0, β_0, η_c, *and* β_c

Joint Uncertainty Model for η_0, β_0, η_c, and β_c

- Using *Ignorance Priors* for all Parameters, The Joint Uncertainty Model for η_0, β_0, η_c, *and* β_c is:

$$pd\left(\eta_0,\beta_0,\eta_c,\beta_c \mid data\right)$$

$$\propto \left[\prod_{i=1}^{N_f}\left(\frac{\beta_0 * e^{\beta_c * N_{rfi}}}{\eta_0 * e^{\eta_c * N_{rfi}}}\right)\left(\frac{TSR_{fi}}{\eta_0 * e^{\eta_c * N_{rfi}}}\right)^{\left(\beta_0 * e^{\beta_c * N_{rfi}} - 1\right)} * e^{-\left(\frac{TSR_{fi}}{\eta_0 * e^{\eta_c * N_{rfi}}}\right)^{\beta_0 * e^{\beta_c * N_{rfi}}}}\right] * \left[\prod_{j=1}^{N_s} e^{-\left(\frac{TSR_{sj}}{\eta_0 * e^{\eta_c * N_{rsj}}}\right)^{\beta_0 * e^{\beta_c * N_{rsj}}}}\right] * \left(\frac{1}{\eta_0}\right) * \left(\frac{1}{\beta_0}\right)$$

with TSR_{fi} being the time since repair of the i^{th} failure with covariate number of repairs N_{rfi}, and TSR_{sj} being the time since repair of the j^{th} survivor with covariate number of repairs/refurbishments N_{rsj}.

- Markov Chain Monte Carlo (*MCMC*) Methods May be Used to Sample this Four Dimensional Joint Uncertainty Model
- These Joint Samples of η_0, β_0, η_c, *and* β_c Provide Samples of Covariate Reliability Uncertainty Model

Covariate Reliability Uncertainty Model

- **The Covariate Reliability Uncertainty Model Resultant from the Covariate Data is *Easy to Formulate***

$$pd\left(R\left(T \mid N_r, \eta_0, \beta_0, \eta_c, \beta_c\right) \mid data\right) = R\left(T \mid N_r, \eta_0, \beta_0, \eta_c, \beta_c\right) * pd\left(\eta_0, \beta_0, \eta_c, \beta_c \mid data\right)$$

- **But, Really only Interested in the Reliability as a Function of Time and N_r based on the Data (not η_0, β_0, η_c, *and* β_c)**
- **Can Obtain via Marginalization Integrals**

$$pd\left(R\left(T \mid N_r\right) \mid data\right)$$

$$= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{0}^{\infty} \int_{0}^{\infty} pd\left(R\left(T \mid N_r, \eta_0, \beta_0, \eta_c, \beta_c\right) \mid data\right) * d\eta_0 \, d\beta_0 \, d\eta_c \, d\beta_c$$

$$= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{0}^{\infty} \int_{0}^{\infty} R\left(T \mid N_r, \eta_0, \beta_0, \eta_c, \beta_c\right) * pd\left(\eta_0, \beta_0, \eta_c, \beta_c \mid data\right) d\eta_0 \, d\beta_0 \, d\eta_c \, d\beta_c$$

This All Looks Impossible!

- **But it isn't!**
  - **With *M* Joint *MCMC* Samples of η_0, β_0, η_c, *and* β_c, these Marginalization Integrals are Easy**
  - **Example: Suppose you wanted to know the *Risk*, based on the Data, that the Reliability at *T* = 2 would not exceed 90% after Two Repair/refurbishments, N_r = 2**

- **Simply Evaluate the Covariate Reliability Function at Joint Samples of η_0, β_0, η_c, *and* β_c, with N_r = 2 and *T* = 2, to Obtain *M* Reliability Samples**
- **Count the Number of These < 0.9 and Divide by *M***

$$P\left(R\left(T=2\,|\,N_r=2\right)<0.9\,|\,data\right)=\frac{\sum_{i=1}^{M}\left[\begin{array}{l} 1\left|\left(e^{-\left(\frac{2}{\eta_{0i}*e^{\eta_{ci}*2}}\right)^{\beta_{0i}*e^{\beta_{ci}*2}}}<0.9\right)\right. \\ 0\left|\left(e^{-\left(\frac{2}{\eta_{0i}*e^{\eta_{ci}*2}}\right)^{\beta_{0i}*e^{\beta_{ci}*2}}}\geq 0.9\right)\right.\end{array}\right]}{M}$$

