Life Qualification of Hall Thrusters By Analysis and Test

Jay Polk and John Brophy

Jet Propulsion Laboratory, California Institute of Technology

July 10, 2019

NASA's Past and Planned Missions with Electric Primary Propulsion

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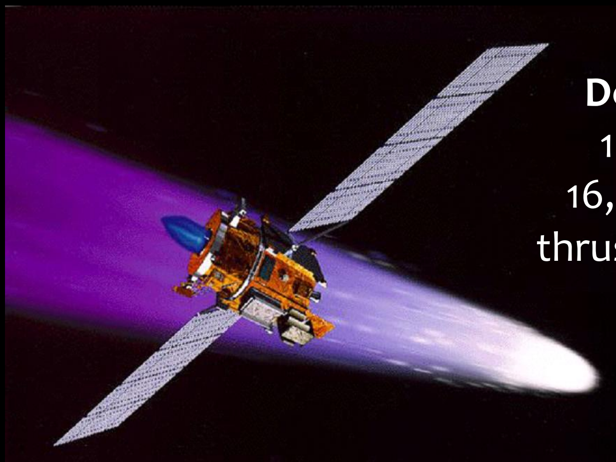
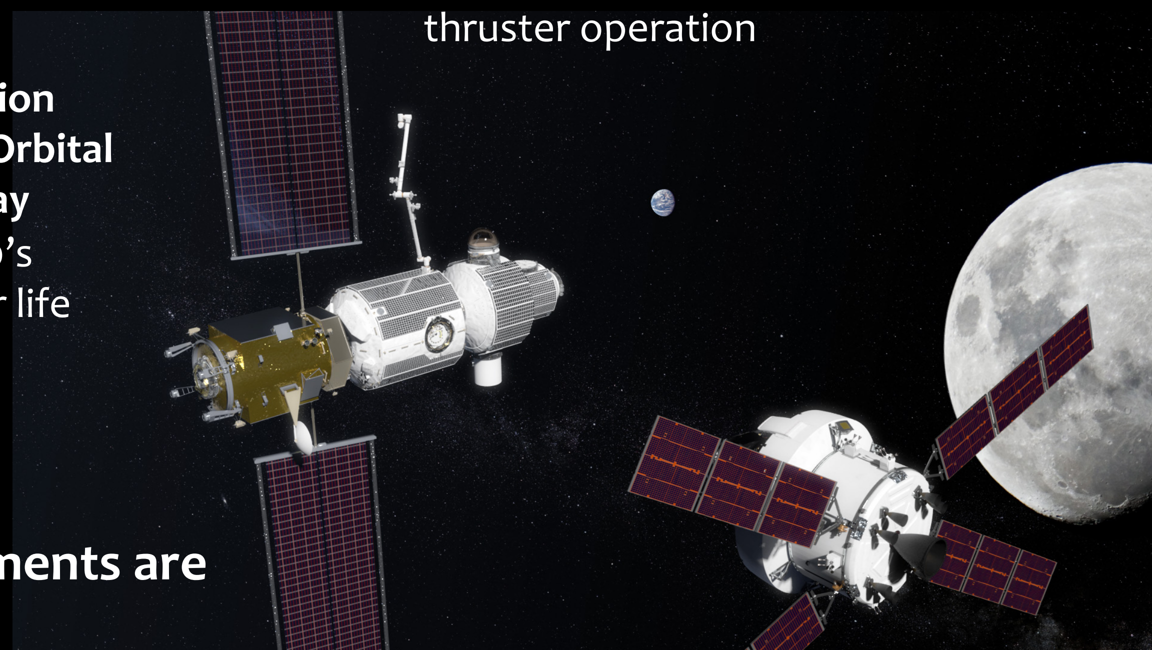


Deep Space 1
1998 – 2001
16,265 hours of thruster operation

Dawn
2007 – present
9468, 19141, and 22251 hours of thruster operation

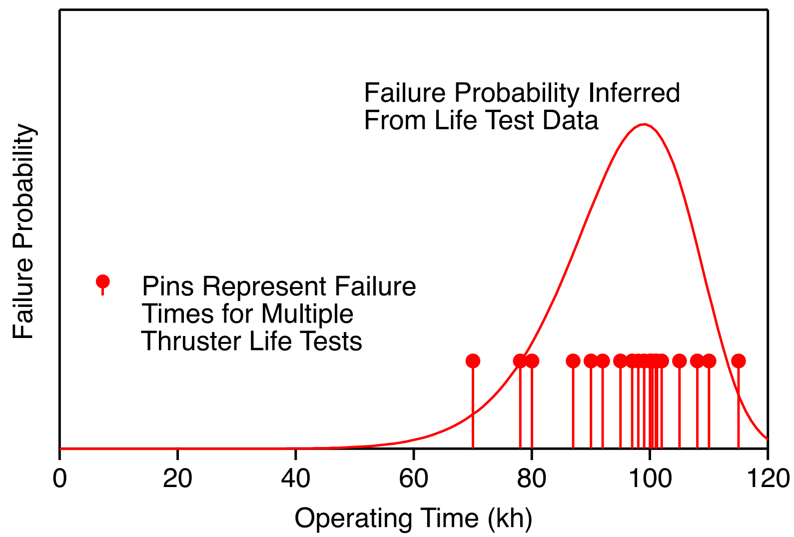


Power and Propulsion Element of the Lunar Orbital Platform--Gateway
Proposed for 2020's
23,000 hour thruster life requirement

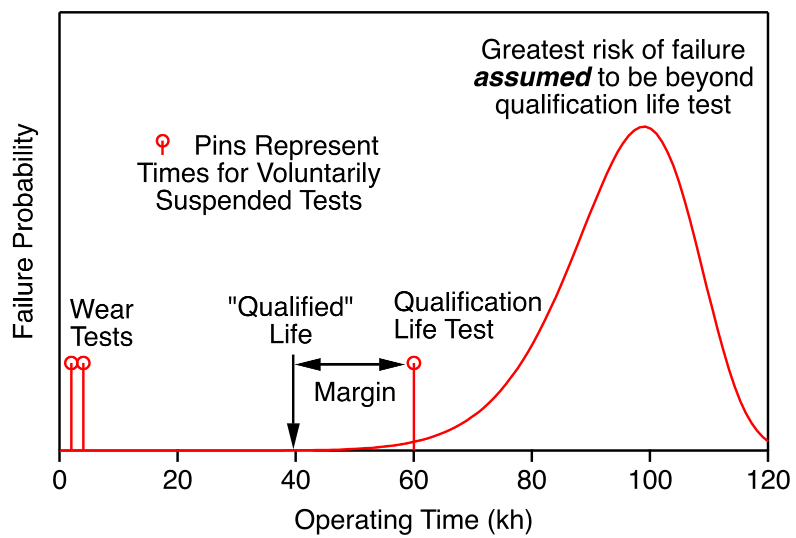
Electric Thruster Life Requirements are Very Challenging

Approaches to Thruster Life Qualification

- **Ideal Approach**
  - Multiple thrusters life-tested to failure
  - Faiure probability distribution determined from statistical analysis of actual failure data



- **Actual Industry Practice**
  - Multiple long duration tests too expensive
  - Reliance on a single test with margin (1.5 –2 X mission requirement)

