National Aeronautics and Space Administration

NASA Physics of Failure (PoF) Handbook Update

June 3, 2024

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For the PoF Handbook Development Team: Jeff Dawson (GSFC), Nobel Sindjui (GSFC), Doug Sheldon (JPL), Nancy Lindsey (HQ/GSFC), Anthony DiVenti (NASA R&M Technical Fellow), and many contributing authors

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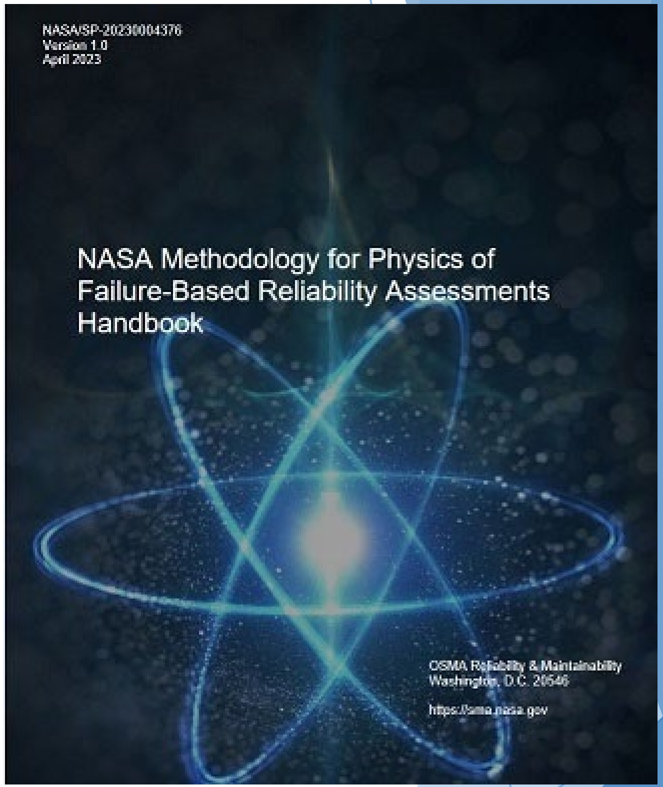
MASCD

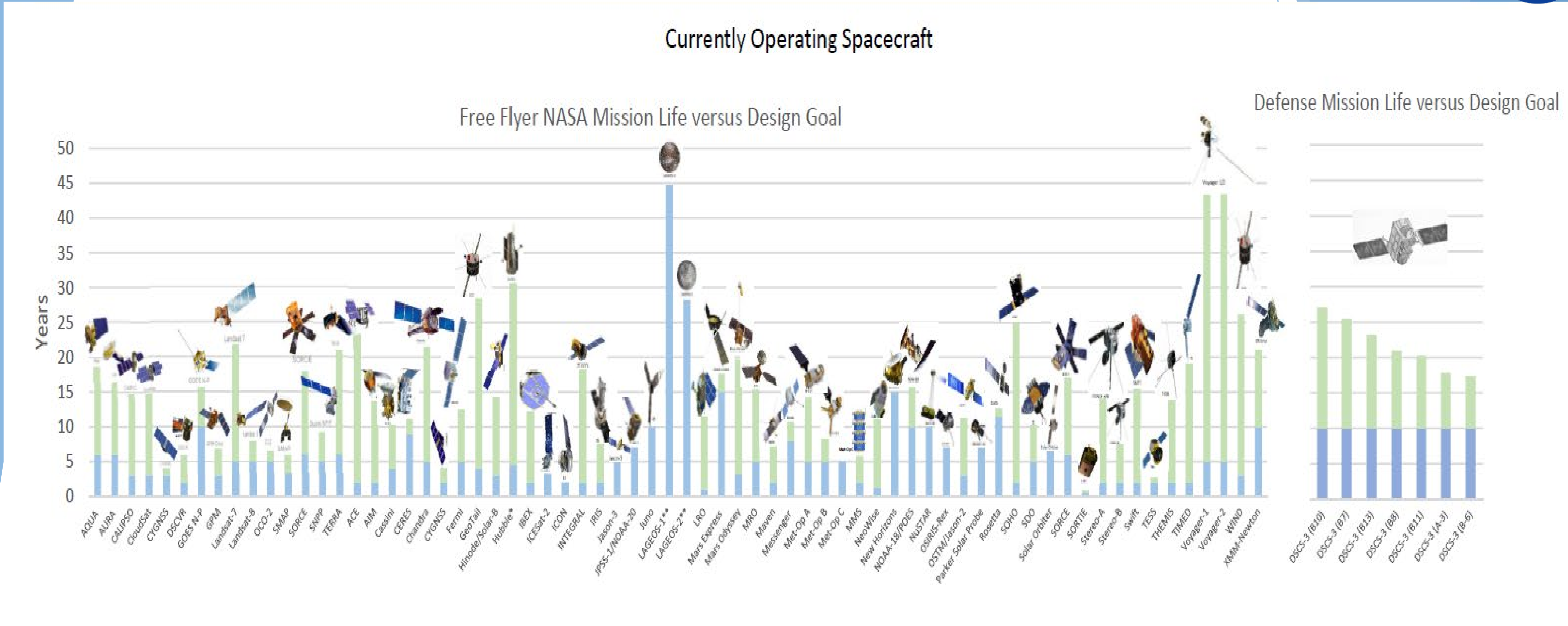
Outline

- Why Physics of Failure ?
- Physics of Failure (PoF) Handbook (NASA/SP-20230004376)
- PoF Use & Examples
- How can the Community Contribute?
- Questions



https://ntrs.nasa.gov/citations/20230004376

Why Physics of Failure (PoF)?

