RW211

Traditional Markovian Modeling vs. Cumulative Damage Modeling

Robert Youngblood[a] and Karl Fleming[b]

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[a] Bob Youngblood Consulting LLC, Idaho Falls, ID, USA, rwyoungblood@gmail.com
[b] KNF Consulting Services, LLC, Spokane, WA, USA, karlfleming@comcast.net

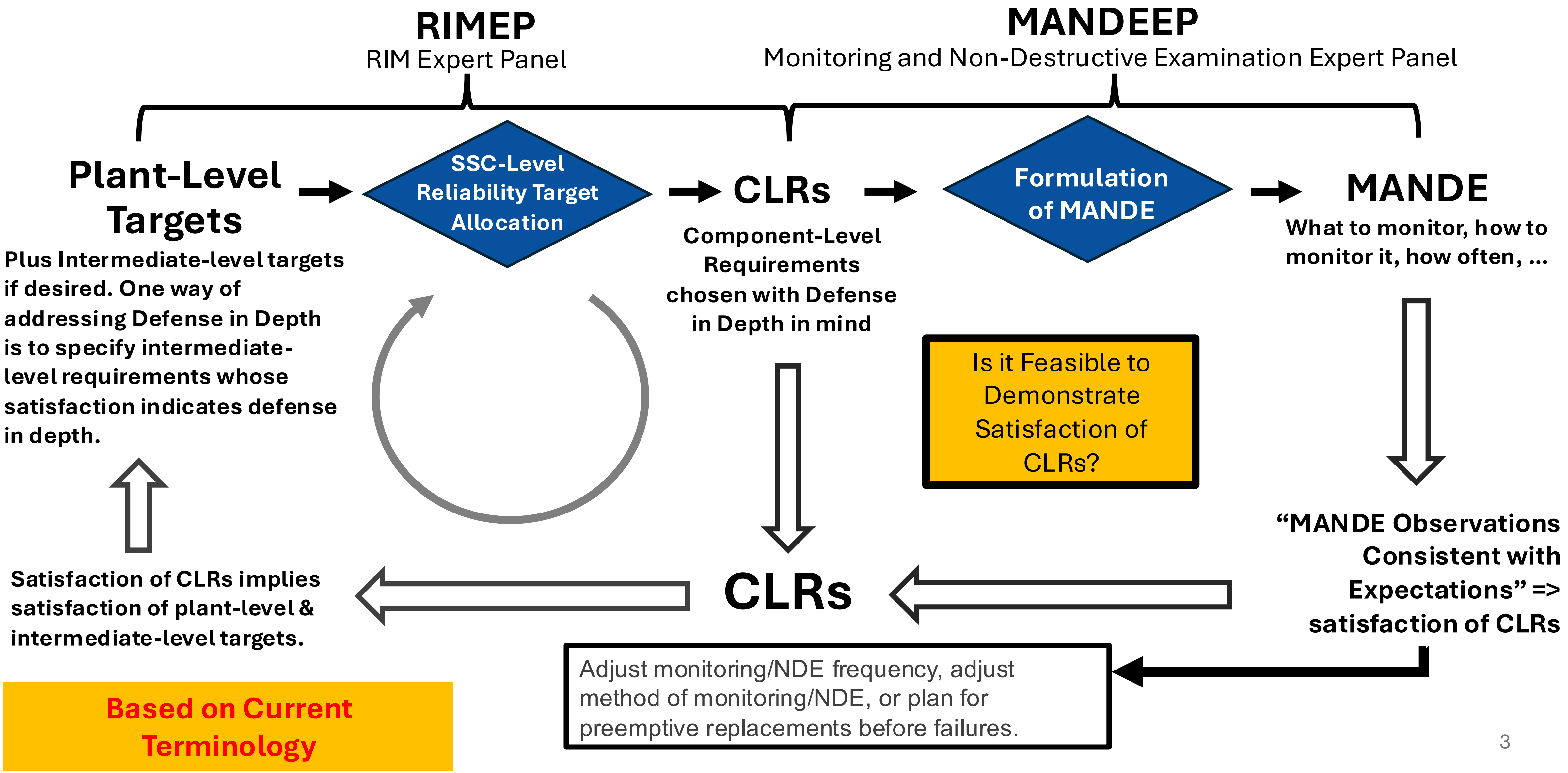
Themes

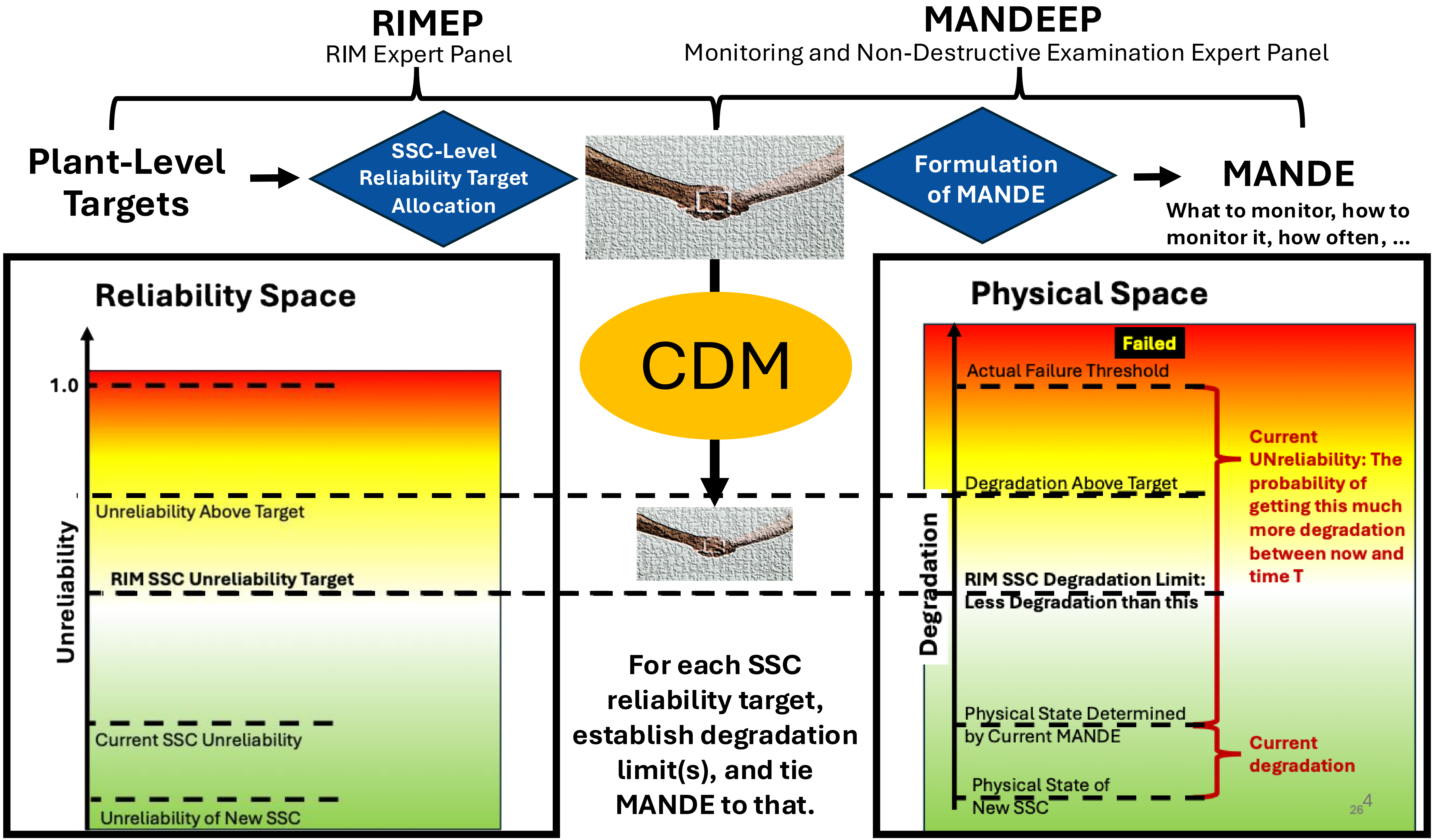
- General context of this paper:
  - Operating history is generally relevant, but novel reactors may not be able to rely on it as heavily as the current fleet has done.
  - Novel reactors may well need to rely more on explicit modeling of component behavior (as opposed to traditional reliability modeling).
- Specific context of this paper:
  - Reliability Integrity Modeling (RIM): ASME BPVC XI Division 2 is a highly risk-informed, performance-based approach to managing risks associated with loss of integrity of passive SSCs.

