Extended Wear Testing of the 12-kW Advanced Electric Propulsion System Engineering Test Unit Hall Thruster

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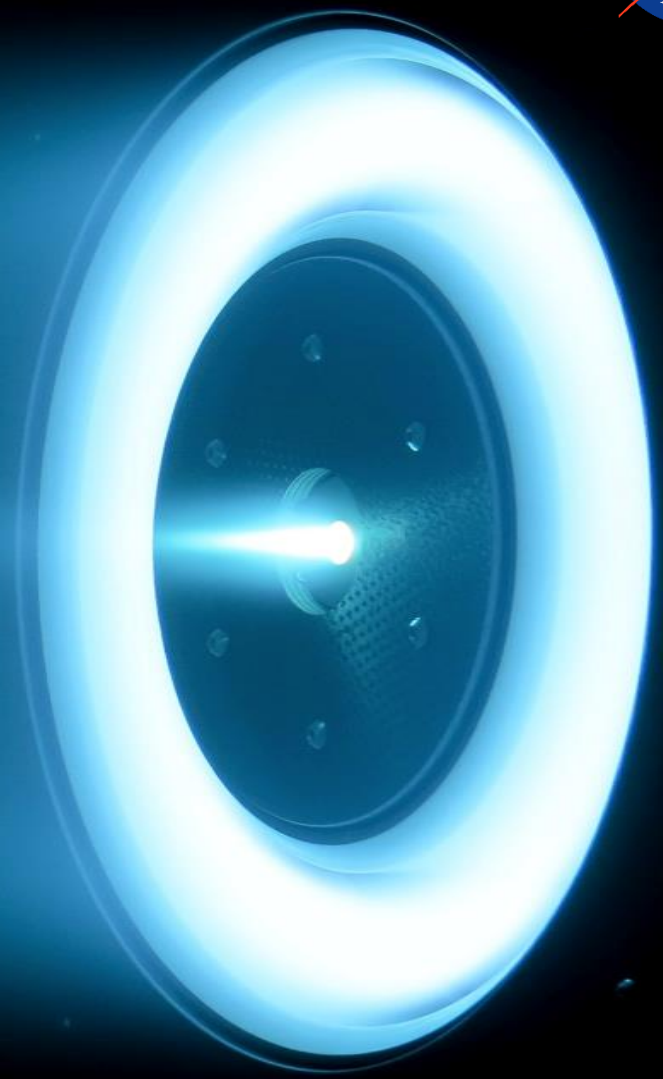
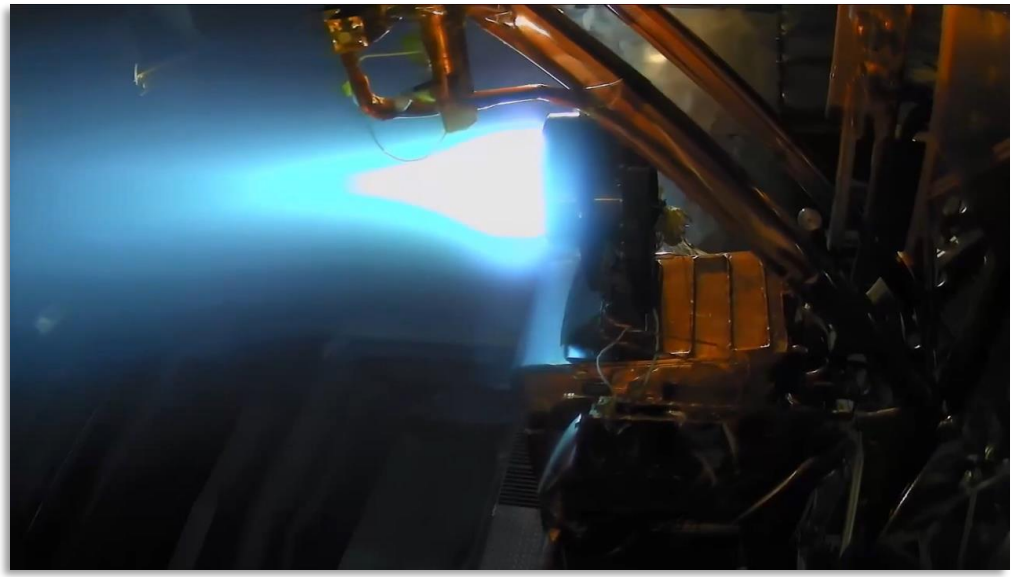


Introduction

- High-power (40-kW) SEP capability has been identified as enabling for near term and future NASA exploration architectures
  - Example: Maxar Power and Propulsion Element of NASA's Gateway
- Since 2012, NASA has been developing the Hall Effect Rocket with Magnetic Shielding (HERMeS) to serve as a SEP capability building block
- Technology development transitioned to Aerojet Rocketdyne (AR) via Advanced Electric Propulsion System (AEPS) contract
  - AR has produced two AEPS Engineering Test Unit (ETU) thrusters and is leading a detailed test campaign to assess design compliance with AEPS requirements
  - NASA continues to support AEPS development by leveraging in-house expertise, plasma modeling capability, and world-class test facilities



Previous HERMeS/AEPS Wear Tests

HERMeS Technology Demonstration Units (TDUs)

- 2016 TDU-1 Wear Test: AIAA Paper 2016-5025
  - Provided first quantitative insights into wear and performance trends over an extended period of operation
  - 1700 h of operation at 600 V/12.5 kW
- 2017 TDU-3 Short Duration Wear Test: IEPC Paper 2017-207
  - Quantified thruster life at a range of operating conditions
  - 200 h segments (7x) each performed at a different operating condition
- 2017-2018 TDU-3 Long Duration Wear Test: AIAA Paper 2019-3895
  - Pathfinder test for the planned AEPS life qualification campaign
  - 3,570 h of operation split between six test segments