Sounds Good in Theory

- Really Should *Validate* the Concept
  - Pick Representative Values of η_0, β_0, η_c, *and* β_c to use as a Truth Model
  - Generate Set of Failure and Survivor Data for Various N_r
  - Formulate and Run the *MCMC*
  - Compare *MCMC* Joint Samples of η_0, β_0, η_c, *and* β_c based on the Generated Data with True Values

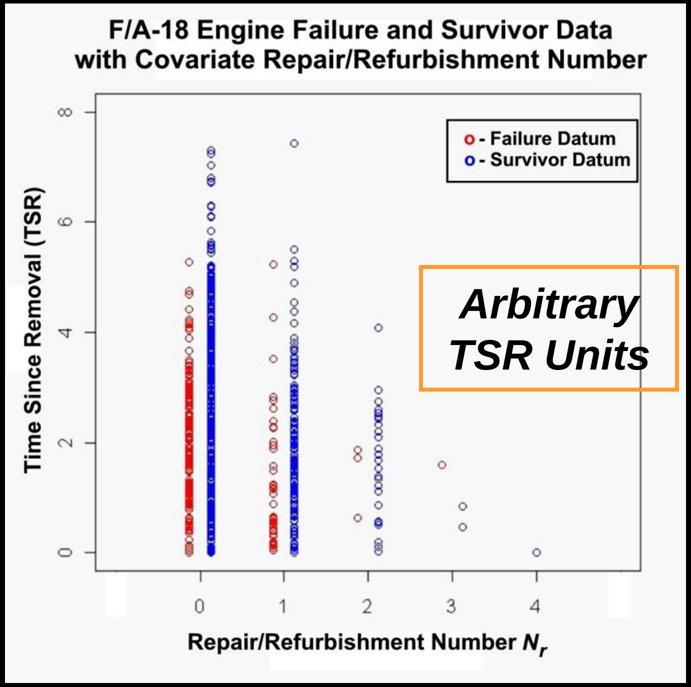
Validation Data Numbers

N_r	0	1	2	3
Failures	794	798	773	792
Survivors	206	202	227	208

Validation Statistics

Parameter	Minimum	Maximum	Mean (True)	σ
η_0	273.9	318.6	295.4 (300)	6.58
β_0	1.38	1.66	1.49 (1.5)	0.039
η_c	-0.162	-0.040	-0.105 (-0.1014)	0.017
β_c	-0.315	-0.214	-0.264 (-0.2747)	0.014