➢ Cumulative Damage Modeling (CDM) can arguably help RIM.

Simplified Diagram of RIM

- Materials Degradation
- Reliability Targets
- RIM Strategies




RIMEP
RIM Expert Panel
MANDEEP
Monitoring and Non-Destructive Examination Expert Panel
Plant-Level Targets
SSC-Level Reliability Target Allocation
Formulation of MANDE
MANDE
What to monitor, how to monitor it, how often, ...
Reliability Space
1.0
Unreliability
Unreliability Above Target
RIM SSC Unreliability Target
Current SSC Unreliability
Unreliability of New SSC
CDM
For each SSC reliability target, establish degradation limit(s), and tie MANDE to that.
Physical Space
Failed
Actual Failure Threshold
Degradation Above Target
Degradation
RIM SSC Degradation Limit: Less Degradation than this
Physical State Determined by Current MANDE
Physical State of New SSC
Current UNreliability: The probability of getting this much more degradation between now and time T
Current degradation

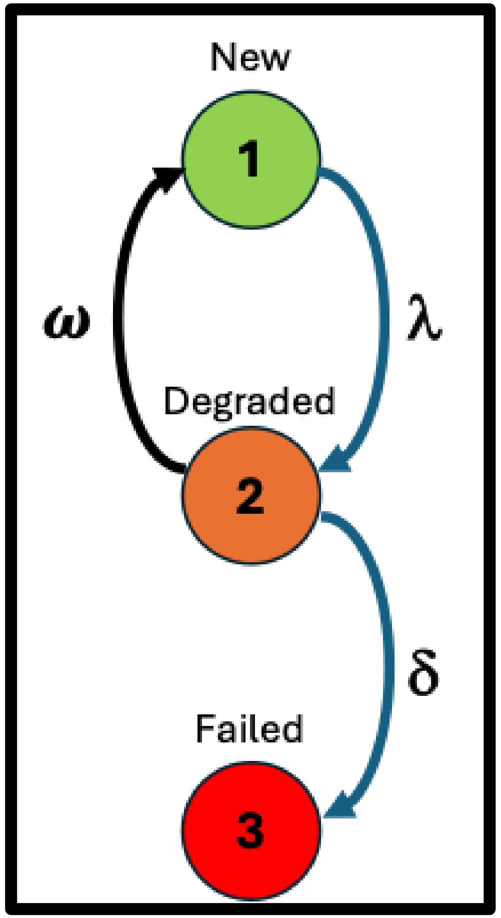
Outline

- Reliability Integrity Management (RIM):
  - **(1) RIM Program scope definition**
  - **(2) degradation mechanism assessment (DMA)**
  - **(3) facility and SSC Reliability Target allocation originating from the probabilistic risk assessment (PRA)**
  - **(4) identification and evaluation of RIM strategies**
  - **(5) evaluation of uncertainties**
  - **(6) RIM Program implementation**
  - **(7) performance monitoring and RIM Program updates**

  } Current Wording of RIM in ASME BPVC XI Division 2

- Cumulative Damage Modeling (CDM) is an application of event-driven simulation formulated to understand the interplay between component degradation mechanisms and various management strategies that may be implemented to manage the risk associated with passive component failure.
- CDM models situations in which component functionality is lost when a particular threshold of degradation is exceeded as a result of the cumulative effect of degradation mechanisms whose severity may fluctuate in time.
- Constant-failure-rate (e.g., Markovian) modeling has previously been applied to passive component reliability, but if threshold effects dominate in a particular context, there may be limitations to the applicability of a Markovian result in that context, and CDM may help.
  - Markov modeling is a special case of CDM, and it is straightforward to blend Markov modeling with threshold-based damage modeling.
  - Examples of CDM have existed for some time (e.g., Probabilistic Fracture Mechanics), but the present formulation of CDM is more general and more oriented to supporting formulation and implementation of Monitoring and Non-Destructive Evaluation (MANDE).
- The present paper uses simple examples to compare traditional Markov modeling with CDM, with a view to:
  - highlighting relative strengths and weaknesses of the two approaches,
  - integrating monitoring and inspection models with physical damage models, to support detailed exploration of approaches to monitoring and inspection,
  - assessing what properties CDM needs to have to improve meaningfully on Markovian modelling.

Figure 1. Three-State Model Used in the present paper.