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AEPS Engineering Test Units (ETUs)

- 2019-2020 ETU-2 Wear Test: AIAA Paper 2020-3625
  - Quantified performance and wear trends of the AEPS ETU design to assess compliance with requirements and provide a comparison to the HERMeS Technology Demonstration Units (TDUs)
  - 730 h of operation split between six test segments
- ➢ 2021: ETU-2 Extended Wear Test
  - Goal: acquire wear data at discharge currents other than 20.83 A
  - Three test segments:
    - 294 h at 600 V/11 kW
    - 302 h at 600 V/12 kW
    - 267 h at 600 V/9 kW

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Over 8,000 hours of wear testing performed at the development level

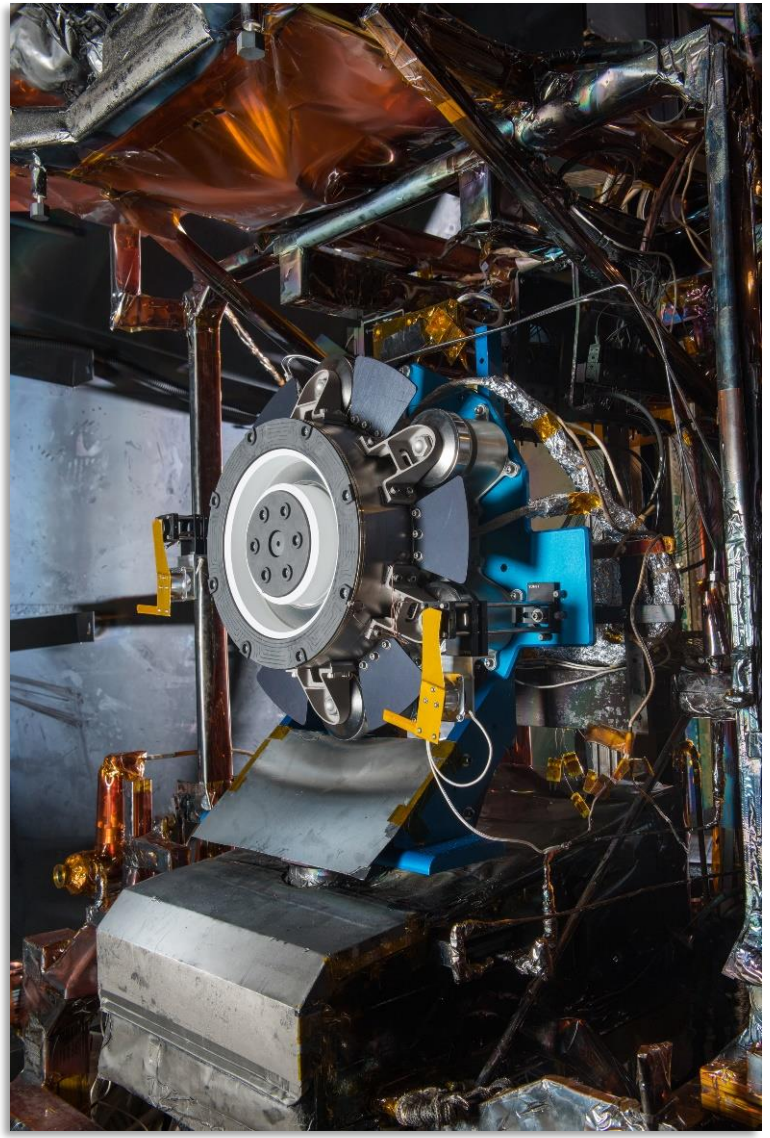
Thruster and Facility

Aerojet Rocketdyne AEPS ETU-2

- ETU design derived from and preserves key features of the HERMeS TDUs, but includes modifications to improve manufacturability and ability to meet environmental and spacecraft interface requirements
- Thruster electrically configured per recommendations from Peterson et al. (AIAA Paper 2016-5027)
  - Thruster body electrically tied to cathode
  - Dielectric coating on all surfaces within 1 m of exit plane
- Power and propellant supplied using calibrated commercial laboratory systems
  - Flow rate uncertainty: 0.6-1.3 sccm
  - Voltage uncertainty: ±0.06 V
  - Current uncertainty: ±0.03 A