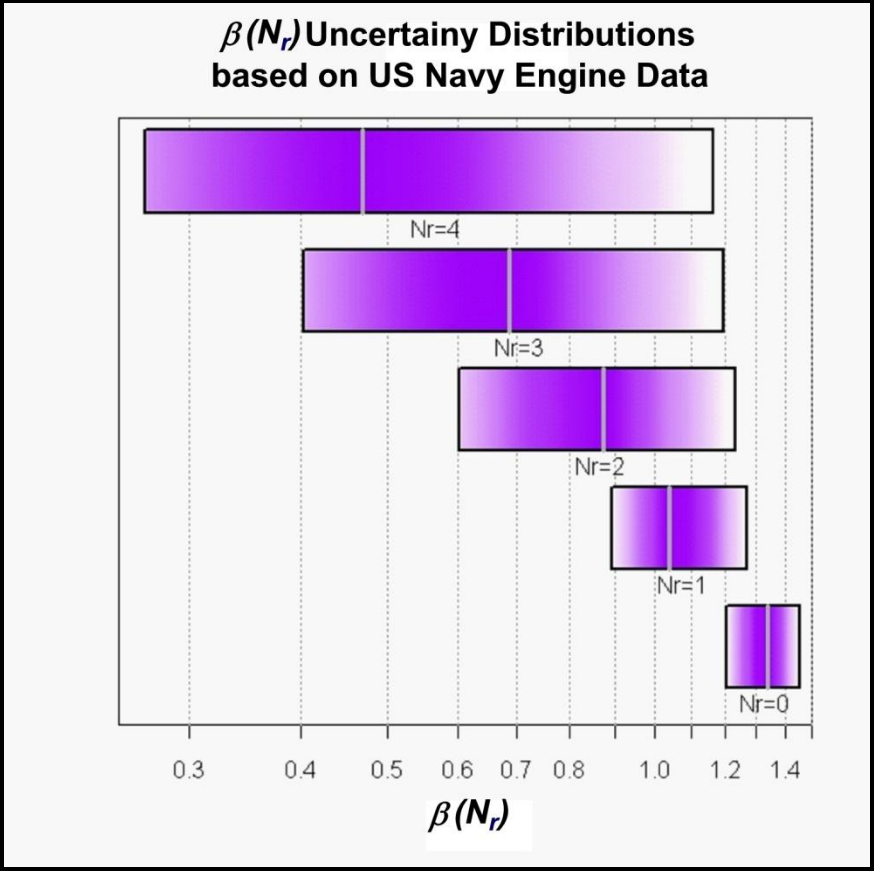
Processing the F/A-18 Engine Data



Statistics from 10,000 Joint *MCMC* Samples of η_0, β_0, η_c, *and* β_c from the F/A-18 Engine Data

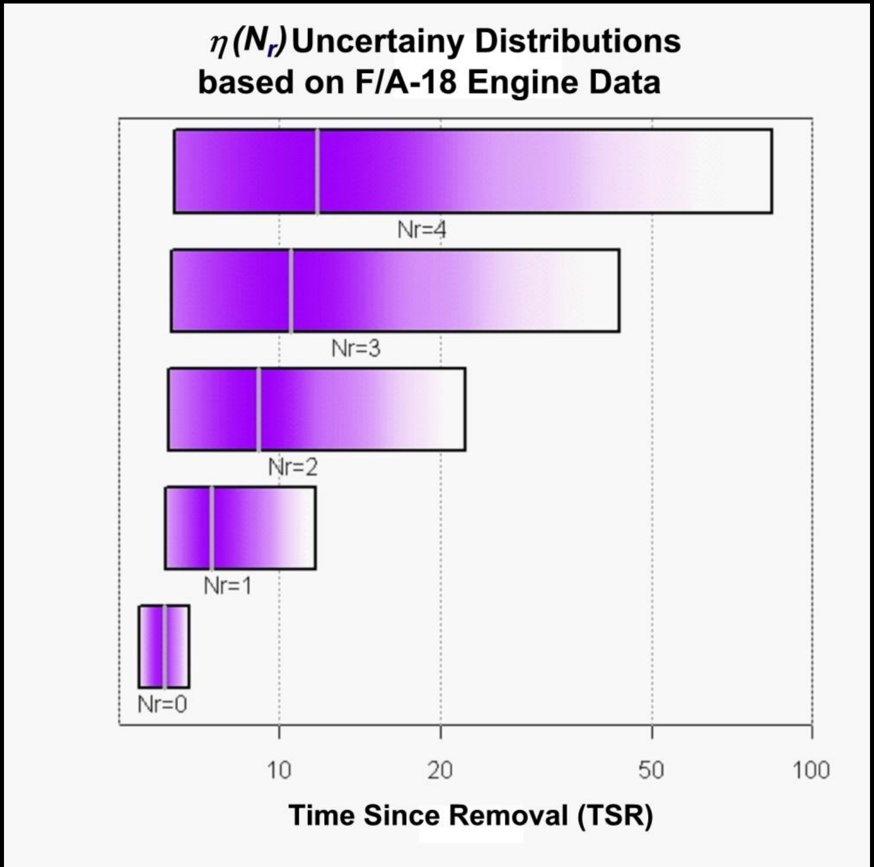
Parameter	Minimum	Maximum	Mean	σ
η_0	4.77	7.47	6.06	0.407
β_0	1.09	1.56	1.33	0.079
η_c	-0.216	1.127	0.303	0.210
β_c	-0.693	0.211	-0.220	0.126

What Does it Mean for F/A-18 Failure Modes?