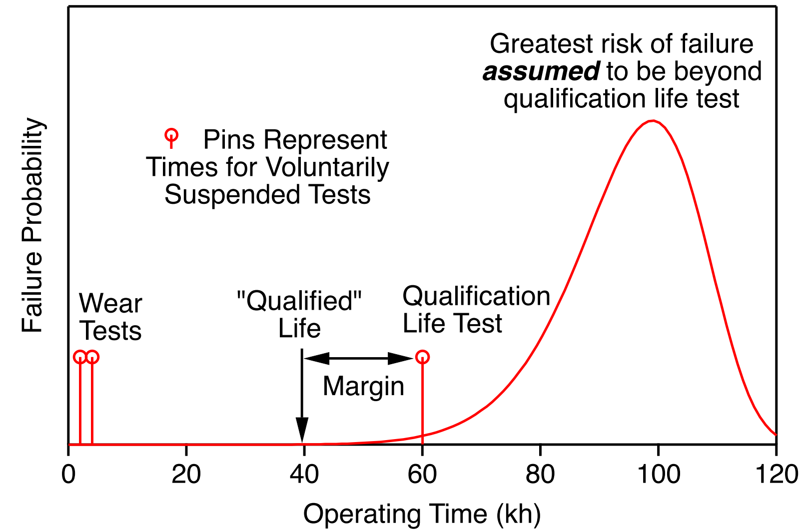


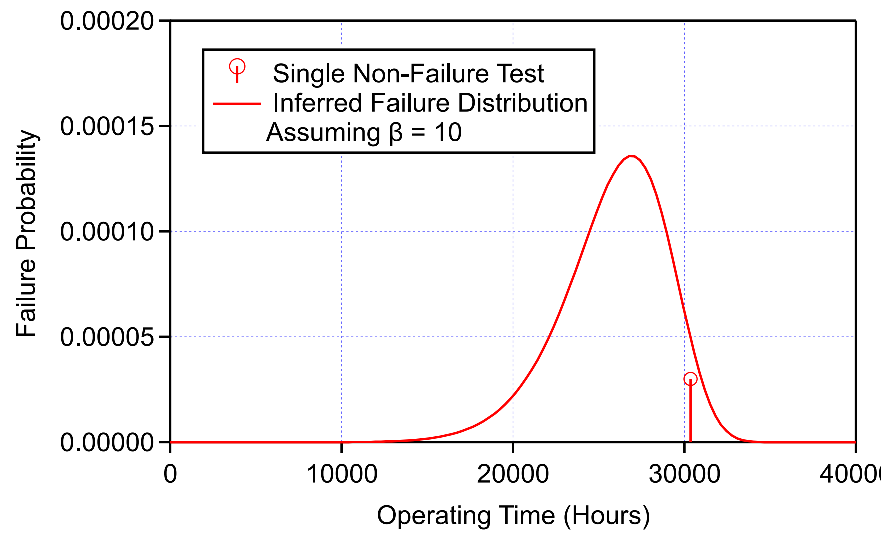
Disadvantages of the Traditional Approach

- **Impractical for planetary missions because of long life requirements and short development schedules**
  - Advanced Electric Propulsion System (AEPS) development plan currently includes a test of 100% of requirement
  - Maintaining funding for long tests is very difficult
- **High reliability cannot be established by limited life testing alone**
  - A single test provides little statistical information about failure distribution
- **Planetary missions tend to push thruster lifetime to the limit**
  - Margins are eroded as mission requirements grow

High Reliability Cannot Be Established by Limited Testing Alone

- **Relying on a single test of 1.5X mission duration assumes:**
  - Width of failure probability distribution is narrow
  - Peak in failure distribution lies well beyond life test duration
- **Problems with this assumption:**
  - A single life test is a weak source of information about the location of the failure distribution
  - A single test provides ***no*** information on the width of the distribution
- **Example: NSTAR 30,000 hour wear test**
  - Assume a narrow distribution (Weibull $\beta = 10$)
  - Best estimate of location parameter (peak) with 95% confidence is about 27000 hours





High Reliability Cannot Be Established by Limited Testing Alone

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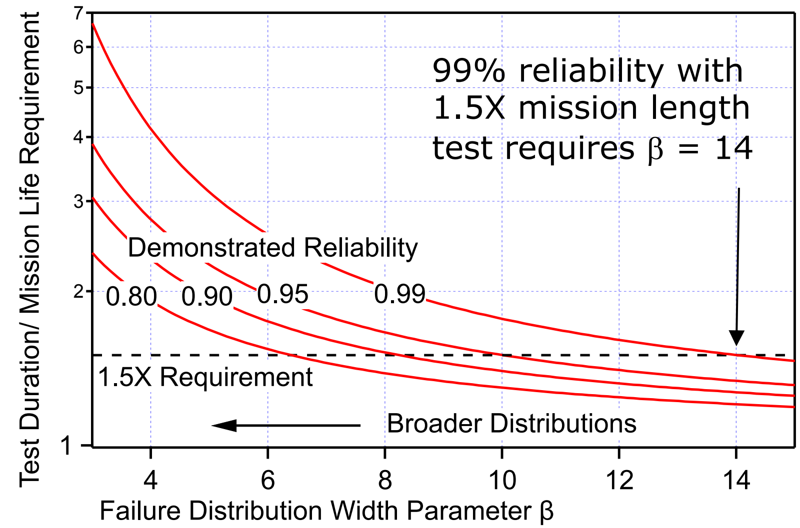
- **Relying on a single test of 1.5X mission duration is inherently risky**
  - High reliability can only be demonstrated if failure distribution is very narrow
  - The test gives no information on what the width actually is!

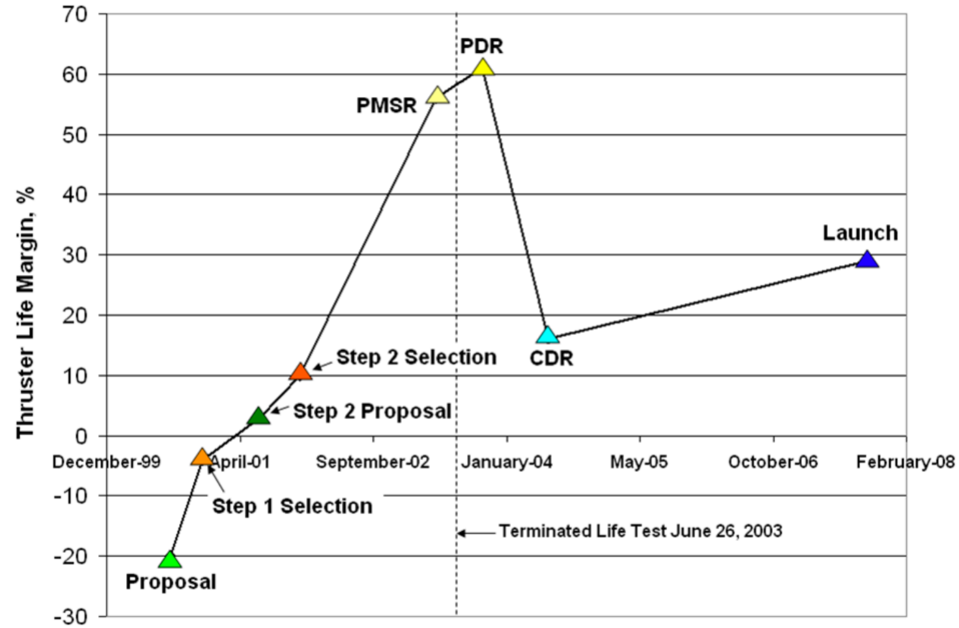


- **EXAMPLE: The SERT II life Test "M" demonstrated 154% of the mission requirement, but**
  - Both thrusters failed before demonstrating the required life in flight
  - Root cause: behavior of the key failure mode not well understood