Markovian Treatment:

$$\frac{d}{dt}p_{New} = -\lambda p_{New} + \omega p_{Degraded}, \tag{1}$$

$$\frac{d}{dt}p_{Degraded} = \lambda p_{New} - \omega p_{Degraded} - \delta p_{Degraded}, \tag{2}$$

$$\frac{d}{dt}p_{Failed} = \delta p_{Degraded} \tag{3}$$

$$p_{New} + p_{Degraded} + p_{Failed} = 1$$

Cumulative Damage Treatment:

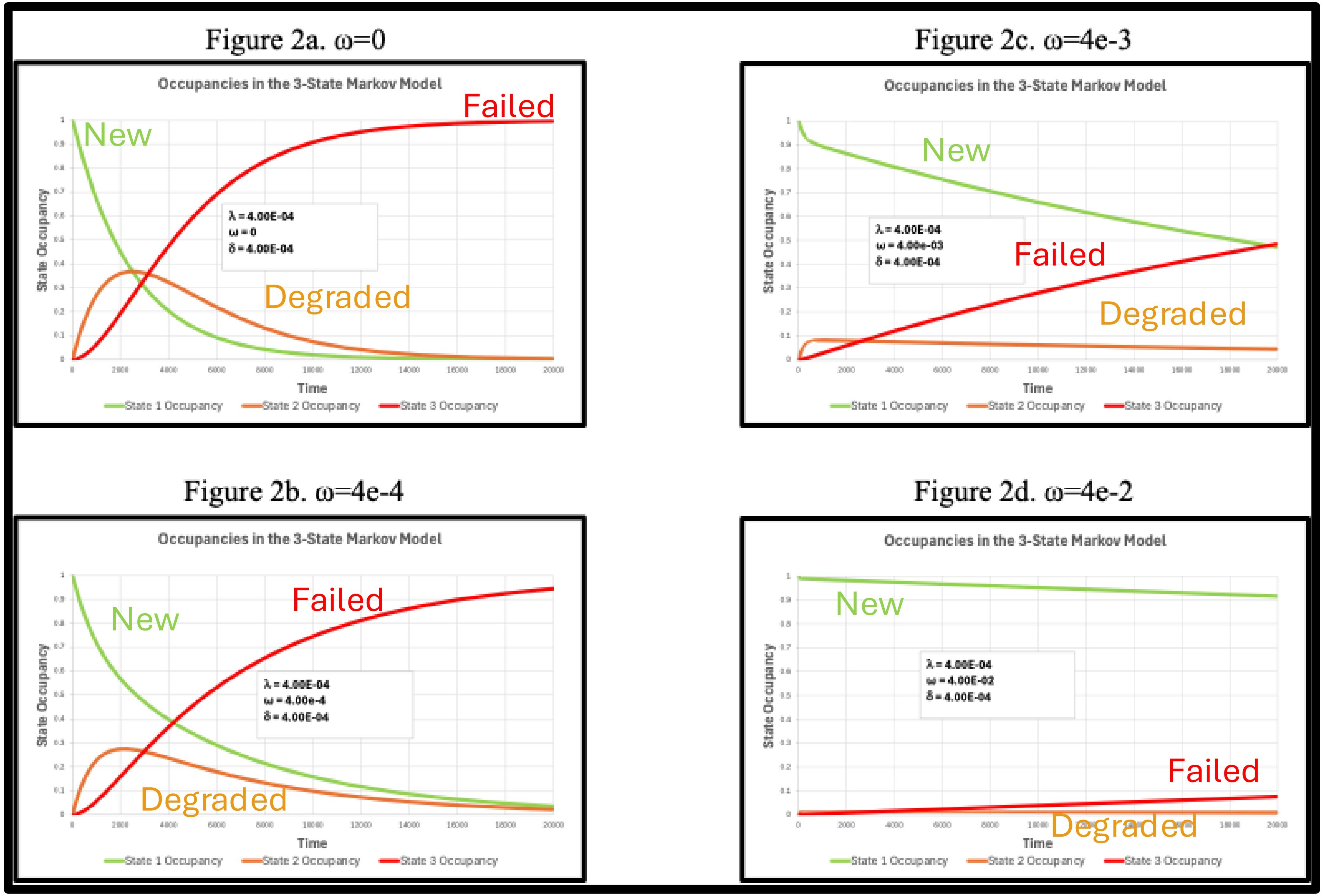
Develop a model of environmental stressors that degrade the component.

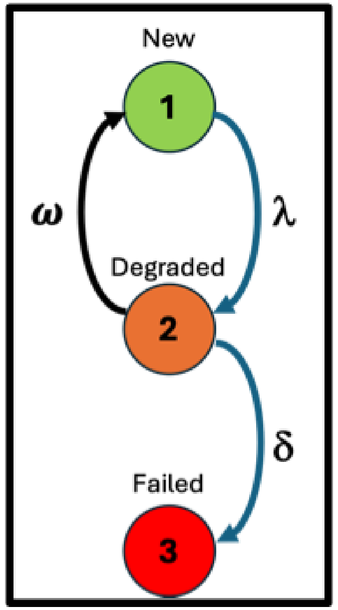
For each arc, define threshold damage values at which damage occurs.

Time histories will differ if the timing of the stressors varies from one history to another.