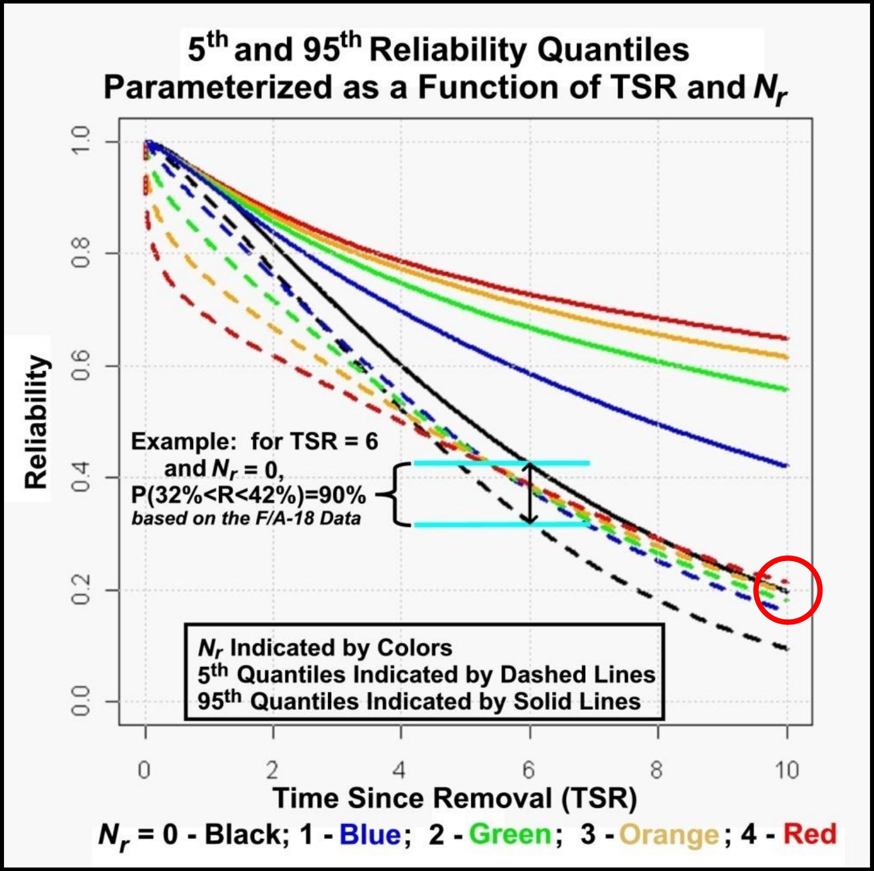
- **F/A-18 Engine Failure Modes Trend More to *Infant Mortality* as N_r Increases**
- **Uncertainty on Failure Mode Increases as N_r Increases**
- **Median F/A-18 Engine Failure Modes Trend More Dramatically to Infant Mortality as N_r Increases**

What Does it Mean for F/A-18 Critical Life?



- **F/A-18 Engine *Critical Life* Increases as N_r Increases**
- **Uncertainty for *Critical Life* Increases as N_r Increases**
- **Median F/A-18 Engine *Critical Life* Increases Exponentially as N_r Increases**
- **More Probability *Meat* at Higher Values**

What Does it Mean for F/A-18 Reliability?