A single life test is a weak source of information about the location of the failure distribution and provides *no* information on the width of the distribution

Planetary Mission Demands Push Thruster Technologies to Their Lifetime Limits

- **Planetary missions that will use EP must have large post-launch ΔV requirements (typically > ~8 km/s)**
- **Strong pressures exist to fly the smallest, lightest, least expensive EP system**
  - Do not want to add thrusters "just" to handle the propellant throughput
  - This is what Dawn did resulting in a significant impact to the system complexity and cost
- **Changes during the spacecraft development will likely aggravate this situation**
  - Requirements creep (eg. Dawn)
  - Spacecraft mass, power, etc.



JPL Design Principles for Electric Thruster Life Qualification

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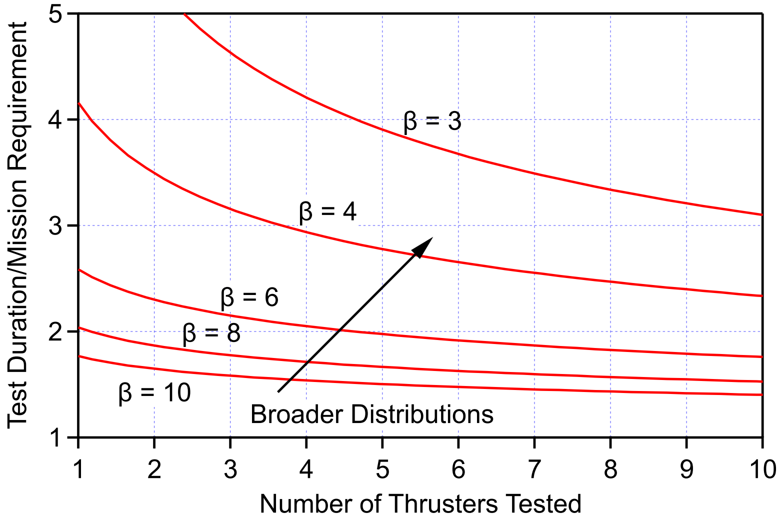
JPL Design Principles

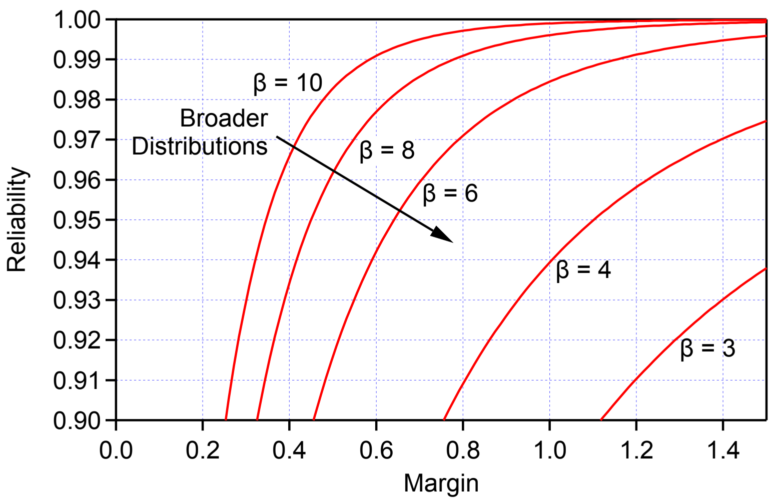
4.7.3.4 Electric thruster life margins – Electric thrusters shall demonstrate by life test a total impulse capability of 100% of the planned worst-case mission usage, and by test or analysis, a margin of at least 33% (factor of 1.5 times the required life). Electric thrusters shall demonstrate by test greater than 33% margin beyond the planned worst-case number of deep thermal cycles (factor of 1.5 times the required number of cycles).

A life qualification standard similar to this has also been included by NASA in the last few Discovery and the New Frontiers solicitations

- **The design principles allow a combination of testing and analysis for life qualification**
- **The AEPS thruster qualification is consistent with these guidelines**
  - One test of 100% mission duration (plus other shorter duration wear tests)
  - Analysis to demonstrate the thruster has margin against the dominant wearout failure modes
- **The key to managing risk:**
  - Due diligence on event-consequent failure modes that can be handled by design and process control
  - Understand the key wearout failure modes

How Much Life Testing Must Be Done and How Large Should the Margin Be?





- **If testing alone were the source of information, long test durations are required**
- **With a combination of limited testing and analysis:**
  - 100% seems prudent to find dominant failure modes and characterize their behavior
- **Required margin depends on the width of the failure distribution**

The AEPS Qualification Approach Relies on Analysis and Testing

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- **Identify and classify potential failure modes**
- **Use conservative design and margin testing for event-consequent failure modes. Examples:**
  - Structural failures during vibe
  - Possibly thermal environment margins, although coupling between temperature and wearout failures must be considered
- **Design for life—push wearout failures way beyond required lifetime where possible. Examples:**
  - Magnetic shielding for channel erosion
  - Cathode orifice sizing to eliminate orifice erosion
- **Use a combination of analysis and structured tests and experiments to assess dominant wearout failure risk**
  - Wear tests to identify failure modes and characterize failure drivers
  - Models validated by experiment to understand failure processes and predict time to failure
  - Tests and analysis to characterize variability in failure mode drivers and model uncertainties
  - Probabilistic methods to predict the uncertainty in the time to failure for critical failure modes

Methods for Identifying Failure Modes

- **Testing. Examples from this and previous programs:**
  - Pole texturing by sputter erosion observed in 150 hour tests of H6
  - Cathode keeper-cathode shorting identified as potential failure mode in NSTAR LDT, confirmed in NEXT ELT
- **Experience**
  - Failure modes observed in previous tests
  - Industry Hall thruster experience
  - Experience with other devices (plasma contactor, NSTAR, NEXT)
- **Technology Base**
  - Materials data
  - Engineering analyses
- **FMEA: bottoms-up approach from component failure mechanisms**
- **Fault Tree Analysis: top-down approach from system failure modes**

Failure mode analysis must be an iterative part of the design/development process

Failure Mode Classification and Corresponding Controls (Detection/Prevention)