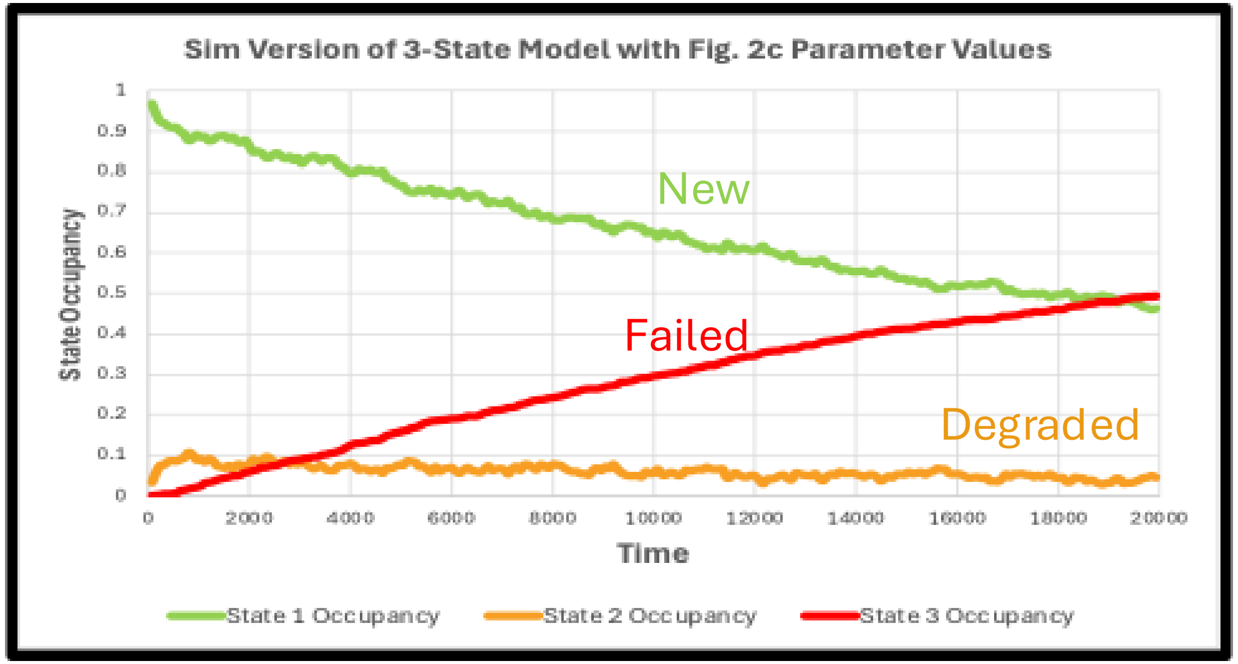
A Markov model is a special case of this model class: damage is proportional to time, and thresholds are chosen randomly based on the Poisson distribution assumed for λ, ⌉, and δ

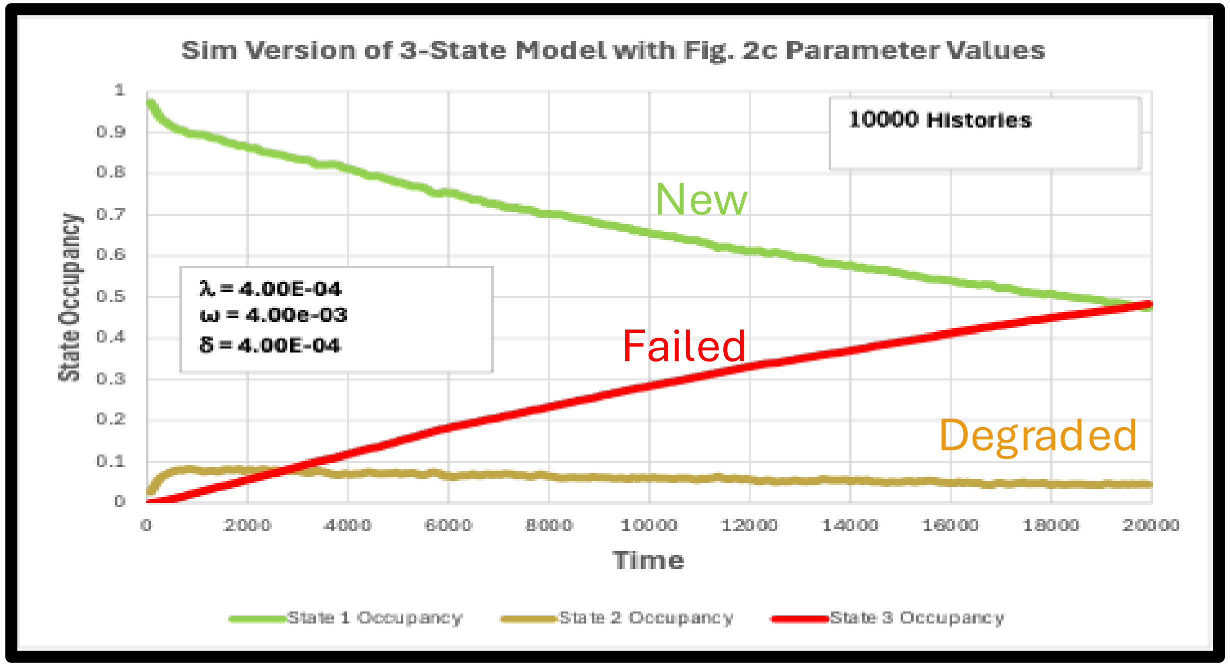
Markov Model Results for Different Values of ⏋





These plots are generated by the cumulative damage model simulation for the Markov model parameter values used in Figure 2c (previous slide). Apart from the jitter associated with the finiteness of the number of simulations, agreement is good.

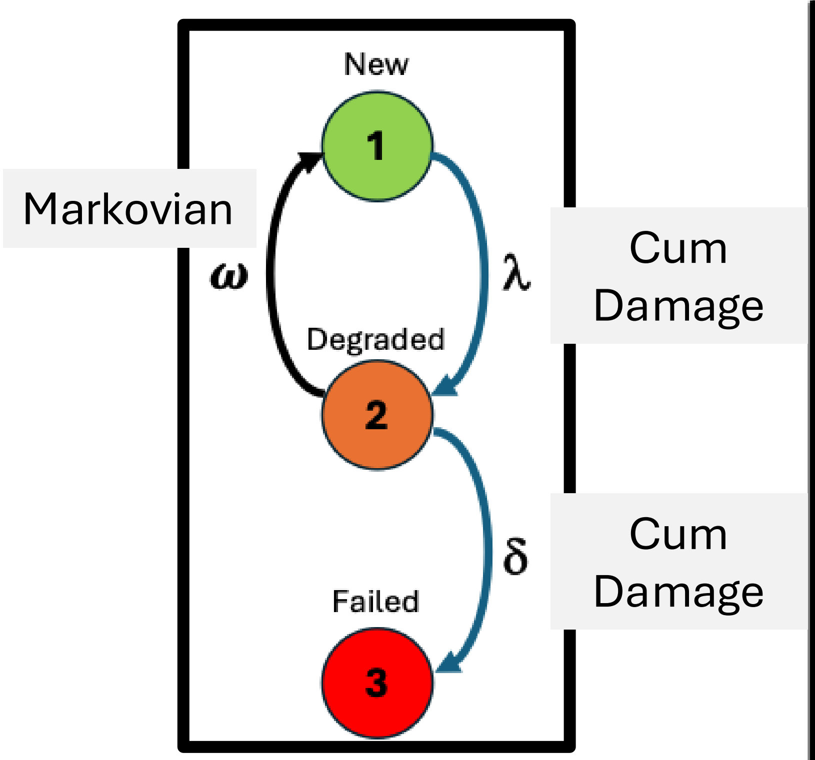




A Markovian treatment is a special case of a cumulative damage treatment

Doing a Markov model within CDM:
Let "damage" = "elapsed time", and in each time history, sample each arc's thresholds from the time distribution implied by the Markovian transition rates.