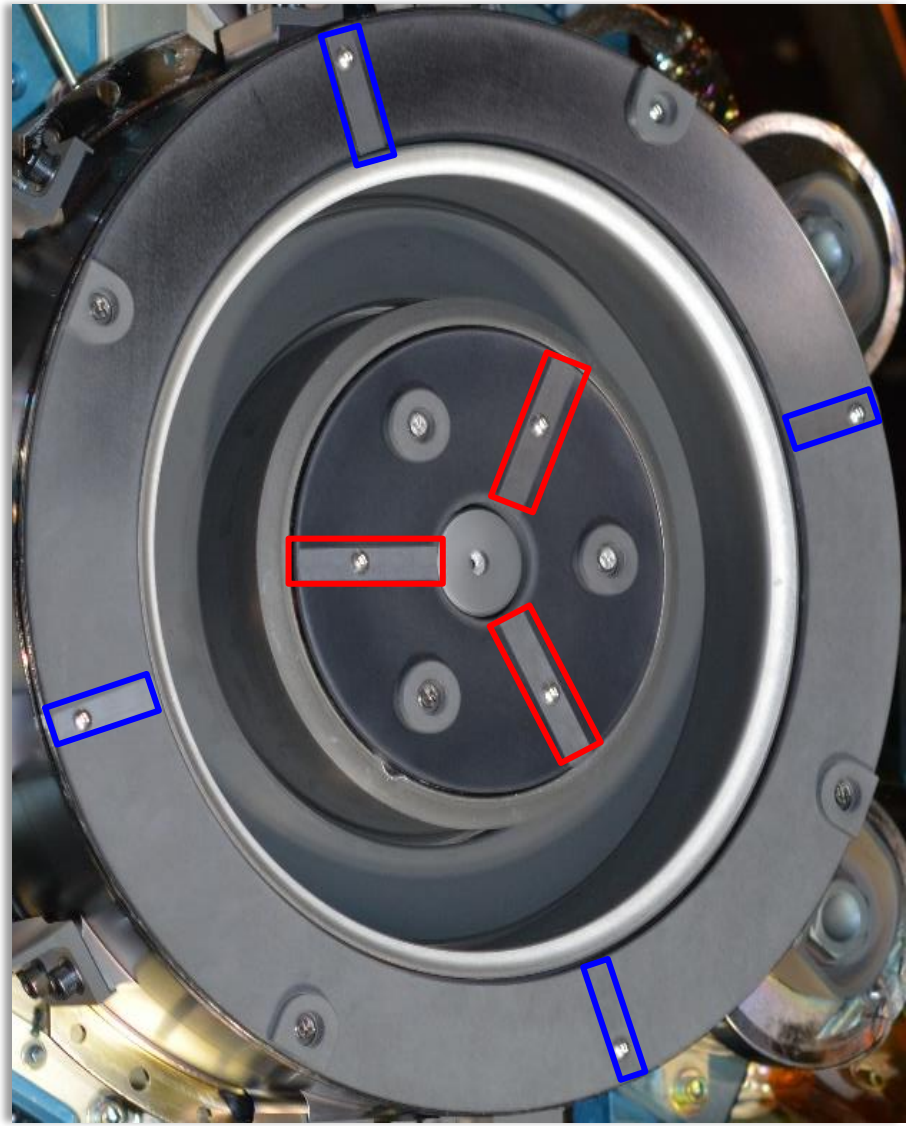
NASA Vacuum Facility 5

- Nominal pumping speed: ~700 kl/s on xenon
- Nominal operating pressure: ~4.0 µTorr at 12 kW throttle point
- Facility includes an inverted pendulum thrust stand with ± 0.8% uncertainty used extensively in previous TDU and ETU testing (AIAA Paper 2018-4516)



Wear Measurement Approach

- Wear measurements obtained using the same approach as during previous TDU and ETU wear tests
- Inner front pole cover (IFPC) and outer front pole cover (OFPC) modified to enable wear measurements
  - Graphite components polished pre-test to maximize surface uniformity
  - Graphite masks installed to provide unexposed reference surfaces:
    - IFPC: series of graphite strips covering approximately 95% of radius
    - OFPC: series of graphite strips covering approximately 95% of radius
- Erosion measurements made with a chromatic, white-light, non-contact profilometer
  - Data analyzed per ISO 5436-1 guidance for a type A1 step
  - Typical uncertainties on the order of ±2 µm accounting for:
    - Instrument error
    - Surface roughness
    - Non-flat surface geometry



Performance Results

- Thruster performance and stability characterized before and after each wear block at 9 Reference Firing Conditions (RFCs)

Discharge Voltage (V)	Discharge Current (A)	Discharge Power (W)	Inclusion Rationale
300	10.00	3000	Low-power performance characterization
300	15.00	4500	
300	20.00	6000	
300	20.83	6250	Point-of-comparison to prior testing
600	20.83	12500	
600	15.00	9000	Wear test conditions of interest
600	16.67	10000	
600	18.33	11000	
600	20.00	12000	
Cathode Flow Fraction, All Conditions		$1.0\ CFF_{nominal}$	
Magnetic Field Strength, All Conditions		$1.0\ B_{nominal}$	

Performance Results

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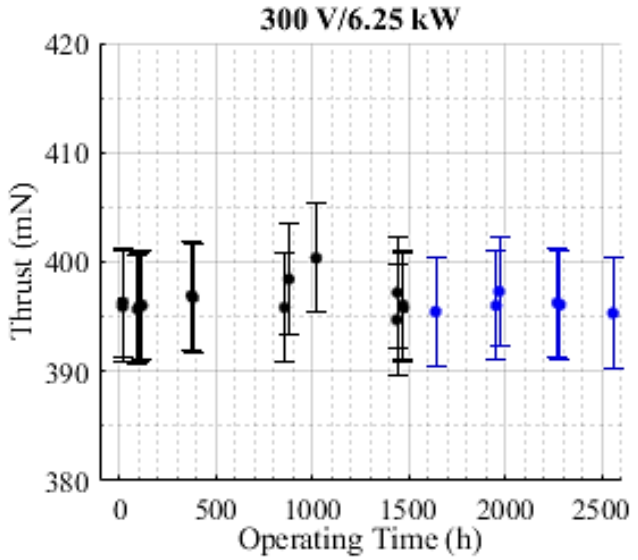
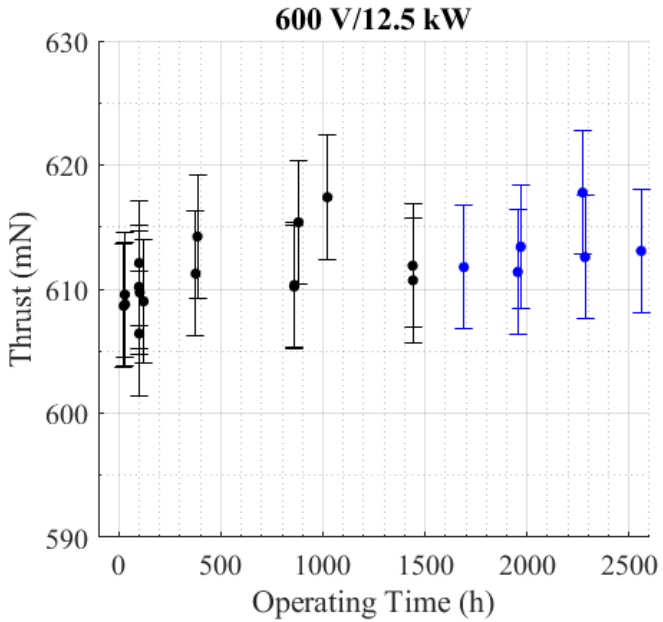
- Thrust of ETU-2 matched historical means to within the empirical uncertainty for all RFCs and did not vary with operating time