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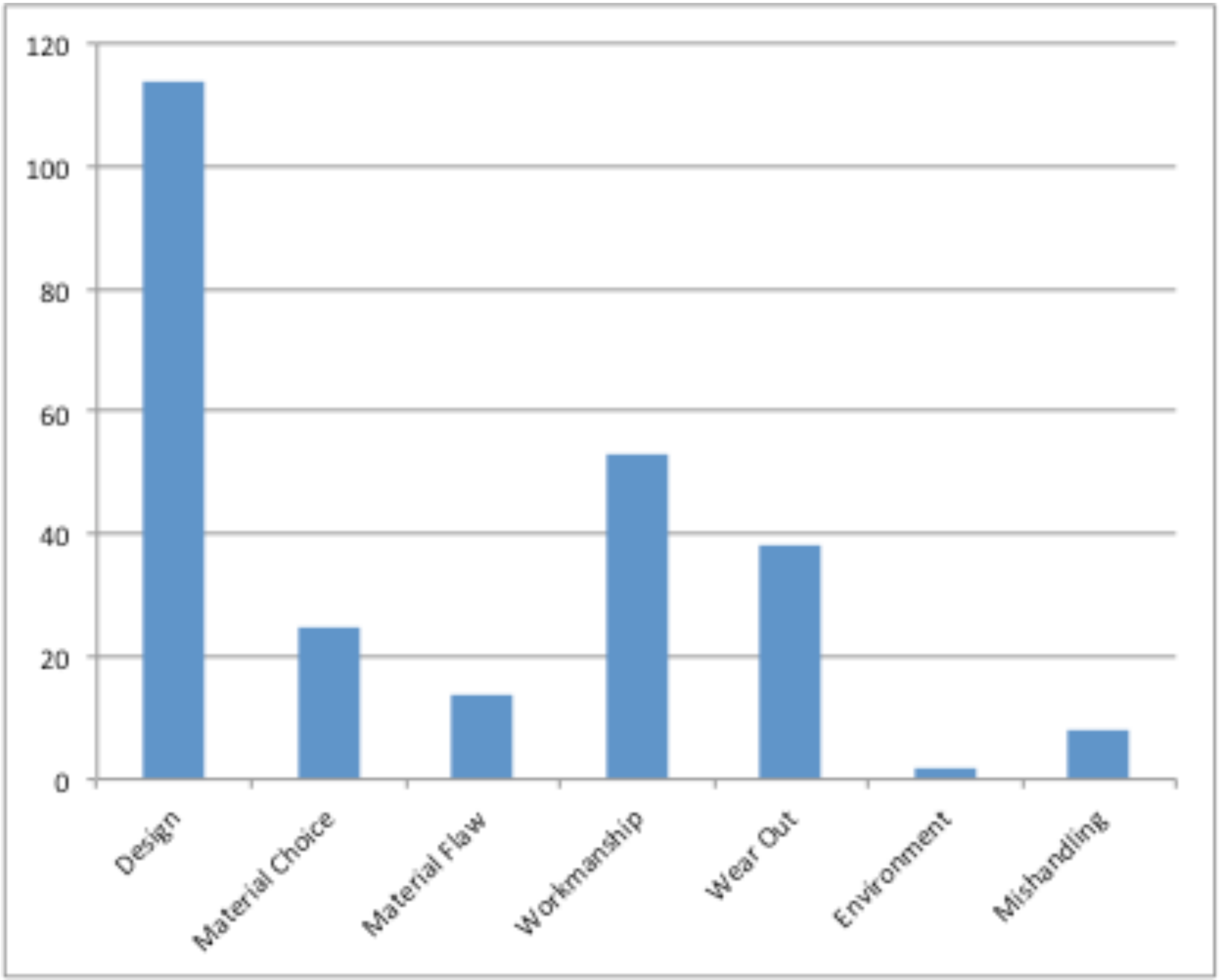
CLASSIFICATIONS	CONTROLS
Classification based on type of failure cause	
– Event consequent: failure due to a single event in which "stress" exceeds "strength" →	Can generally be handled with deterministic design and margin testing
– Wearout: loss of function due to gradual damage accumulation →	May require more complex analysis and testing
Classification based on when root cause occurs	
– **Design** (improper design) →	Design analysis Materials testing TDU/EDU tests Qualification tests
• Design flaw (D) • Poor material choice (MC) • Requirement misspecification*	
– **Manufacturing** (proper design improperly made) →	Inspections Material certifications Component tests Acceptance testing
• Material flaws (MF) • Workmanship errors (W) • Process problems (P)	
– **Use** (proper design, properly built, improperly used or unavoidable aging) →	Wear tests Accelerated tests Analyses and structured tests
• Different environment (E) • Wearout (WO) • Misuse* • Mishandling (MH)*	

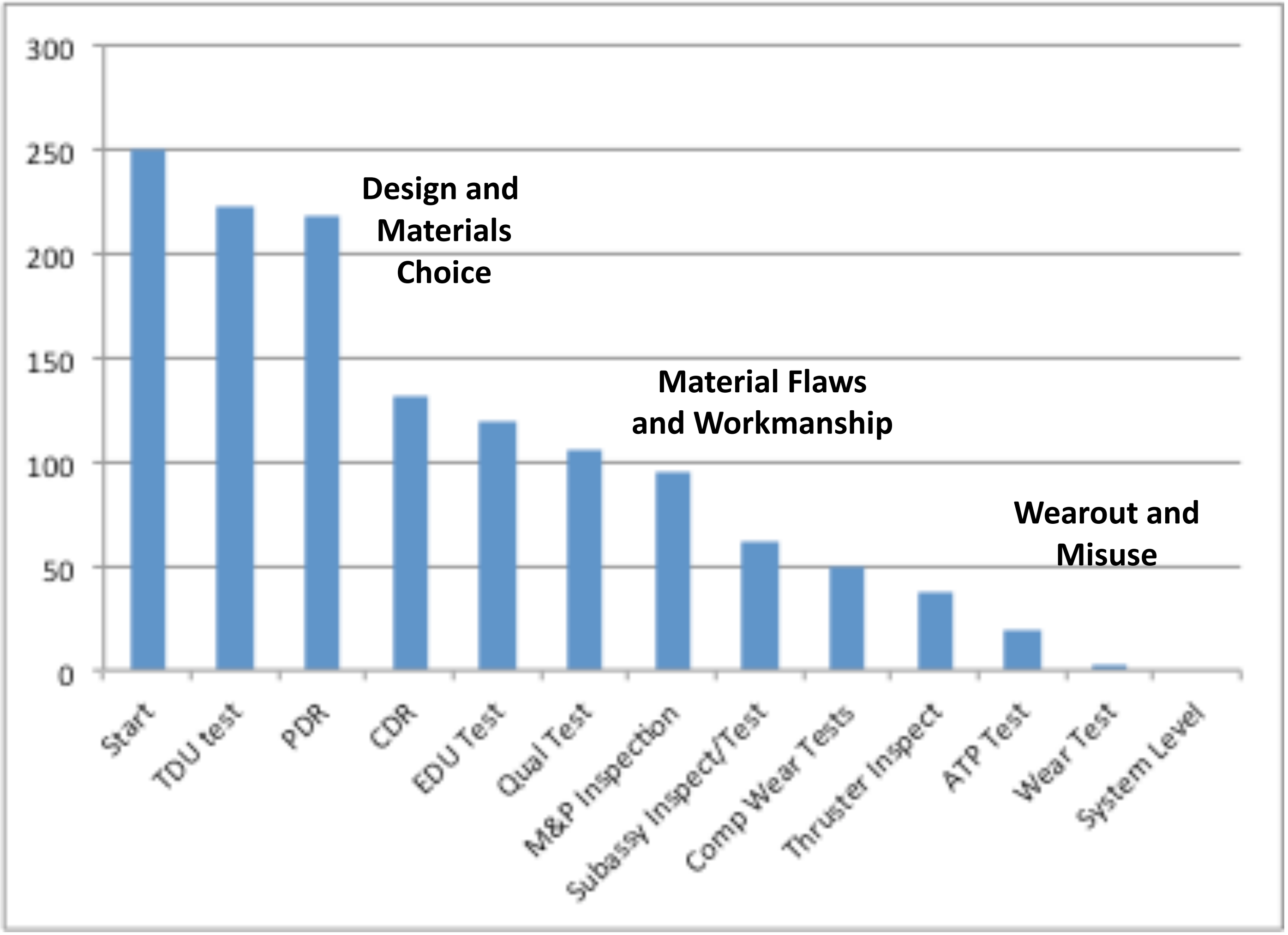
***Not generally dealt with in thruster life qualification**