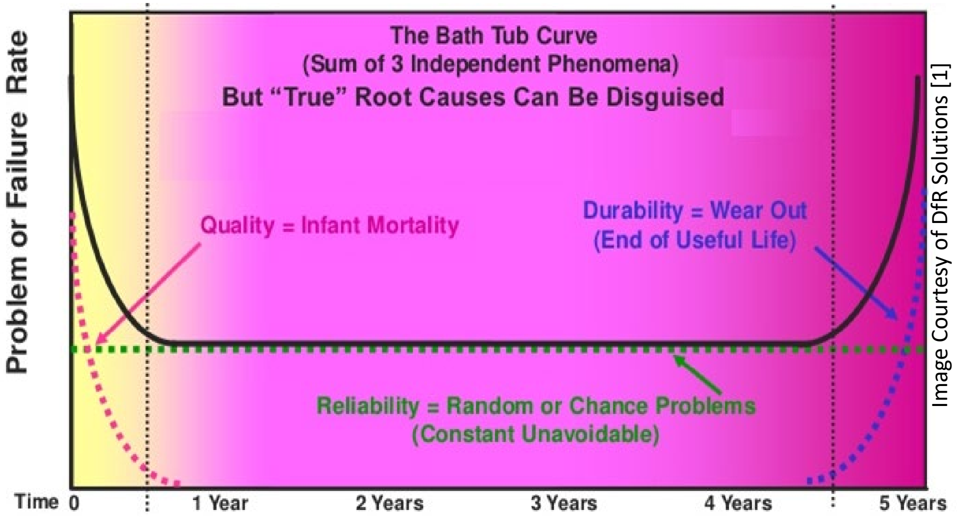


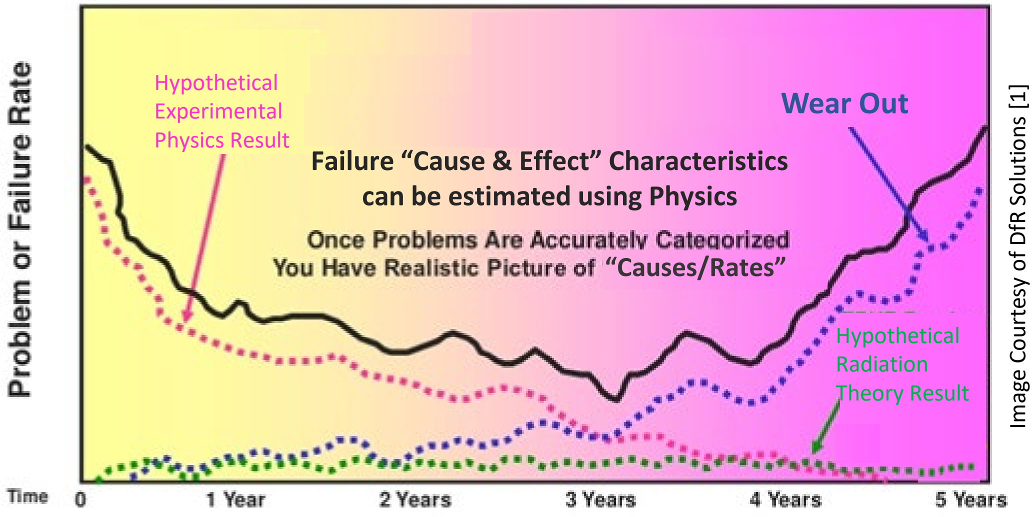
Unrealistically conservative estimations of life are being assumed based on our highly conservative predictions.

Why Physics of Failure (PoF)?

Transition from bathtub curve assumptions

to Root Cause Models for more realistic risk assessments.





$$\sum_{L=1}^{All}$$

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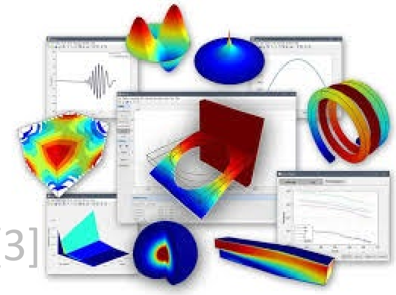

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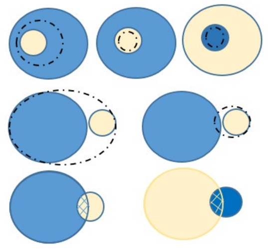

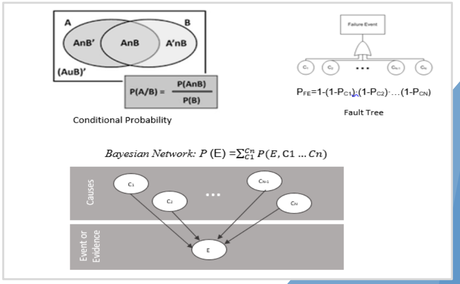

[5]

(…………………………………………………………. Data/Models…………………………………………………………)

(………… Likelihood Relationships and Statistical Fusion Processes……………)

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NASA Physics of Failure (PoF) Handbook