RFC	Thrust (mN)	
	Mean	Wear
300 V/3.00 kW	184	184
300 V/6.25 kW	395	396
600 V/9.00 kW	446	446
600 V/12.00 kW	591	590
600 V/12.50 kW	611	613
Uncertainty	± 5 mN	

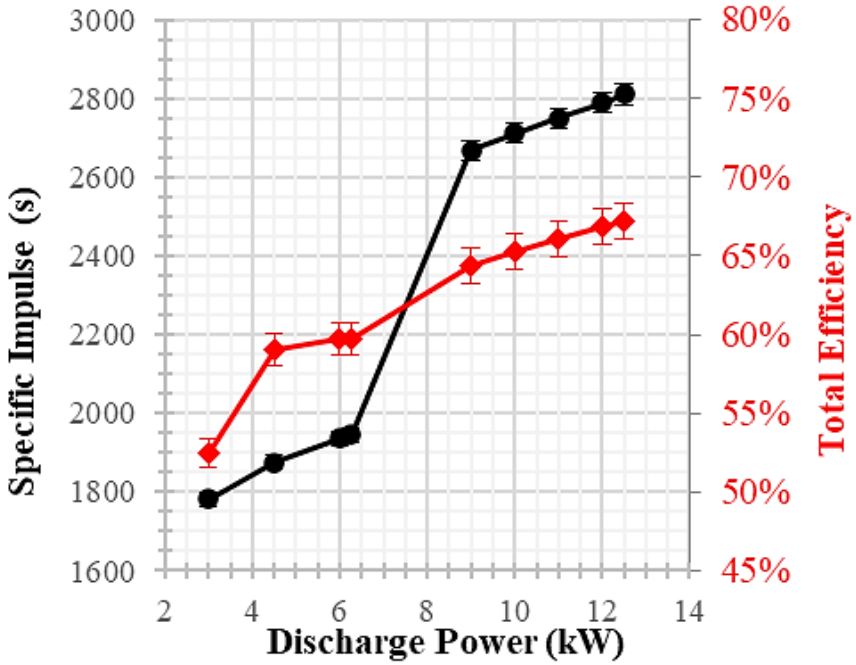
Wear Measurements





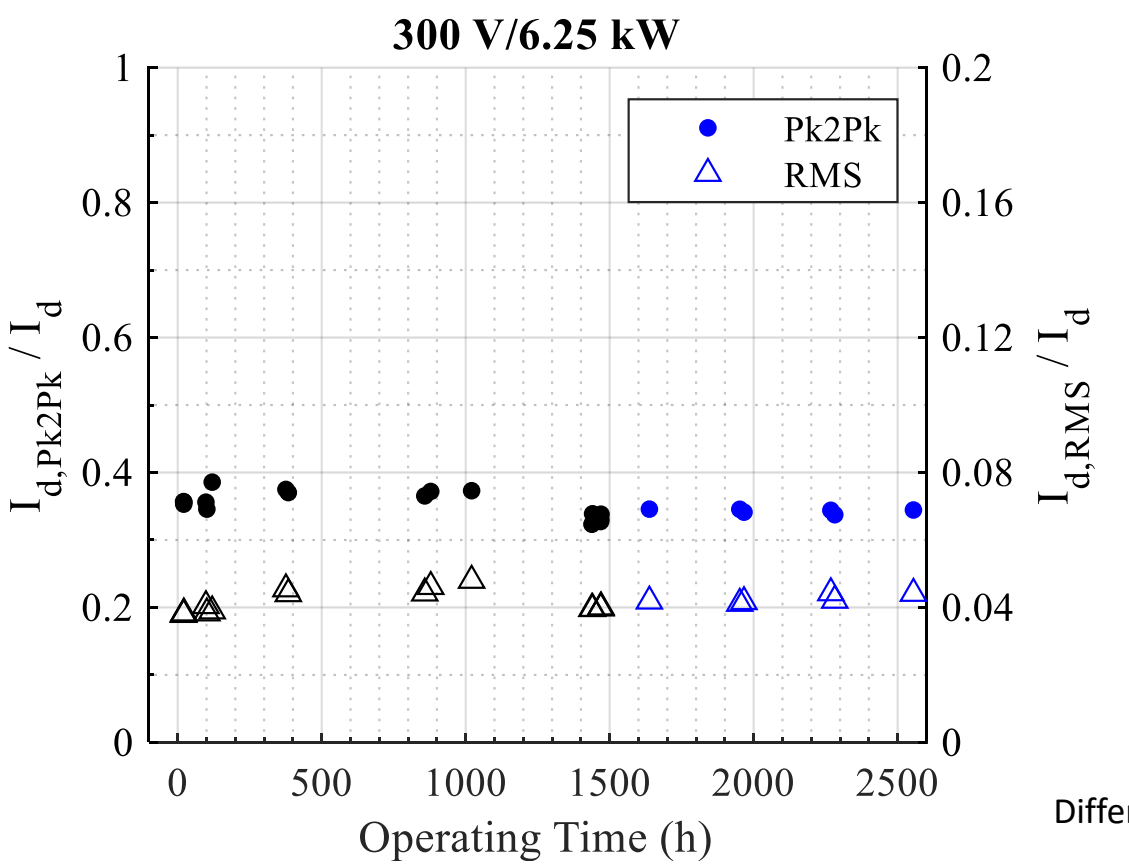
Performance Results

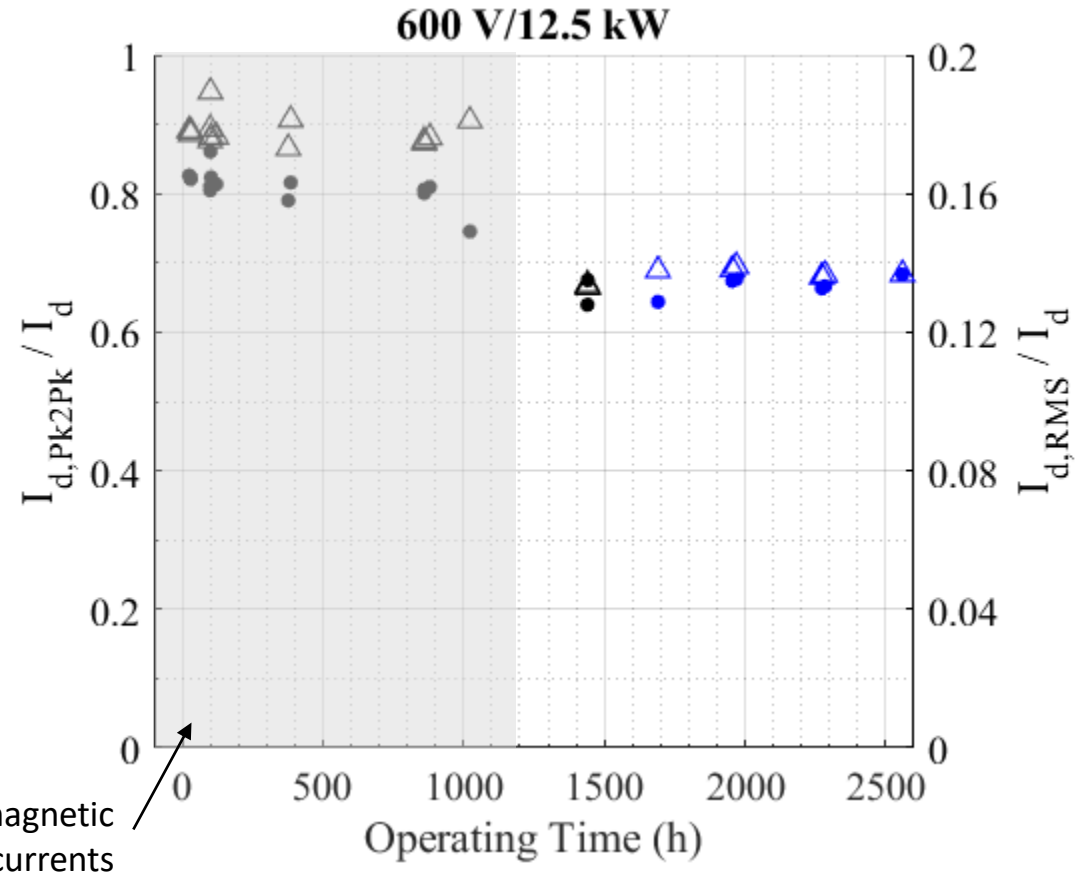
- Thruster performance and stability characterized before and after each wear block at 9 Reference Firing Conditions (RFCs)
- Thrust of ETU-2 matched historical means to within the empirical uncertainty for all RFCs and did not vary with operating time
- Specific impulse and total efficiency followed similar trends to thrust



RFC	Thrust (mN)		Specific Impulse (s)		Total Efficiency (%)	
	Mean	Wear	Mean	Wear	Mean	Wear
300 V/3.00 kW	184	184	1785	1781	52.2	52.4
300 V/6.25 kW	395	396	1945	1944	59.6	59.8
600 V/9.00 kW	446	446	2674	2668	64.5	64.4
600 V/12.00 kW	591	590	2795	2789	67.0	66.8
600 V/12.50 kW	611	613	2802	2810	66.8	67.2
Uncertainty	± 5 mN		± 0.9%		± 1.7%	