Figure 4. Arc 2 is Markovian; Sharp thresholds have been assigned to Arcs 1 and 3.



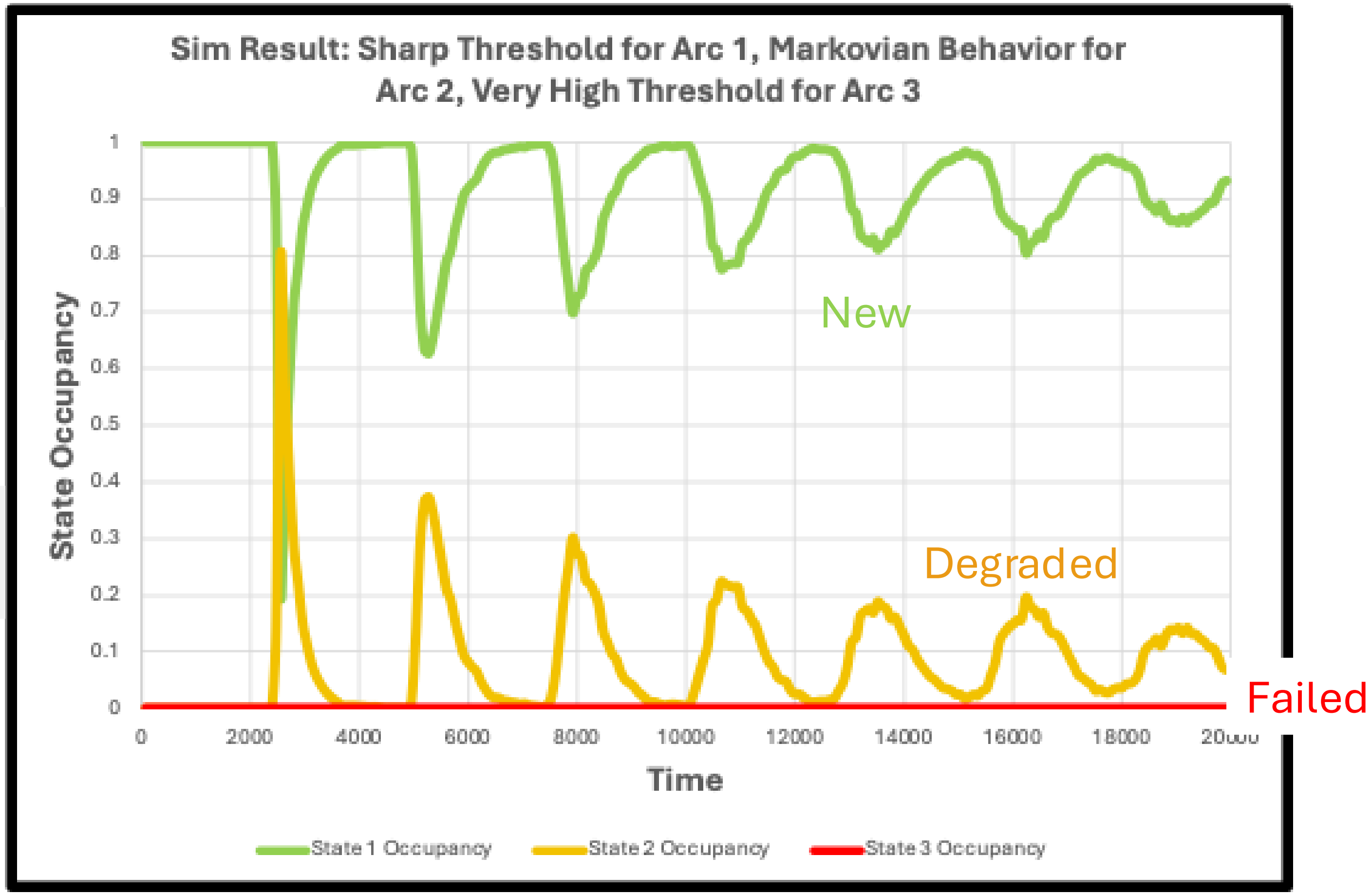


Figure 5: Coupled Models

Actual Damage Model

- The model of plant-induced stressors and component response that governs damage accumulation

Estimated Damage Model

- What plant staff think is going on, based on monitoring between inspections, and considering recent history

Perceived-Damage Model

- Conclusions drawn by plant staff after an inspection, considering uncertainties and possible incompleteness, and considering recent history