NASA/SP-20230004376

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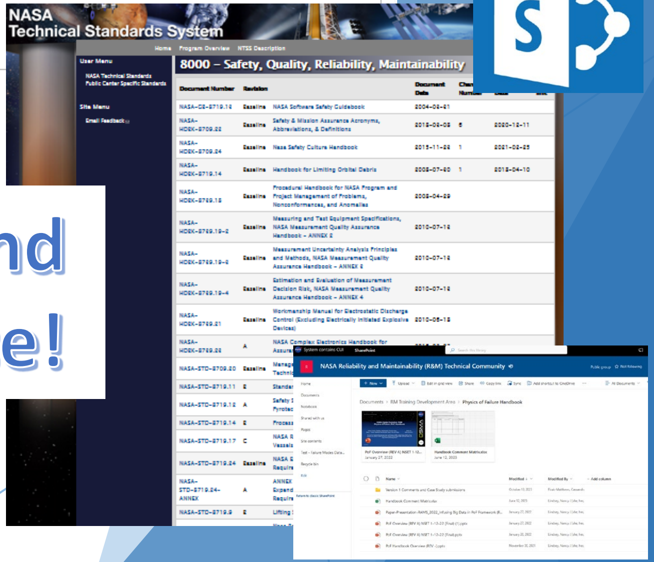
Empirical: Analysis methods that study the failure history of parts under given conditions, then fits the failure data to a probability distribution. Responsive to new concepts.

Deterministic: Analysis methods that involve the study of the predicted underlying physical processes/causes that could cause failure and results in a mathematical relationship describing the failure potential. Responsive to new concepts.

Aggregation: Using a single method or multiple methods concurrently with or in lieu of reference rates (e.g., handbook data) to develop system failure likelihood using statistical techniques and considering dependencies of individual findings. . Responsive to capability/concept advancement uncertainties, model-based, etc.

Future: Technology advancement infusion of Multiphysics tools, Artificial Intelligence, and Machine Learning.

Case Studies: NASA examples of application (separate and controllable); Ever increasing set – Community sourcing!



Share and Advance!

Assurance Standards and Capabilities Division
OSMA HQ-GD000

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Physics of Failure (PoF) Use & Examples

1. Frame Overall Analysis goal and seek/evaluate data available(susceptibilities (process or mechanisms), exposures/stresses, in-situ/planned use/design configuration).
2. Match data with appropriate PoF methodologies to derive a likelihood of failure from the specific data.
3. Create model(s) that captures system and is compatible with PoF method.
4. Validate if model is a “digital twin” with sufficient details for the system being analyzed.
5. Evaluate likelihood of failure result for accuracy and relationship of the specific data driven likelihood to other results or data.
6. Determine if all plausible failure scenarios/modes have been evaluated and if all data has been used.
7. Aggregate results and any reference data that may still be applicable to determine overall likelihood distribution or point estimate for the goal (mode/scenario likelihood of occurrence.
8. Communicate findings and Uncertainties with customer and iterate as warranted.
9. Share handbook Case Studies; corrections and update recommendation with Handbook Custodians.

SEE CHAPTERS 3, 4, AND CASE STUDY APPENDIX

SEE CHAPTER 5

HANDBOOK UPDATES OR TECHNOLOGY INNOVATION (See CHAPTER 6)

Mission Use Case

1) Estimate failure probability of Payload with history on similar missions of 7,127,352 hrs and no failures

2) Estimate failure probability a structural failure mode in a PWB/ PWB part on a Sounding Rocket or life with planned stress exposure

3) A mission system is planning to use a proven and well-known terrestrial component (Ps =0.8 at the mission duration) in a space application, and it has been determined via radiation susceptibility testing, that the probability of failure from radiation, Pf, equals 0.7. What is the full Pf?

Approach/Result

1) Bayes’ estimation

$$\delta = \frac{1}{[CoV\,(\lambda)]^2} = 4$$

$$E(\lambda) = 1.33\ x\ 10^{-6} [Parts\ Count\ Failure\ Rate].$$

$$\rho = \frac{\delta}{E(\lambda)} = 3.01\ x10^{6}\ \ hours$$

$$T = 7{,}127{,}352\ hrs\ \ and\ the\ number\ of\ failures\ r\ = 0$$

$$\lambda_{Bayesian} = \frac{\delta'}{\rho'} = \frac{\delta + r}{\rho + T} = 3.95x10^{-7}\left(\frac{1}{hours}\right).$$

2) Fatigue Analysis estimation

Board: disconnect/failure in 1.71E3 hours

Site ID	Failure Mode	Damage Ratio
RL1	interconnect-open	5.85E-01
RL3	interconnect-open	4.68E-01
LS1	interconnect-open	2.69E-01
LS3	interconnect-open	2.60E-01
D4	solder-open	7.06E-02
D2	solder-open	3.92E-02
J762	interconnect-open	1.86E-02
LS2	interconnect-open	1.74E-02
J763	interconnect-open	1.49E-02
D6	solder-open	1.42E-02

Part hours to failure 6.62E1

Part Id:	U9
Condition Name:	stress_1
Conditon Number:	1
Damage Ratio:	15.114873
Damage:	1.511487e+001
Applied Time:	1000.000000 hrs
Days to failure:	*2.76E0*
Hrs to failure:	6.62E1
Max. PSD:	0.020543