Potential AEPS Thruster Failure Modes Fall into Seven Categories



Based on AEPS Thruster Failure Modes and Effects Analysis

Plan for Managing Failure Modes



Number of potential failure modes/mechanisms remaining *after* each event

Determining Margin by Analysis to Meet the JPL Design Principles

The full 12-step program:

1. Identify the relevant failure modes
2. Identify the fundamental physical mechanism for the failure process
3. Define drivers of the failure mode
4. Develop a model of the failure process
5. Validate key model components experimentally
6. Characterize drivers in the thruster
   a. Define model input parameters
   b. Understand margins—sensitivity to variations in thruster operating conditions
7. Determine the effects of environment (ground/space, component/thruster, etc.)
8. Develop a deterministic failure prediction
9. Quantify intrinsic variability and uncertainties in model input parameters
10. Determine model uncertainties/limits of applicability
11. Perform probabilistic risk analysis if necessary
12. Quantify life margin

Offramps:

- Steps 2–7 → Modify design to eliminate failure mode (ideal)
- Step 8 → If time-to-failure is far beyond mission requirement and uncertainties are small, this may be sufficient
- Step 12 → Full process required for dominant failure modes with significant uncertainties

The Role of Testing

- **Testing is a weak source of statistical information about the location and width of the failure distribution with small sample sizes**

- **However, testing is a rich source of information for:**
  - Identifying failure modes
  - Determining the failure mechanisms
  - Characterizing failure mode behavior during the approach to failure
  - Guiding the development of models
  - Specifying model input parameters
  - Validating failure models
  - Characterizing uncertainties in models and model input parameters

The Role of Modeling and Analysis

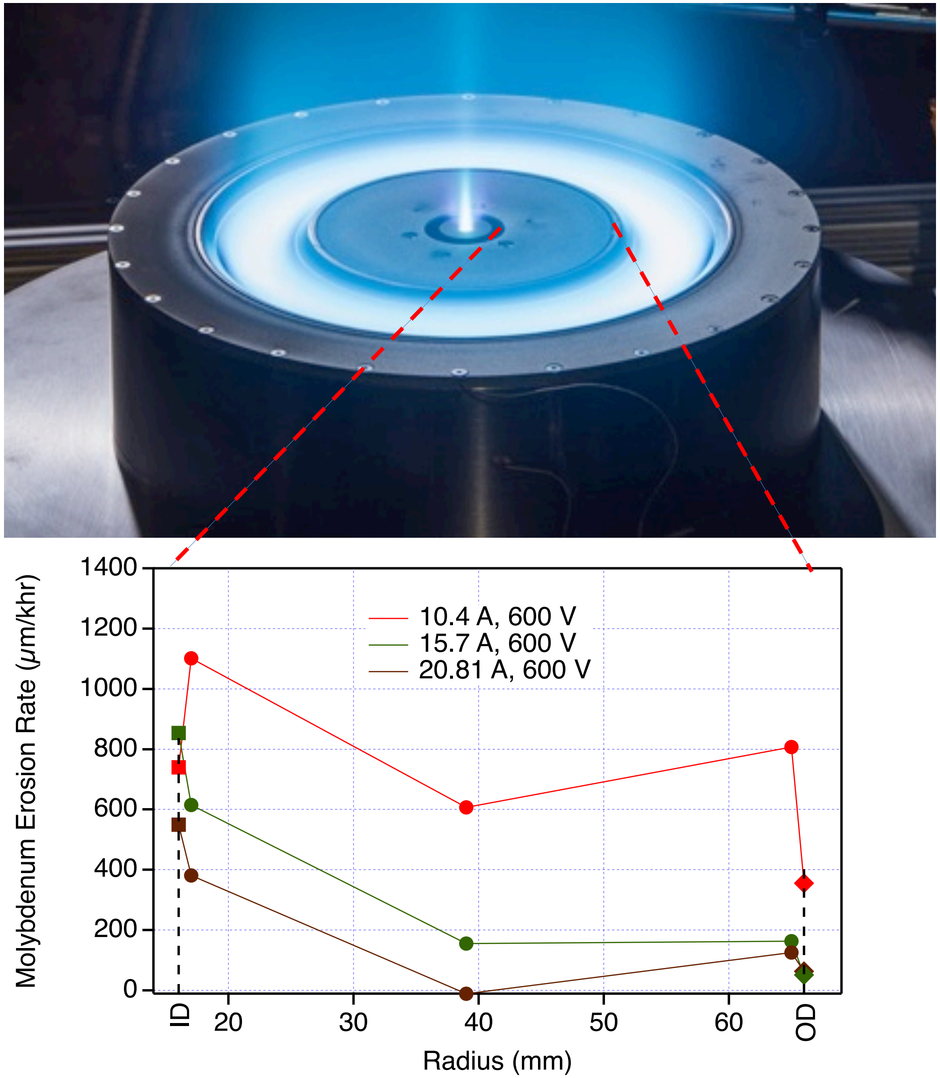
- **Modeling and analyses provide the understanding that ties information from testing with mission requirements to establish reliability**
- **Unlike thruster testing alone, modeling and analyses can provide a quantitative estimate of failure probability**
- **Properly validated models can also provide insight into operating conditions and environments that differ from those tested**
- **Modeling and analysis can be used to assess the impact of design changes**

Relying on experimentally validated, physics-based models to determine failure risk is the best approach for critical failure modes