Discharge Current Oscillation Results

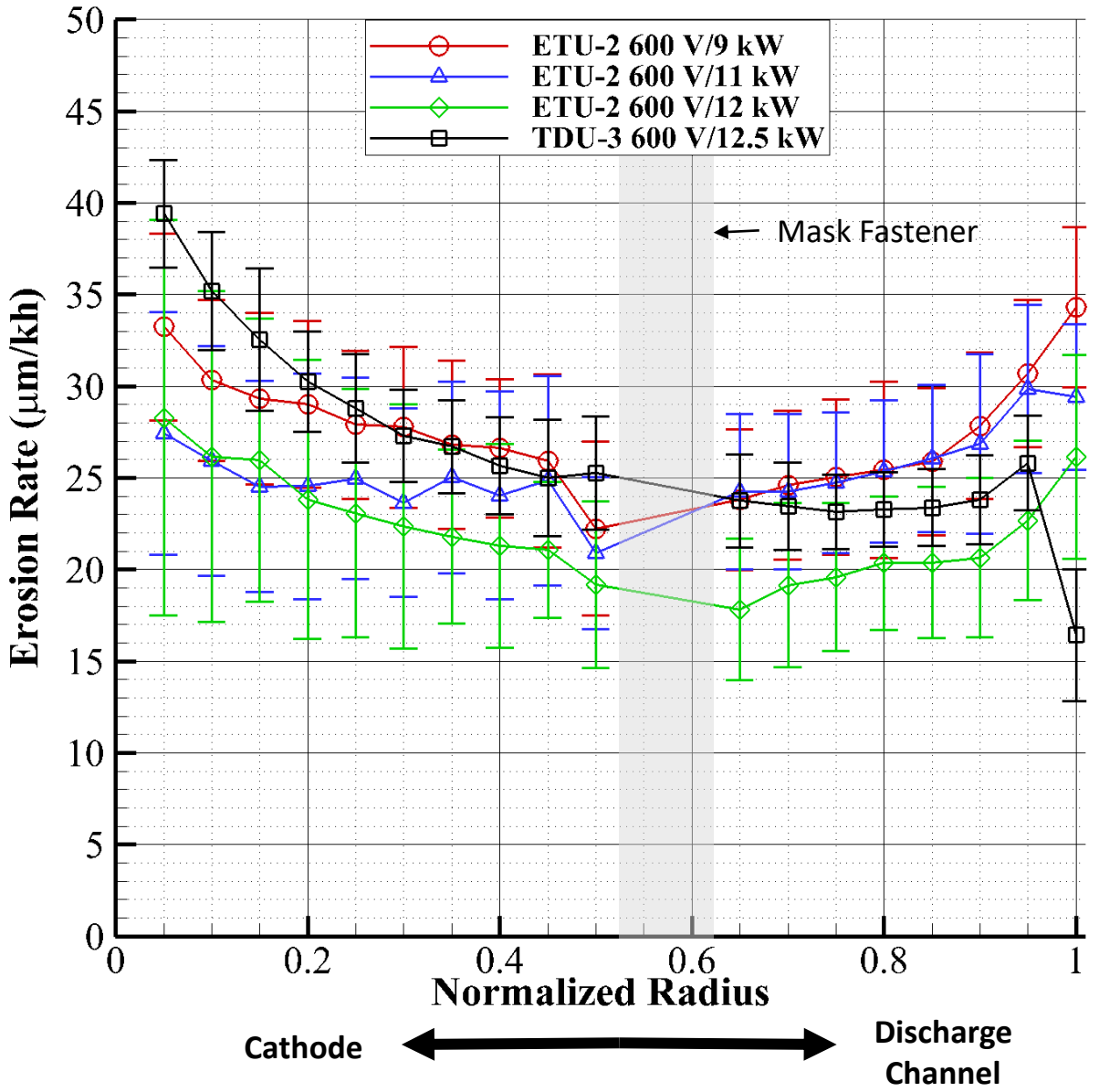




Invariance with operating time also observed in ETU-2 discharge oscillation characteristics

Wear Results: Inner Front Pole Cover

- The erosion rates measured at 9 kW, 11 kW, and 12 kW were equal to within the empirical uncertainty at all normalized radii and matched previous results obtained at 12.5 kW
  - Outlier near the discharge channel at 12.5 kW likely an artifact of increased uncertainty due to edge effects



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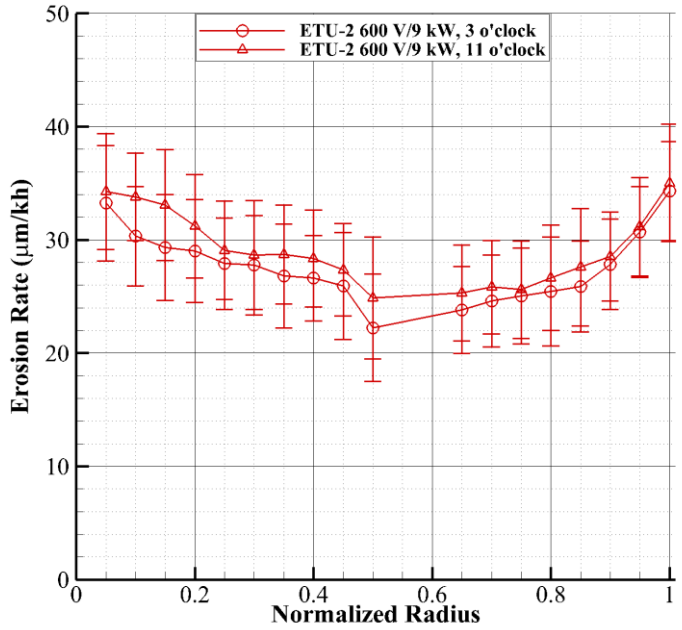