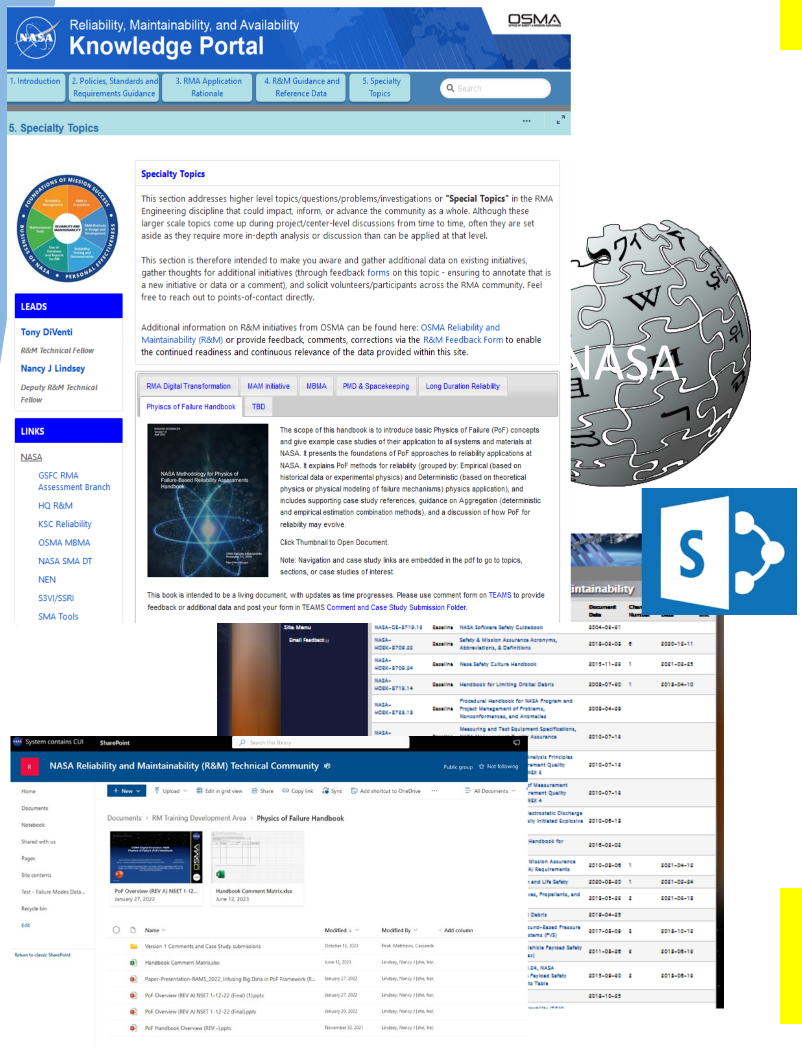
3) Assuming that the terrestrial and radiation failure mechanisms are independent or disjointed, and would use a fault tree or a Bayesian network to find Pf:

$$(1\text{-}P_{ST}) + Pf_R - Pf_{TANDR} = 0.2 + 0.7\text{-}\ (0.7*0.2) = 0.76$$

$$\sum (P(F|T, R) = (P(F|R)*Pf_R *1\text{-}Pf_T) + (P(F|T)*\ Pf_T * 1\text{-}Pf_R) + (P(F|(R|T))*(Pf_R *Pf_T)*(1\text{-}Pf_{others}))$$

$$\sum (P(F|T, R) = 1*0.7*0.8 + 1*0.2*0.3) + (1*(0.7*0.2)*1) = 0.76$$

Community Engagement for R&M Physics of Failure (PoF) Handbook Advancement/Continued Evolution



Use PoF Methods in Mission Work

RMA: PoF Handbook on NASA RMA Knowledge Portal (https://rmakp.nasa.gov/display/RMAKP/5.+Specialty+Topics#tabs-6) and SharePoint (https://nasa.sharepoint.com/teams/Reliability930/Shared%20Documents/Forms/AllItems.aspx?csf=1&web=1&e=yqhHiB&CID=cc906f35%2D98aa%2D46f7%2Db770%2D1afb8a5c99fa&FolderCTID=0x012000C152158E956F544CAF8CF887EDB162DE&id=%2Fteams%2FReliability930%2FShared%20Documents%2FRM%20Training%20Development%20Area%2FPhysics%20of%20Failure%20Handbook)

SMA: Continue to share existence and solicit feedback/participation in the community of practice via conferences and discipline peers. Gather data/Case Studies

Engineering: Share on other virtual/collaboration platforms. Conduct research and synthesize experience data. Establish a formal Community of Practice or become a branch from another one like NSET? Or NESC? Gather data/Case Studies

NASA/NEPP: Share on other virtual/collaboration platforms. Maintain handbook as a formal NASA handbook. Add Methodology to STEP/SATERN. Conduct research and synthesize experience data. Gather data/Case Studies

Industry/Academia/Partners: Share with and gather data/Case Studies at Conferences.

We are counting on All of NASA and beyond to participate/ support continued research and data sharing!

Questions

Backup

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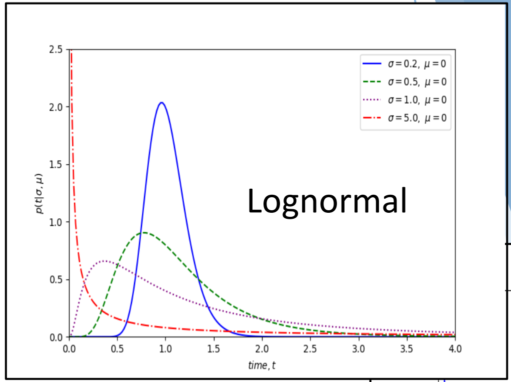
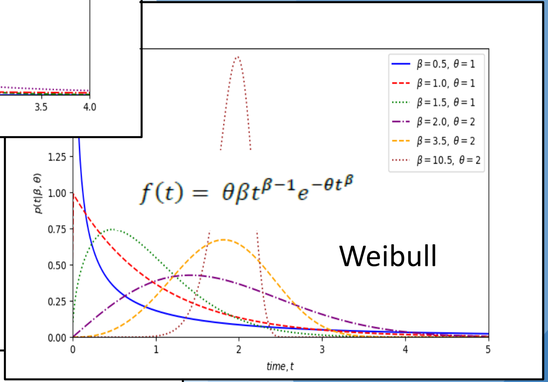
Case Studies: NASA examples of application (separate and controllable); Ever increasing set – Community sourcing!