Three Examples of Wearout Failure Modes

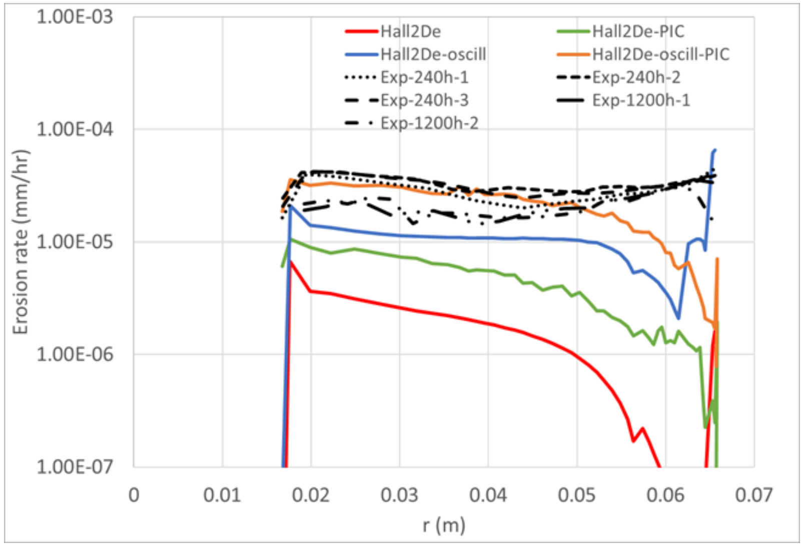
- **Cathode heater failures**
  - Opportunity to test multiple units and apparent narrow failure probability distribution allow more conventional statistical approach
  - Focused tests and analytical modeling of dominant failure processes will supplement life demonstration in cycled tests
- **Cathode emitter failure due to barium depletion**
  - Considered to be the first failure mode for the cathode
  - Models are relatively mature and the drivers are well-understood, with the possible exception of the effect of time-varying currents in Hall thrusters
  - Anticipate that analysis and test will show that this does not require probabilistic risk assessment
- **Pole erosion**
  - Currently considered to be the first failure mode
  - Engineering solution that needs to be validated
  - Models gaining maturity; may require a full probabilistic risk assessment

Pole Erosion is a Critical Potential Failure Mode



Measured erosion rates on a molybdenum pole cover over a range of operating conditions

- **Energetic ions from the plume and cathode can erode the inner front face of the thruster**
- **A graphite cover is designed to protect the pole piece and should provide adequate life**
- **Much progress has been made modeling pole erosion, but it is not fully understood yet**

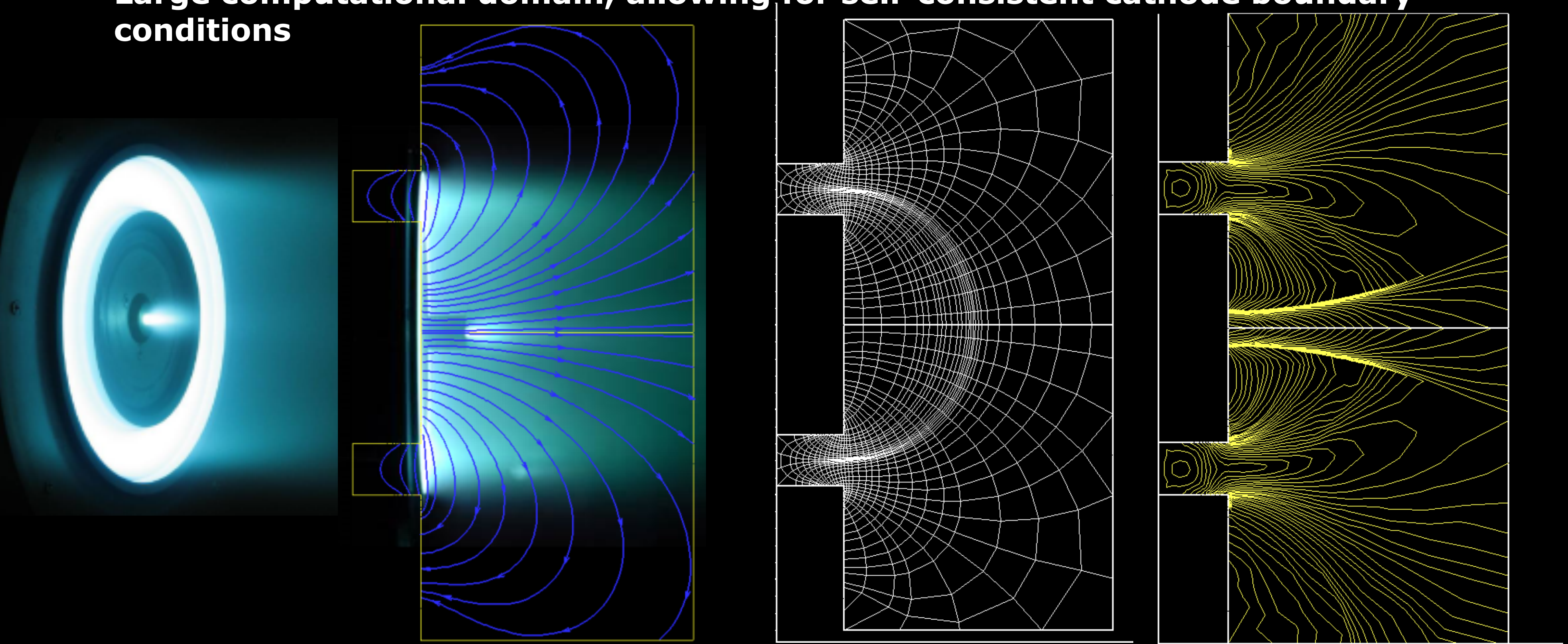


Comparison of simulations and measured erosion rates for a graphite cover at 600 V, 20.8 A

The Hall2De Code Is Being Modified to Model Pole Erosion

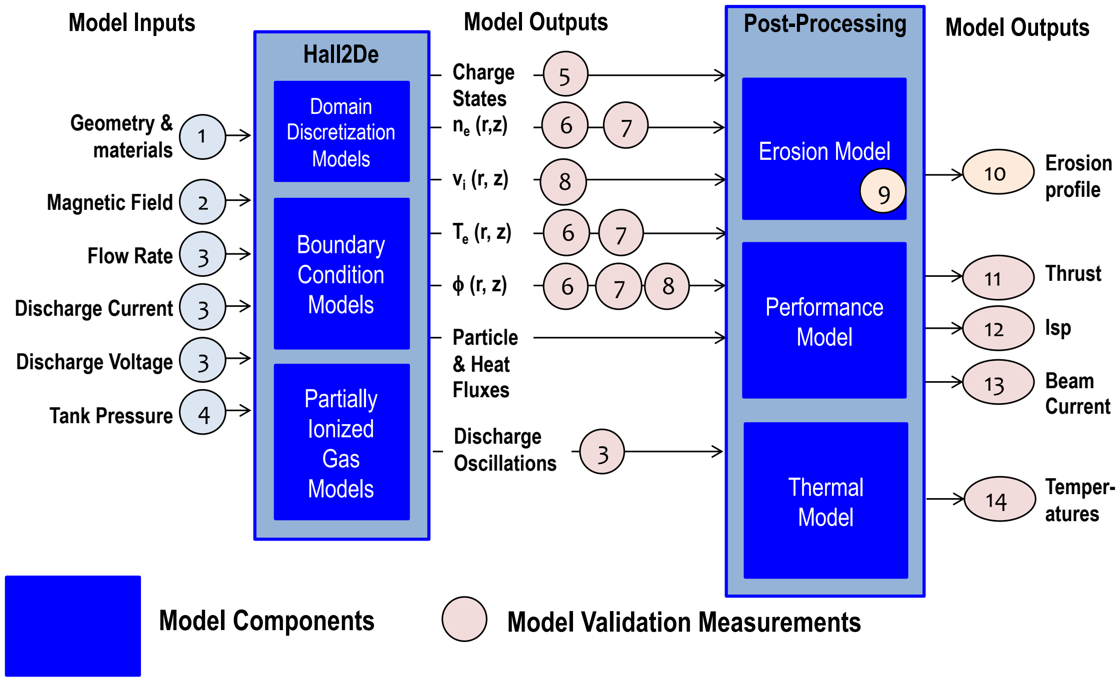
The 2-D axisymmetric code Hall2De is a physics-based plasma and erosion solver that began development at JPL in 2008 to support the design and life qualification of Hall thrusters for NASA science missions.