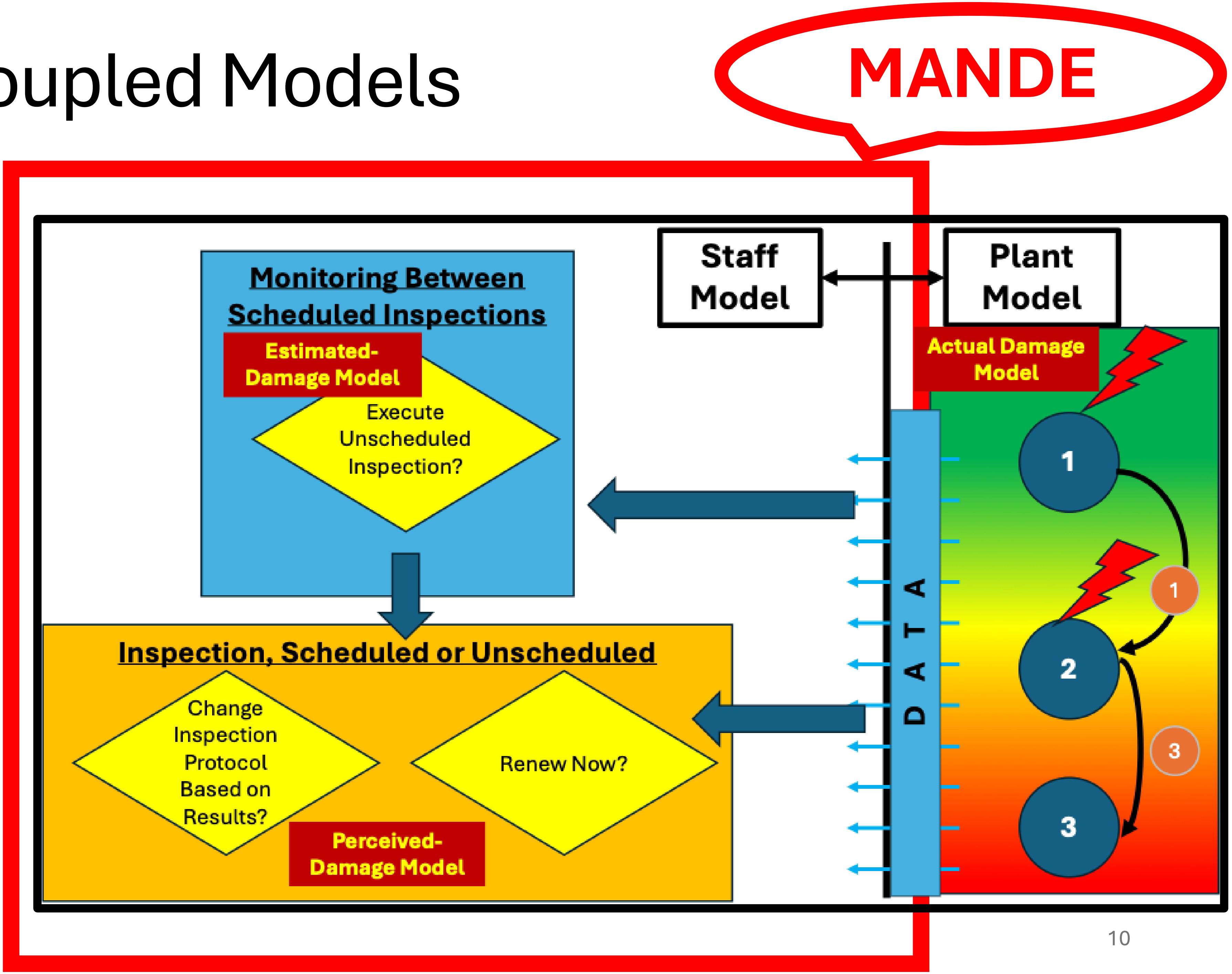


Figure 6. Comparison of results without, and with, Markovian renewal arc.

Figure 6a: No renewal.

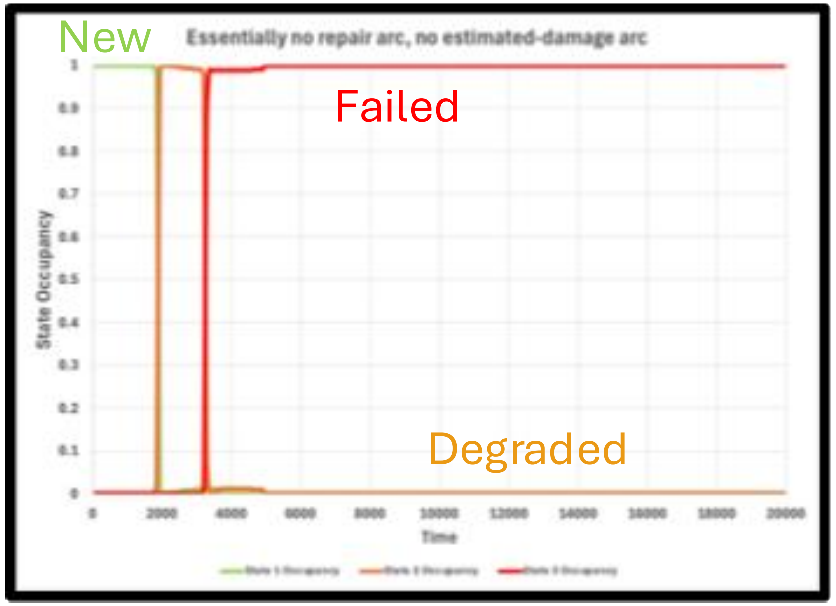
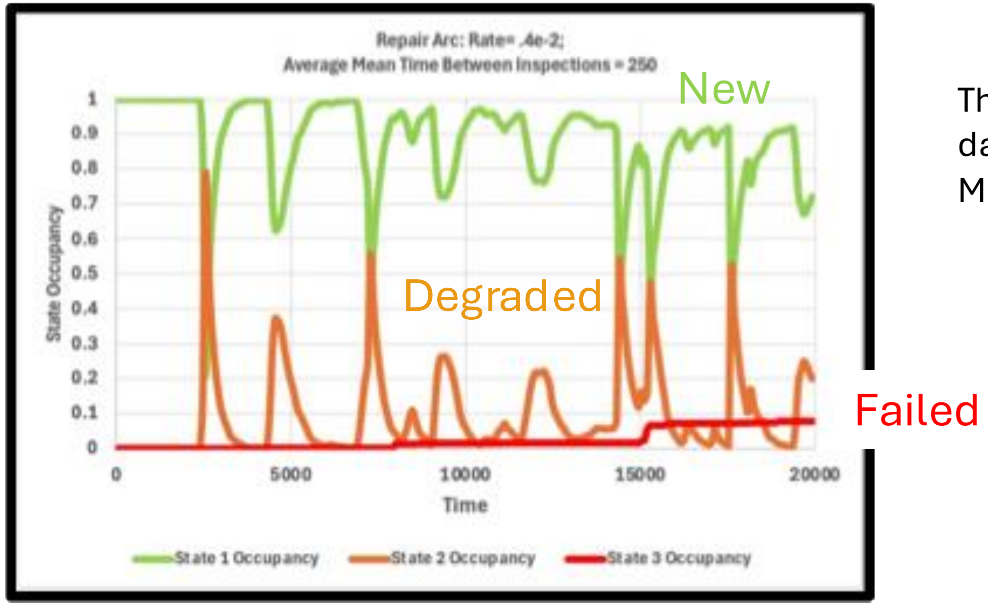