Empirical analysis uses operations and experimentation that exposes a system to multiple branches of physics (e.g., Thermodynamics, Kinematic/Static Mechanics, Acoustics, Fluids, Optics, Electrical) and the exhibited performance can be used to formulate the likelihood of failure of like systems under similar exposures using statistical approximations (e.g., Normal, Lognormal, Weibull, Thermal, Bayesian, Electromigration).





Thermal/Electrical

$$L_{med} = \left[\frac{A}{J^n}\right] \cdot exp\left[-\frac{E^*}{k_B T}\right],$$

$$t_f = A(RH)^{-n} e^{\frac{Ea}{kT}}$$

Bayesian

$$\lambda_{Bayesian} = \frac{\delta'}{\rho'} = \frac{\delta + r}{\rho + T}$$

$$\text{given } \rho = \frac{\delta}{E(\lambda)} \text{ and } \delta = \frac{1}{[CoV(\lambda)]}$$

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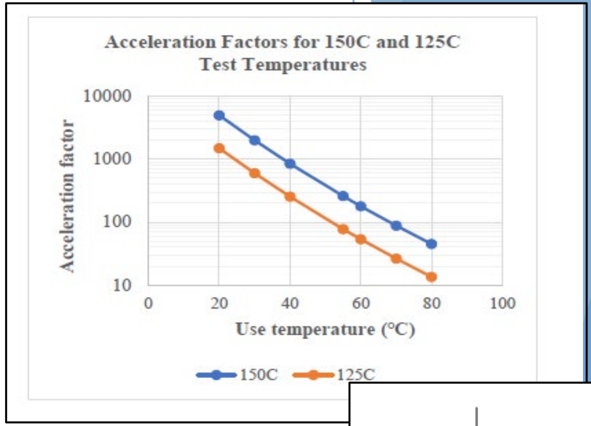
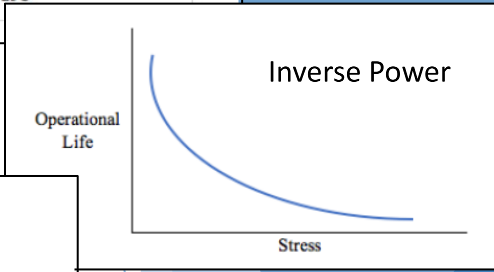
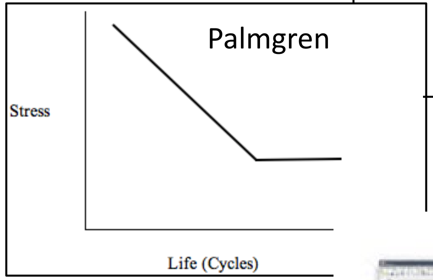
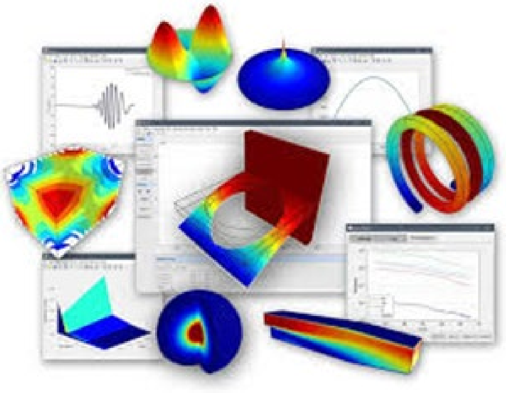
Case Studies: NASA examples of application (separate and controllable); Ever increasing set – Community sourcing!

Deterministic analysis uses the theories of physics (e.g., Thermodynamics, Kinematic/Static Mechanics, Acoustics, Fluids, Optics, Electrical) to formulate the likelihood of failure based on hypothetical or non-use-case (accelerated performance) exposures. These analysis depend on detailed system models and an understanding of the phenomenon that contribute to eventual or sudden failure of a system to formulate a prediction.