- **Discretization of all conservation laws on a magnetic field-aligned mesh (MFAM)**
- **Two components of the electron current density field accounted for in Ohm's law**
- **Sheath physics modeled in appropriate boundary conditions**
- **Large computational domain, allowing for self-consistent cathode boundary conditions**



6 kW Lab Hall thruster — Magnetic field streamlines — Hall2De computational mesh — Ion density line contours

Pole Erosion Model Structure and Validation



1. Hardware inspection and/or manufacturer specs
2. Hall probe measurements
3. Macroscopic thruster measurements
4. Pressure gauge measurements near thruster
5. ExB probe measurements in plume
6. Centerline high speed probe measurements
7. Wall probe measurements
8. Laser induced fluorescence measurements
9. Near-threshold sputter yield measurements
10. Direct erosion measurements
11. Thrust stand measurements
12. Thrust stand and flow rate measurements
13. Integrated beam current density measurements
14. Thermocouple and thermal camera measurements

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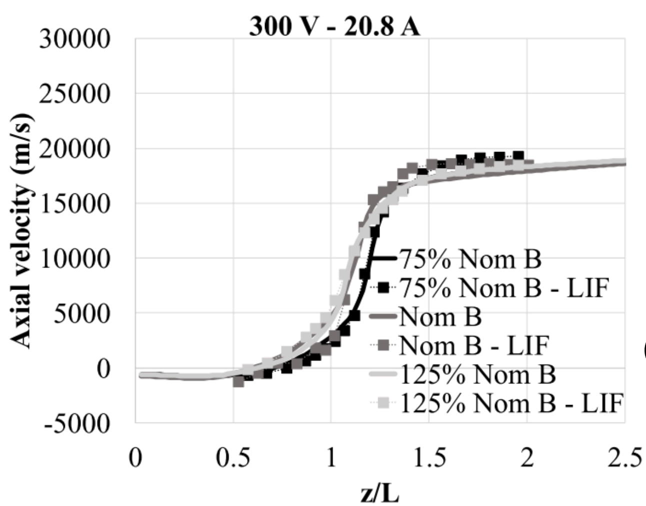
Ion Velocities (measured and predicted)



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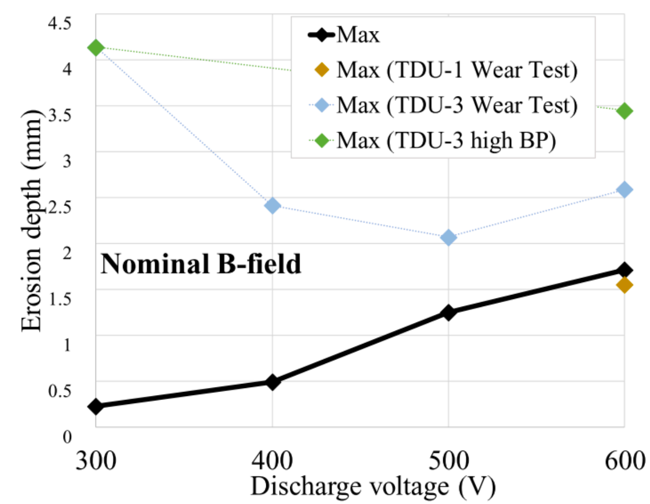
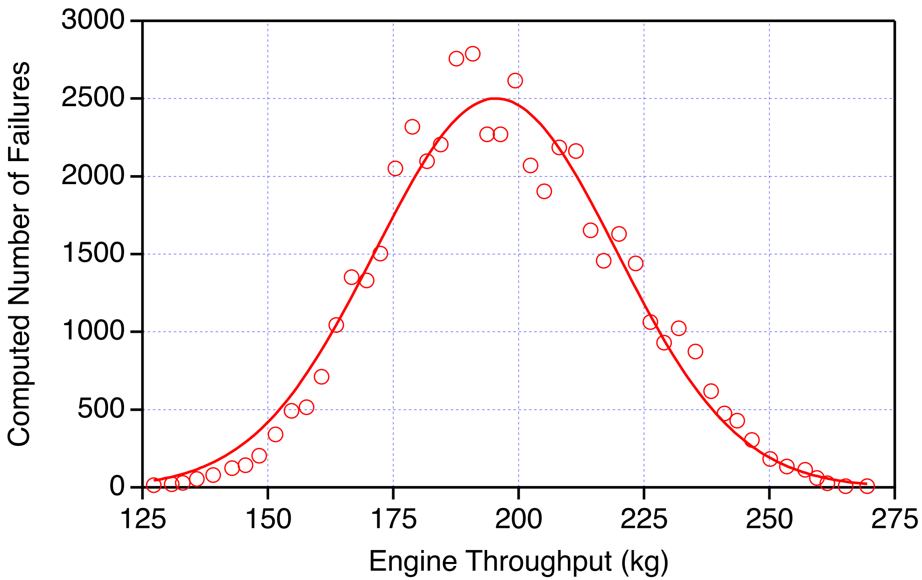
Projected erosion depth after 34500 hours (measured and predicted)



Probabilistic Failure Analysis (PFA) for Critical Failure Modes



Example calculation for Dawn ion thrusters: electron backstreaming due to accelerator grid hole erosion at full power

- **If predicted failure time is not much greater than required life, more detailed analysis is required to demonstrate margin**
- **PFA process:**
  - Characterize variability and uncertainty in input parameters with appropriate distribution
  - Sample from input parameter distributions to calculate large number of failure time predictions in Monte Carlo simulation
  - Bin results to approximate failure probability distribution
- **Benefits**
  - Quantitative assessment of failure risk
  - Captures intrinsic variability as well as lack of knowledge
  - Sensitivity analysis can help prioritize investments to reduce uncertainties

Conclusions

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- **Development programs can afford only limited wear testing, which is a weak source of information for statistical assessment of failure risk**
- **Combining test data and validated, physics-based models of dominant failure modes is a better way of managing risk**
  - Depends on identifying all relevant failure modes (process fails if there are surprises)
  - Allows assessment of design changes
  - Provides tools for assessing failure risk for different throttle profiles
- **Implementation in AEPS Hall thruster development**
  - Rigorous process to identify potential failure modes
  - Development and validation of physics—based models
  - Currently refining deterministic predictions and characterizing uncertainty in models
  - Will likely require probabilistic analysis for critical failure modes like pole erosion

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BACKUP

"The thruster looked fine at the end of the test, it must have lots of life left"

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- **It's easy to come to this conclusion, but dangerous...**
- **Three potential dangers related to intrinsic variability:**
  - **Extreme sensitivity to a driving parameter**
    - Example: many erosion processes occur near the sputtering threshold, where small changes in ion energy can lead to orders of magnitude more erosion
  - **Differing ground test and flight environments**
    - Example: SERT II experience—the mitigation for a recognized failure mode did not work as expected in zero g
  - **Some failure modes are highly dependent on throttling profile**
    - Example: Low power operation in the NSTAR life test revealed neutralizer orifice clogging that caused plume mode operation. If the wear test had not included extended operation at low power, this would have gone undetected.