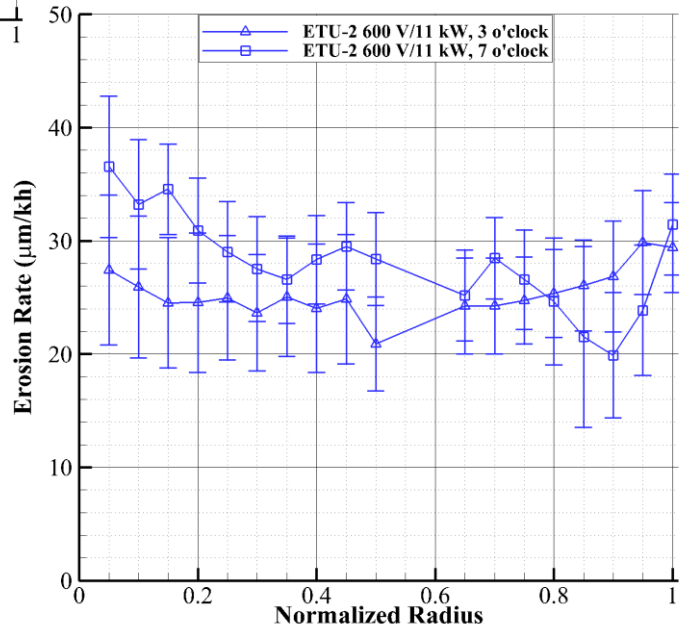

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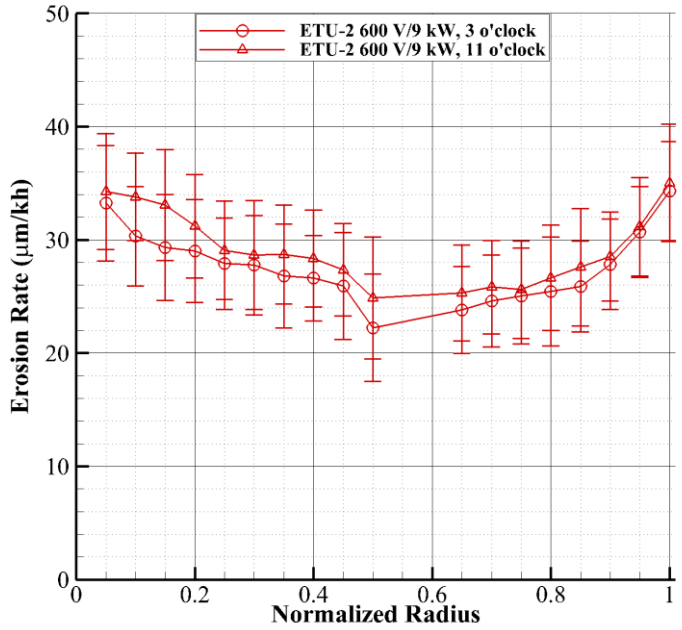

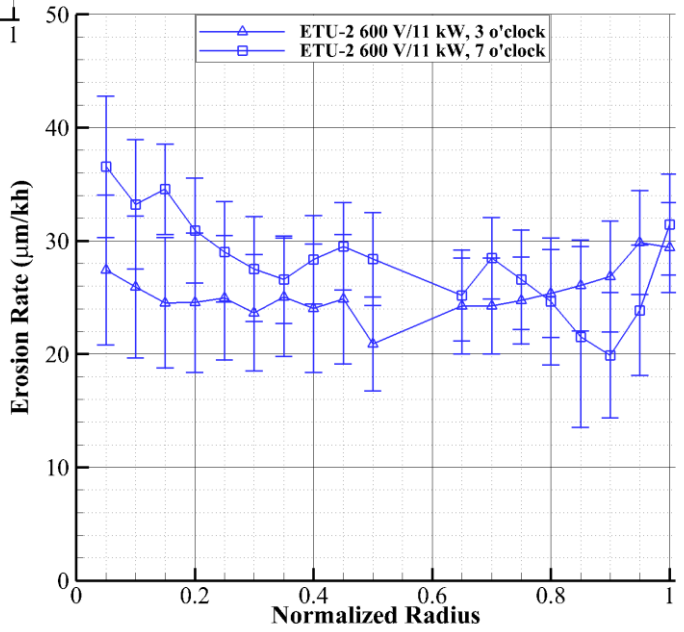

Minimal differences in IFPC wear between the extensively characterized 12.5 kW condition and the new 9 kW, 11 kW, and 12 kW conditions