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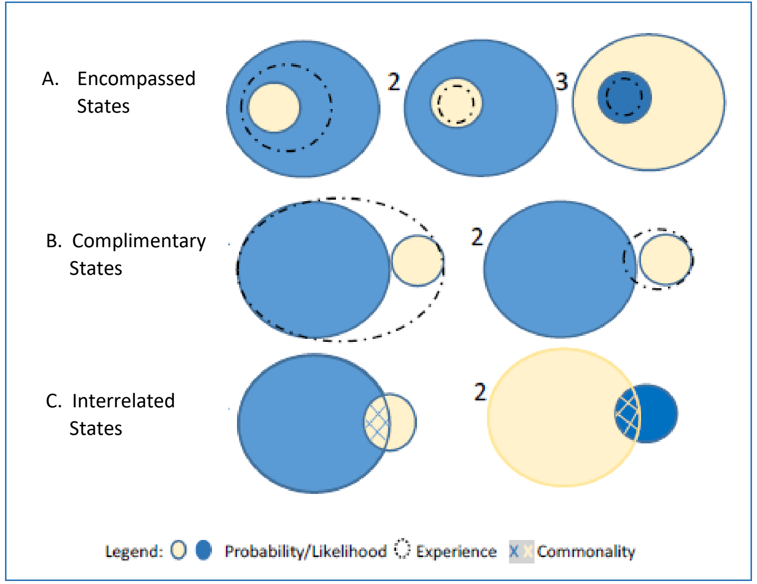
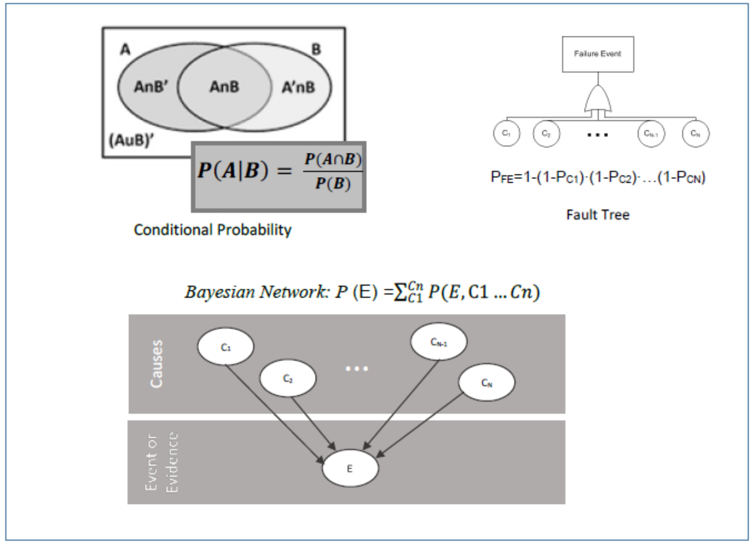
Empirical and Deterministic analyses are not necessarily mutually exclusive and can either independently or in combination inform the final likelihood of failure assumed for a system. Considering this, it is important for the analyst to evaluate the magnitude, independence, and dependence of each likelihood given by each physics of failure methodology on a case-by-case basis, so that statistical techniques, such as Fault Trees, Bayesian Networks, or Conditional Probability can be applied once or multiple times until all likelihoods are combined or considered.





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Future: Technology advancement infusion of Multiphysics tools, Artificial Intelligence, and Machine Learning.

Case Studies: NASA examples of application (separate and controllable); Ever increasing set – Community sourcing!

Case Studies are included for clarity and as part of the living nature of the document:

- A General Reliability Model for Ni-BaTiO3-Based Multilayer Ceramic Capacitors
- Reliability Analysis of Aero-Equipment Components Life Based on Normal Distribution Model
- An Investigation of the Electrical Short Circuit Characteristics of Tin Whiskers
- GOES-T GSFC Magnetometer Reliability Model
- Analysis of Space Shuttle Flight Hardware Crack or Crack-Like Defect Data
- Bayesian Approach for Reliability Assessment of Sunshield Deployment on JWST
- Analysis and Life Testing for Design of Cryogenic Bearing Assemblies on the James Webb Space Telescope Optical Telescope Element
- Single-Event Transient Case Study for System Level Radiation Effects Analysis
- EOS Aqua Extended Mission Reliability Study Report, Revision C
- New Approach to Total Dose Specification for Spacecraft Electronics
- Improving Reliability of High-Power Quasi-CW Laser Diode Arrays Operating in Long Pulse Mode
- Damage Propagation Modeling for Aircraft Engine
- Degradation of Leakage Currents and Reliability Prediction for Tantalum Capacitors
- X-43A Rudder Spindle Fatigue Life Estimate and Testing
- A Thermal Runaway Failure Model for Low Voltage BME Ceramic Capacitors with Defects
- Analysis of Thermomechanical Fatigue of Unidirectional Titanium Metal Matrix Composites
- An Evaluation of Effects of Molding Compound Properties on the Reliability of Ag Wire Bonded Components
- Comparison of Experimental and Theoretical Thermal Fatigue Lives for Five Nickel Base Alloys
- Effect of High Temperature Storage in Vacuum, Air, and Humid Conditions on Degradation of Gold/Aluminum Wire Bonds in PEMs
- And More

Today we have Multiphysics tools (e.g., COMSOL, MATLAB, Windchill, Ansys Sherlock, Cadence, Altair, etc.) to assist in the assessment of failure likelihood but these have limitations.

Based on the ongoing research, in the future PoF modeling will likely Include Artificial Intelligence and Machine Learning to enable a more complete evaluation with the application of predictive and statistical learning techniques.

For this to be possible research and data are needed from the community and must be shared with the community.

National Aeronautics and Space Administration

www.nasa.gov

R&M Physics of Failure (PoF) Handbook

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Future: Technology advancement infusion of Multiphysics tools, Artificial Intelligence, and Machine Learning.

Case Studies: NASA examples of application (separate and controllable); Ever increasing set – Community sourcing!

Appendix B: Case Study Chart

Section of PoF Handbook	Case Study Title	Link
3.0 Empirical Methods		
3.1 Empirical Reliability Approach	*TBS - Please consider submitting a case study for inclusion*	
3.2 Statistical Modeling Analysis		
3.2.1 Exponential	*TBS - Please consider submitting a case study for inclusion*	
3.2.2 Weibull	- A General Reliability Model for Ni-BaTiO3-Based Multilayer Ceramic Capacitors - Effect of High-Temperature Storage in Vacuum, Air, and Humid Conditions on Degradation of Gold/Aluminum Wire Bonds in PEMs	https://ntrs.nasa.gov/api/citations/20140008978/downloads/20140008978.pdf https://ntrs.nasa.gov/api/citations/20070016662/downloads/20070016662.pdf
3.2.3 Normal	- Reliability Analysis of Aero-Equipment Components Life Based on Normal Distribution Model	https://ieeexplore.ieee.org/document/8740448
3.2.4 Lognormal	- An Investigation of the Electrical Short Circuit Characteristics of Tin Whiskers - New Approach to Total Dose Specification for Spacecraft Electronics	https://ntrs.nasa.gov/api/citations/20130011768/downloads/20130011768.pdf https://ntrs.nasa.gov/api/citations/20170004853/downloads/20170004853.pdf
3.2.5 Binomial	*TBS - Please consider submitting a case study for inclusion*	
3.2.6 Bayesian Statistical Interference	- GOES-T GSFC Magnetometer Reliability Model	https://meta.gsfc.nasa.gov/IntelexLogin/Intelex/Application/SCMSConfigMan/ModernProjLibInventory/DefaultView/SCMSConfigMan_DocumentsSCMSObject/View/a668a2c5-98a6-4d39-82a6-9cb4fa857c9f