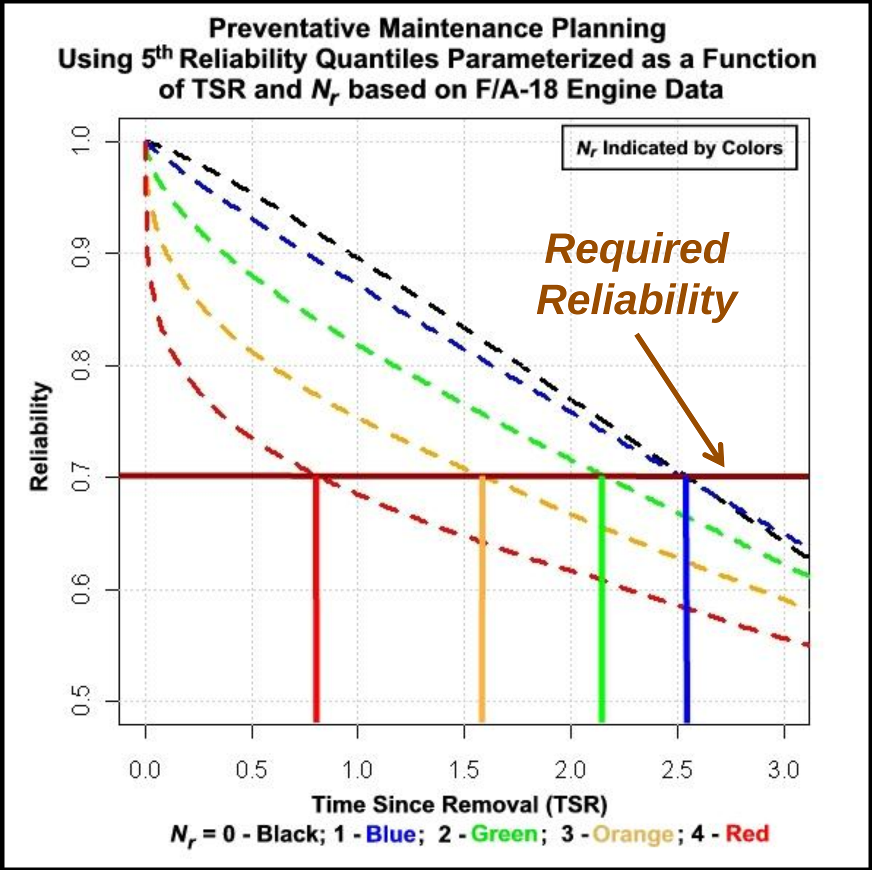


- **95th Quantile Reliabilities Increase as N_r Increases**
- **5th Quantile Reliabilities behave *Non-Intuitively***
  - **At TSR = 10, 95% Probability that Reliability < 20% with N_r = 0, based on the Data**
  - **At TSR = 10, 95% Probability that Reliability > 20% with N_r = 4, based on the Data**

What Could it Mean for F/A-18 PM Planning?

Hypothetical Example:

- Suppose Required Reliability was 70% for Mission Length of 0.5 in TSR Units
- Suppose *Maximum Acceptable Risk* of Achieving 70% Reliability for this Mission was 5%
- Vertical Lines Show Maximum PM Intervals Based on Data and N_r that Meet the Reliability at Risk Level



Conclusions

1. **Covariate Weibull Model Used with Conditional Inferential and *MCMC* Methods Can Provide Insights into Reliability as a Function of Successive Repair/refurbishments**
2. **For the F/A-18 Engine Covariate Data, 95% Sure that *Critical Life* Increases with Successive Repair/refurbishments**
3. **For the F/A-18 Engine Covariate Data, 97% Sure that Failure Mode Moves towards *Infant Mortality* with Successive Repair/refurbishments**

More Conclusions

4. **Based on Hypothetical Example, Availability, Mission Assurance, and Operational Effectiveness Could be Potentially Improved for the F/A-18 Engine**
5. **The *MCMC* Samples Obtained via the F/A-18 Engine Data Can be Used to Obtain an Optimal Cost Preventative Maintenance Scheme**
6. **Non-Intuitive Results thus Obtained Justify Collection of Additional Data to Better Understand What Drives Them**
7. **This Method may be Used for Any Aerospace System that is Returned to Service after Successive Repair/refurbishments**

Final Summary

- A Novel Approach to Investigating Repair/refurbishment Effectiveness Developed, Validated, and Used for the F/A-18 Engine
- Interesting, Potentially Useful, and Some Non-intuitive Results were Obtained for the F/A-18 Engine Covariate Data
- Problems with RCM or PHM that Just Seem Impossible to Solve?

If you Have Data, Contact Me!

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