These are examples of intrinsic variability that produces wide failure distributions

Long Lifetime Requirements Make Extensive Testing Infeasible

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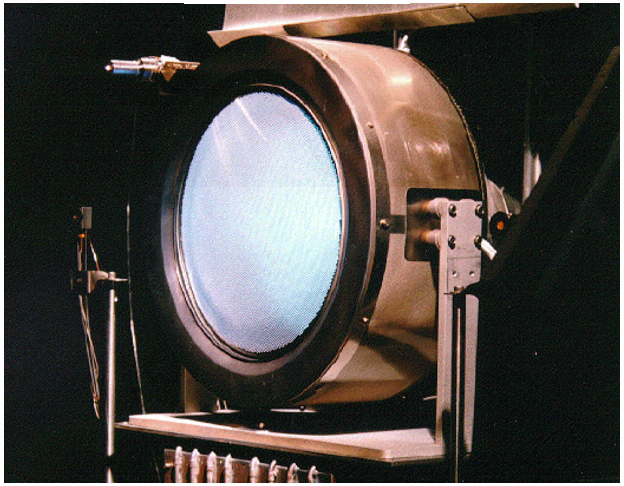
- **Life tests can take 5 years or more**
  - Dawn thruster life requirement was 25,000 hours per thruster
    - 150% life test at 75% duty cycle is > 6 years!
  - Very difficult to keep sponsors focused for that long
    - The NSTAR ELT had 5 different sponsors over 5 years

- **Must expect changes to be made as a result of long-duration tests – impractical to retest**

Example



- **NSTAR ELT:**
  - Started October 1998
  - Finished June 2003

- **Changes resulting from the test**
  - Keeper material
  - Neutralizer operation
  - Low-voltage propellant isolators

A Survey of Industry Practices

- **Examples of qualified commercial thrusters**
  - Hydrazine resistojets and arcjets (Aerojet for Lockheed Martin)
  - 13 and 25 cm XIPS ion thrusters (L3 for Boeing)
  - SPT-100 Hall thruster (SS/L)
  - BPT-4000/XR-5 Hall thruster (Aerojet for Lockheed Martin)
- **Single fault tolerant (can lose 1 thruster on Day 0)**
- **Industry practice based on one of two sources**
  - An early comsat requirement:
    - A single test of 1.5x mission duration and cycles under worst case conditions (one thruster failure on Day 0)
  - MIL-STD-1540E:
    - A single test of 2x mission life and cycles for nominal mission
    - Sometimes add 15-30% to this
- **Throttling requirements are generally less demanding**
  - Typically 1-2 levels or simple blow-down
  - Each level tested for 1.5x or over a nominal blow-down profile

Current practice relies heavily on a single life test with margin against mission requirements

Life—A Quantity That Can Be Margined?

- **Life qualification traditionally treats life limited by wearout failure modes as a quantity that can be margined, with margin demonstrated in a single wear test**

- **Reasonable approach for event-consequent failure modes (those resulting from a single episode where a load exceeds a component's capability)**
  - Generally well-understood failure processes with well-characterized failure distribution
  - Doesn't require long duration tests to demonstrate margin (a life test is a very long single episode…)

- **Inherently high-risk for wearout failures**
  - Experience is generally insufficient to know how broad the failure distribution is and how much margin must be applied
  - Can result in overly conservative margins
  - A single wear test, particularly if voluntarily terminated, provides no information on the width of the distribution
  - Also provides no information on the margin at operating points and/or environments not tested (space vs. ground, for instance, or with variable input parameters)

28

High Reliability Cannot Be Established by Limited Testing Alone

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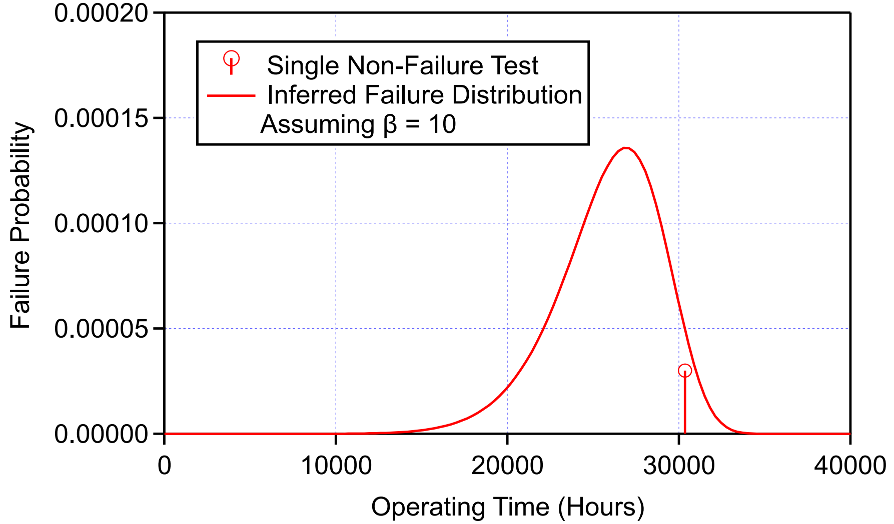
- **Assume failure mode follows a Weibull distribution:**

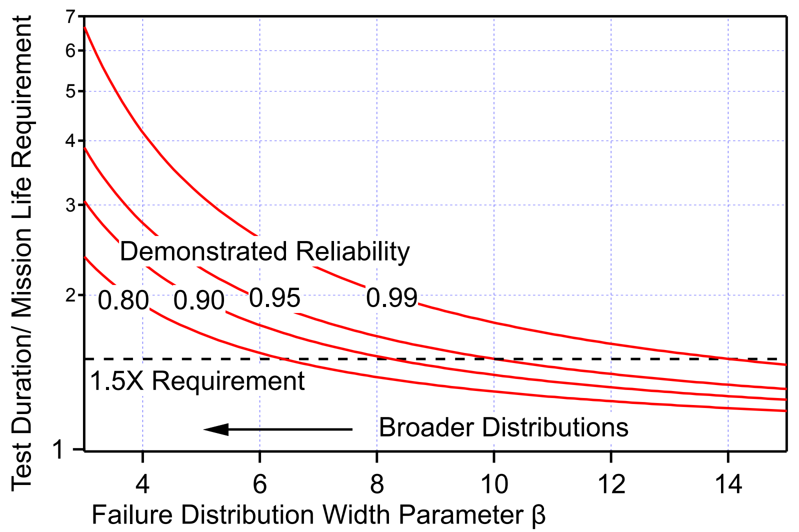
$$P_f = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{(\beta-1)} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

- **Best estimate of the location parameter η is given by**

$$\eta = T\left[-\frac{\ln(1-C)}{N}\right]^{(-1/\beta)}$$

- **Narrow distributions ($\beta \geq 14$) required to demonstrate high reliability (≥ 0.99) with high confidence by a single test of 1.5 x life requirement**





But the test provides no information on the value of β!