Section of Pof Handbook	Case Study Title	Link
3.2.6 Bayesian Statistical Interference	- EOS Aqua Extended Mission Reliability Study Report Revision C -Bayesian Approach for Reliability Assessment of Sunshield Deployment on JWST	https://meta.gsfc.nasa.gov/IntelexLogin/Intelex/Application/SCMSConfigMan/ModernProjLibInventory/Forms/SCMS_DocDetail/View/0d22ecd2-508a-42e7-911b-fb7956609eb5 https://ntrs.nasa.gov/api/citations/20130009067/downloads/20130009067.pdf
3.3 Peck's Temperature-Humidity Relationship Prediction	- An Evaluation of Effects of Molding Compound Properties on the Reliability of Ag Wire Bonded Components	https://ieeexplore.ieee.org/abstract/document/7999992
3.4 Accelerated Performance Analysis	*TBS - Please consider submitting a case study for inclusion*	
3.4.1 Arrhenius	- Degradation of Leakage Currents and Reliability Prediction for Tantalum Capacitors -Improving Reliability of High Power Quasi-CW Laser Diode Arrays Operating in Long Pulse - Damage Propagation Modeling for Aircraft Engine Prognostics - A Thermal Runaway Failure Model for Low-Voltage BME Ceramic Capacitors with Defects	https://ntrs.nasa.gov/citations/20160001192 https://ntrs.nasa.gov/api/citations/20060048507/downloads/20060048507.pdf https://ntrs.nasa.gov/api/citations/20090029214/downloads/20090029214.pdf https://ntrs.nasa.gov/api/citations/20170003045/downloads/20170003045.pdf
3.4.2 Inverse Power	*TBS - Please consider submitting a case study for inclusion*	

Section of PoF Handbook	Case Study Name	Link
3.4.3 Coffin-Manson	- Damage Propagation Modeling for Aircraft Engine Prognostics - X-43A Rudder Spindle Fatigue Life Estimate and Testing	https://ntrs.nasa.gov/api/citations/20090029214/downloads/20090029214.pdf https://ntrs.nasa.gov/api/citations/20050136675/downloads/20050136675.pdf
3.4.4 Zhurkov Equation	*TBS - Please consider submitting a case study for inclusion*	
3.4.5 Palmgren	- Analysis and Life Testing for Design of Cryogenic Bearing Assemblies on the James Webb Space Telescope Optical Telescope Element	https://www.researchgate.net/publication/267595987_Analysis_and_Life_Testing_for_Design_of_Cryogenic_Bearing_Assemblies_on_the_James_Webb_Space_Telescope_Optical_Telescope_Element
3.4.6 Eyring Modeling	- Damage Propagation Modeling for Aircraft Engine Prognostics	https://ntrs.nasa.gov/api/citations/20090029214/downloads/20090029214.pdf
4.0 Deterministic Methods		
4.1 What Are Deterministic Methods?	*TBS - Please consider submitting a case study for inclusion*	
4.2 Electromigration in Electrical and Electronic Components	*TBS - Please consider submitting a case study for inclusion*	
4.2.1 Metals	*TBS - Please consider submitting a case study for inclusion*	
4.2.2 Migration	*TBS - Please consider submitting a case study for inclusion*	
4.2.3 The Fluctuation-Dissipation Theorem	*TBS - Please consider submitting a case study for inclusion*	
4.2.4 Viscous Drag and Brownian Motion	*TBS - Please consider submitting a case study for inclusion*	
4.2.5 Electromigration in Interconnection Traces and Vias in Integrated Circuits	*TBS - Please consider submitting a case study for inclusion*	

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4.3 Thermal Physics of Failure	*TBS - Please consider submitting a case study for inclusion*	
4.3.1 Thermal Failure Mechanisms	- Temperature cycling and fatigue in electronics	https://www.researchgate.net/publication/306135282_Temperature_cycling_and_fatigue_in_electronics
4.3.2 Thermally Induced Failure Likelihood	- Thermal barrier coating life prediction model development - A Thermal Runaway Failure Model for Low-Voltage BME Ceramic Capacitors with Defects -Analysis of thermomechanical fatigue of unidirectional titanium metal matrix composites -Comparison of experimental and theoretical thermal fatigue lives for five nickel-base alloys	https://ntrs.nasa.gov/api/citations/19890003549/downloads/19890003549.pdf https://ntrs.nasa.gov/api/citations/20170003045/downloads/20170003045.pdf https://ntrs.nasa.gov/api/citations/19910022363/downloads/19910022363.pdf https://ntrs.nasa.gov/api/citations/19720016935/downloads/19720016935.pdf
4.3.3 Thermal Failure Uncertainties	*TBS - Please consider submitting a case study for inclusion*	
4.4 Fluid (Pipe Flow)	*TBS - Please consider submitting a case study for inclusion*	
4.5 Electromagnetics (Wave Optics, Ray Optics, AC/DC	- Inferring the Probability Distribution of the Electromagnetic Susceptibility of Equipment from a Limited Set of Data	https://ieeexplore.ieee.org/document/8485108