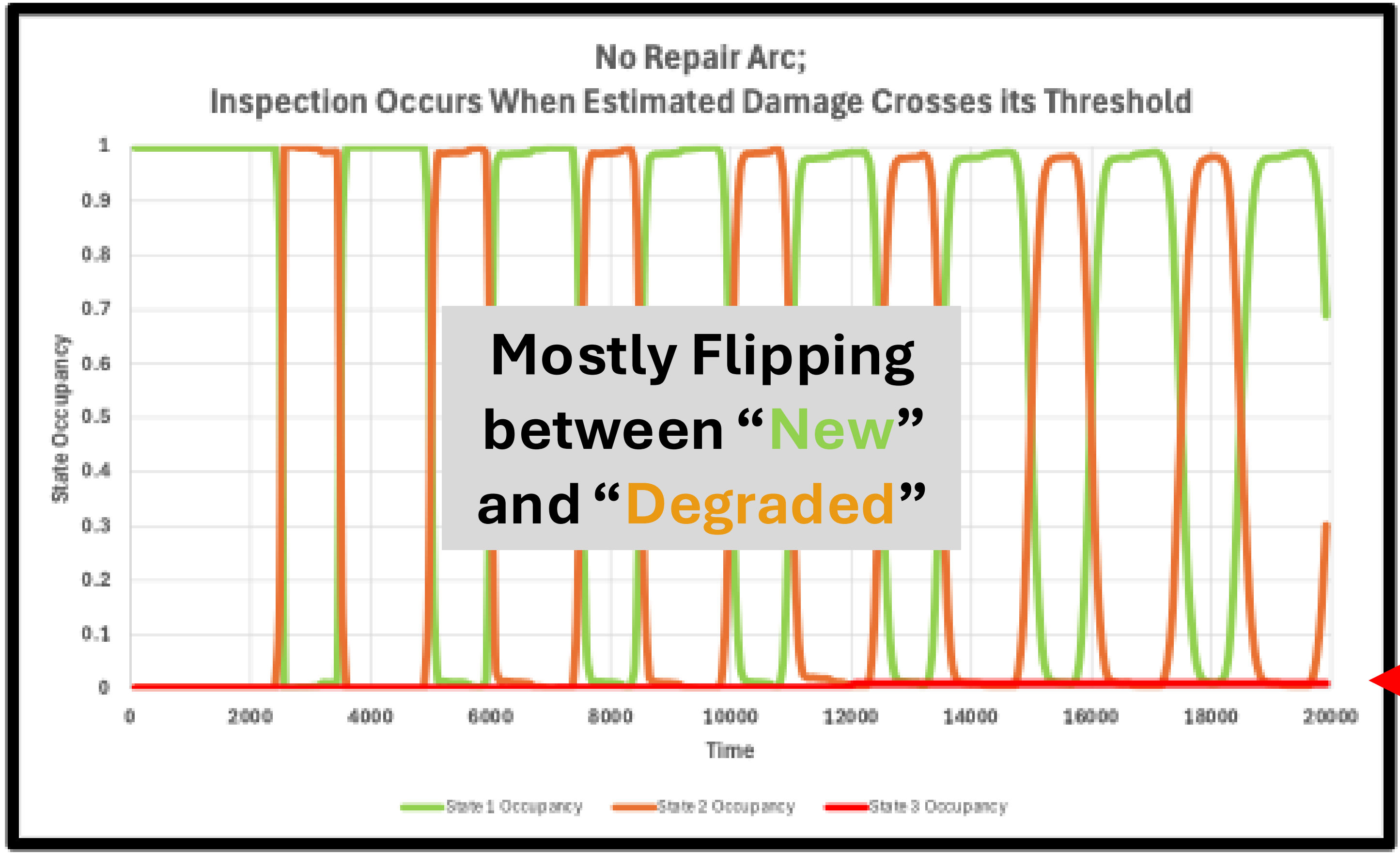
Figure 6b: Markovian renewal Arc

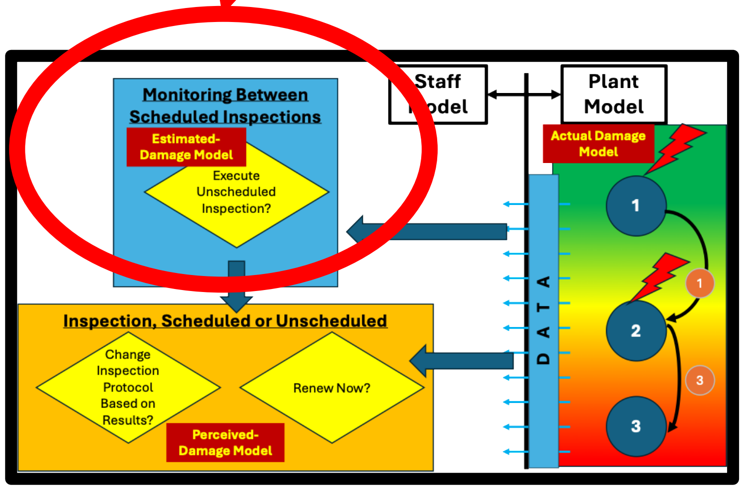


This result contains a damage arc and a Markovian renewal arc.

If degradation occurred only at a constant rate, and one knew that rate accurately enough, then one could simply plan renewal to occur just before failure.
But the chaos in Figure 6b suggests that unless damage accumulation is a simple function of time, a simple approach to scheduling inspection must be either very conservative or not particularly effective.

Figure 7. Still no Repair Arc, but Inspection Occurs when Estimated Damage Crosses a Designated Threshold Value.





Very low occupancy in Failed State

Summary (1)

- RIM [1] calls for demonstrating ongoing satisfaction of explicit reliability targets for SSCs within its scope, which calls for closely coordinating the monitoring, inspection, and renewal of components.
- In some applications, especially certain novel operating environments, we may not be able to rely on operating history to tell us when some components need renewal. It will be important to time renewals to maintain the targeted reliability without incurring unnecessary loss of production.
- This paper has compared traditional Markov modeling with Cumulative Damage Modeling by analyzing a simple state transition model within both modeling approaches. The present Cumulative Damage Model:
  - Is simulation-based;
  - Treats state transitions as occurring when time-history-specific damage thresholds are crossed, rather than basing transitions on quantified transition rates or prescribed inspection intervals. (However, Markovian modeling is shown to be a limiting special case of this class of models.)
  - Separates out the modeling of inspection and renewal policy.

Summary (2)

- Value of Information:
  - In decision-making under uncertainty, it may be possible to improve the expected utility of decisions significantly by reducing uncertainty, and the benefits of obtaining the necessary information are quantifiable.
  - In the present paper, the "estimated" damage model was formulated for use by operators. That is, between scheduled inspections, the operators have access to some information about plant state, and can interpret that information within their model in order to decide when to inspect.
  - For purposes of illustration, that model was taken to be the same as the actual damage model but was applied with a lower threshold (i.e., inspection would occur before failure). This led to significantly improved outcomes (better reliability with less inspection effort).
    - Given uncertainty in the estimated damage model, one would need to choose the threshold more conservatively.
  - In other words: if monitoring can tell us enough, we can do a very good job of timing our inspections and renewals. Although many treatments focus on the value of "perfect" information, the general idea also applies to assessing the value of imperfect information.