Section of PoF Handbook	Case Study Name	Link
4.5 Electromagnetics (Wave Optics, Ray Optics, AC/DC	- Probability of EMC Failure and Sensitivity Analysis With Regard to Uncertain Variables by Reliability Methods	https://hal.archives-ouvertes.fr/hal-01116322/document
4.6 Structural Analysis Modeling		
4.6.1 Fatigue Analysis	- NESC Bellow Material Compatibility - Model-Based Failure Assessment of Sounding Rocket Mission PWAs - X-43A Rudder Spindle Fatigue Life Estimate and Testing - Micromechanics-Based Progressive Failure Analysis of Composite Laminates Using Different Constituent Failure Theories -Resolution of a Reflector Shroud Fatigue Failure	https://rmakp.msfc.nasa.gov/download/attachments/100761794/B.3%20Case%20Study%20Fatigue%20Analysis%20NESC%20Bellows%20Material%20Compatibility%20Assessment.pdf?api=v2 https://rmakp.msfc.nasa.gov/download/attachments/100761794/B.1%20Case%20Study%20MB-Failure%20Assessment%20of%20Rocket%20Mission%20PWAs.pdf?api=v2 https://ntrs.nasa.gov/api/citations/20050136675/downloads/20050136675.pdf https://aims.asu.edu/wp-content/uploads/2019/07/Micromechanics-based-progressive-failure-analysis-of-composite-laminates-using-different-constituent-failure-theories.pdf https://ntrs.nasa.gov/api/citations/20180007283/downloads/20180007283.pdf
4.6.2 Damage Tolerance (Fracture) Analysis	- GEDI RTA Fracture Analysis - Analysis of Space Shuttle Flight Hardware Crack or Crack-Like Defect Data	https://ipdtdms.gsfc.nasa.gov/documentation/index.cfm?id=39474&type=1 https://rmakp.msfc.nasa.gov/download/attachments/100761794/B.5%20Case%20Study%20Space%20Shuttle%20Analysis.pdf?api=v2
4.6.3 Creep	*TBS - Please consider submitting a case study for inclusion*	
4.7 Acoustics	*TBS - Please consider submitting a case study for inclusion*	

Section of PoF Handbook	Case Study Name	Link
4.8 Chemical (Batteries and Fuel Cells, Electrodeposition, Chemical Reactions)	- An Investigation of the Electrical Short Circuit Characteristics of Tin Whiskers -Reliability of Radioisotope Stirling Convertor Linear Alternator	https://ntrs.nasa.gov/api/citations/20130011768/downloads/20130011768.pdf https://ntrs.nasa.gov/api/citations/20060012337/downloads/20060012337.pdf
4.9 Radiation Physics of Failure in Semiconductors		
4.9.1 Total Ionizing Dose	-Statistical Methods for Large Flight Lots and Ultra-high Reliability Applications	https://ntrs.nasa.gov/api/citations/20050210085/downloads/20050210085.pdf
4.9.2 Total Non-Ionizing Dose/Displacement Damage Dose	-New Approach to Total Dose Specification for Spacecraft Electronics	https://ntrs.nasa.gov/api/citations/20170004853/downloads/20170004853.pdf
4.9.3 Single Event Effects	- Single-Event Transient Case Study for System Level Radiation Effects Analysis	https://ntrs.nasa.gov/citations/20210010826
4.9.4 Analysing Radiation-Induced Failure Modes	*TBS - Please consider submitting a case study for inclusion*	
4.9.5 Instantaneous Radiation Failures (Single Event Effects)	*TBS - Please consider submitting a case study for inclusion*	
4.9.6 Likelihood of Radiation Induced Failure Summary	*TBS - Please consider submitting a case study for inclusion*	
5.0 Formulating Comprehensive Results From Individual PoF Findings		
5.1 Aggregation Approach	*TBS - Please consider submitting a case study for inclusion*	
5.2. Inclusive Relationship Finding Aggregation	*TBS - Please consider submitting a case study for inclusion*	

Section of PoF Handbook	Case Study Name	Title
5.3. Complementary Relationship Finding Aggregation	*TBS - Please consider submitting a case study for inclusion*	
5.4 Interrelated Relationship Finding Aggregation	*TBS - Please consider submitting a case study for inclusion*	
5.5 Aggregation Assistance	*TBS - Please consider submitting a case study for inclusion*	
6.0 The Evolution of the Physics of Failure		
6.1 NASA Path Forward	*TBS - Please consider submitting a case study for inclusion*	
6.2 Technology Support	*TBS - Please consider submitting a case study for inclusion*	
6.3 Advanced Technology Infusion		
6.3.1 Artificial Intelligence (AI), Machine Learning (ML)	*TBS - Please consider submitting a case study for inclusion*	
6.3.2 Data Monitoring/ Analytics	*TBS - Please consider submitting a case study for inclusion*	
6.4 Methodology Innovation Infusion		
6.4.1 Remaining Useful Life (RUL)	*TBS - Please consider submitting a case study for inclusion*	
6.4.2 Digital Twin Usage	*TBS - Please consider submitting a case study for inclusion*	https://ntrs.nasa.gov/api/citations/20170007965/downloads/20170007965.pdf