Cumulative Damage Modeling is meant to support
- **Formulation of MANDE (Value of Information) and**
- **Implementation of MANDE**

Backup

Question from Industry at NEI Special Treatment Workshop:
"How do we calculate component reliability in this situation?"

reliability: the probability that a system or component will perform its specified function under given conditions upon demand and for a prescribed mission time.

Answer given at the workshop:

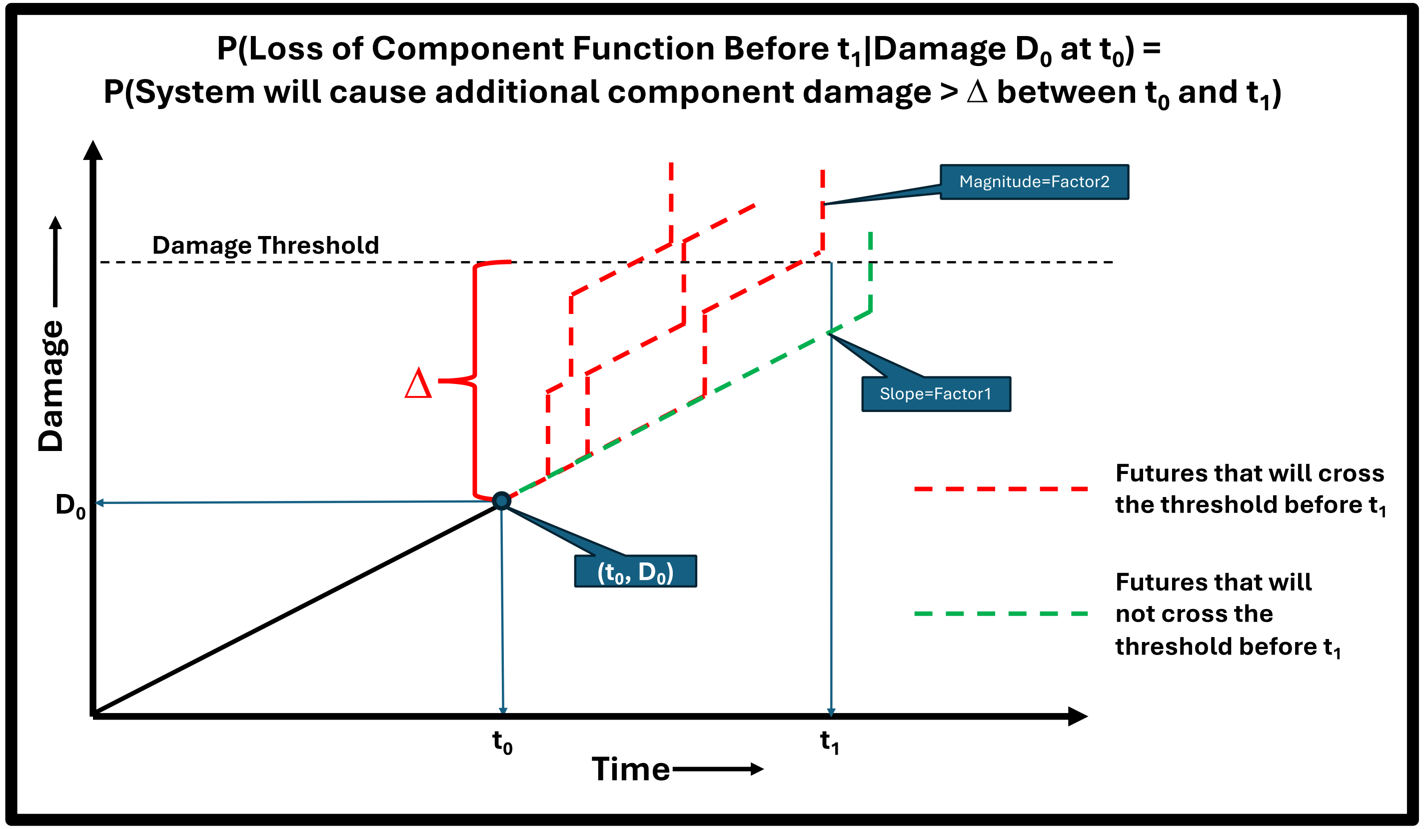
An arguably better answer:

Stop thinking that the needed concept is derivable from a reliability model of the component. Of course, component properties are involved: but the RELIABILITY is the probability that within a given time interval, the environment will NOT finish the job of degrading the component to the point of loss of function.

Model that.

Calculating Component Reliability Given Current Damage

- The lower left of the plot shows damage increasing linearly in time (Factor 1 > 0).
- Beyond t_0, we see occasional step changes in damage, corresponding to ES.
- Given the damage level at t_0, we know whether Factor1 will cause a loss of function at or before t_1.
- In the green time history, Factor1 will not by itself cause a threshold crossing, so a transition occurs only if some ES occur.
- Were Factor2 zero, the reliability in this situation would be 1; but it is not zero, and in the red time histories, enough ES occur to cause the transition.



The "unreliability" (probability of failure before t_1, given damage level at t_0) is the probability of enough damage accruing before t_1 to cause a transition to a failed state.

Very Simple Damage Model

Damage=Factor1*Operating Hours + Factor2 *(# of episodic stressors)

Parameters	Values
Factor1 (Damage Model)	1
Factor2 (Damage Model)	1000
Parameters (m,s) of Gaussian Distributions for Flaw, Leak, Rupture Thresholds:	
Flaw (m,s)	(8760,100)
Leak (m,s) (additional damage given flaw)	(12000,100)
Rupture (m,s) (additional damage given flaw)	(14000,100)
Average rate of episodic stressors (their times are Poisson distributed)	3.42E-4 / hr (about 3 per year)

Clip from MIL-HDBK-217F (Reliability Prediction of Electronic Equipment)

3.4.4 Part Failure Rate Models - Part failure rate models for microelectronic parts are significantly different from those for other parts and are presented entirely in Section 5.0. A typical example of the type of model used for most other part types is the following one for discrete semiconductors:

$$\lambda_p = \lambda_b \pi_T \pi_A \pi_R \pi_S \pi_C \pi_Q \pi_E$$

where:

- λ_p is the part failure rate,
- λ_b is the base failure rate usually expressed by a model relating the influence of electrical and temperature stresses on the part,
- π_E and the other π factors modify the base failure rate for the category of environmental application and other parameters that affect the part reliability.

The above clip demonstrates elaborate recognition of the importance of environmental influences but remains anchored to the failure rate concept