Wear Results: Outer Front Pole Cover

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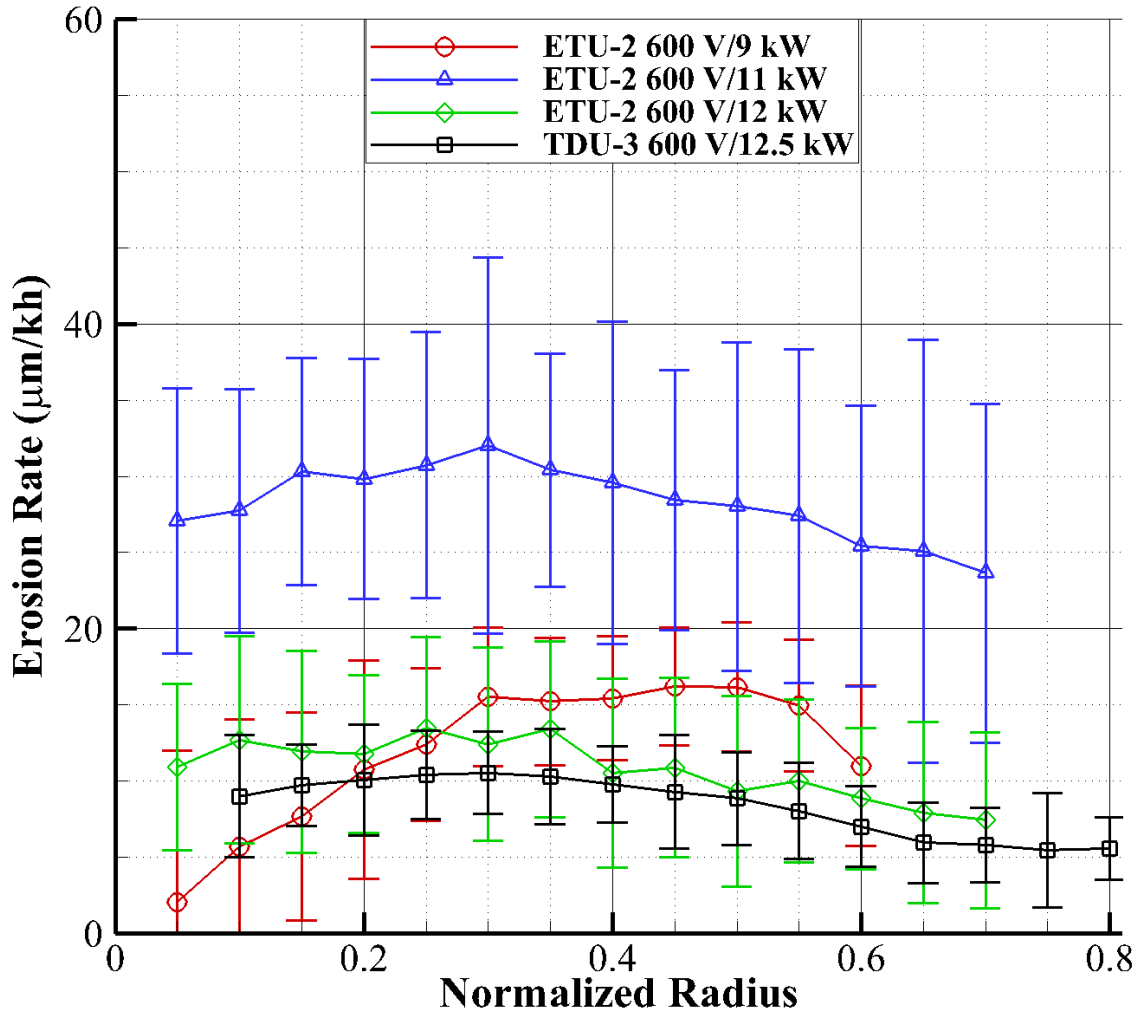
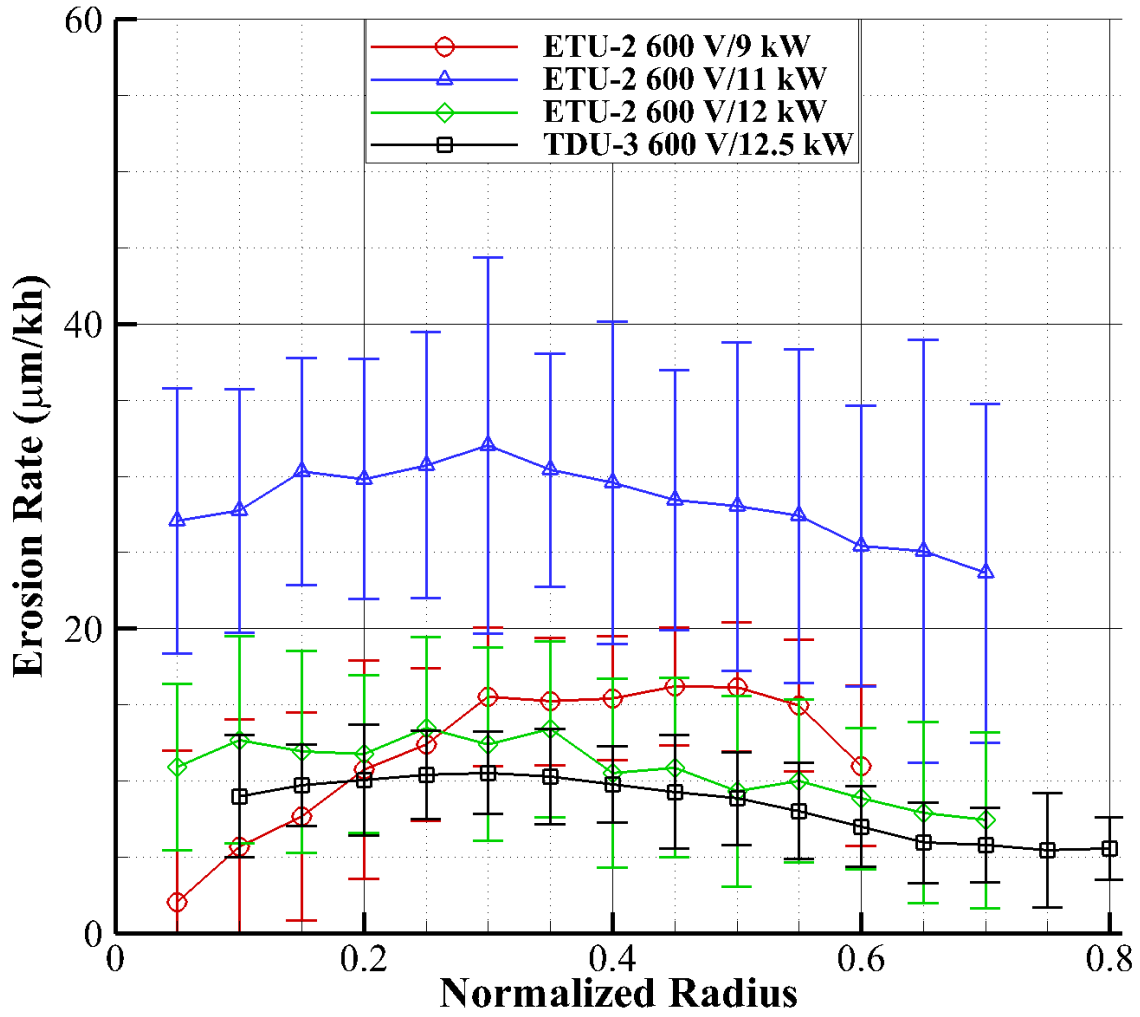


Wear Results: Outer Front Pole Cover

- The erosion rates measured at 9 kW, 12 kW, and 12.5 kW were equal to within the empirical uncertainty at all normalized radii
- The erosion rates measured at 11 kW were approximately 200% greater, on average, than those at the other 600 V conditions
  - OFPC erosion rates at 11 kW were comparable to those measured on the IFPC
  - This result is unique as all other tested conditions show the IFPC as the wear life-limited component



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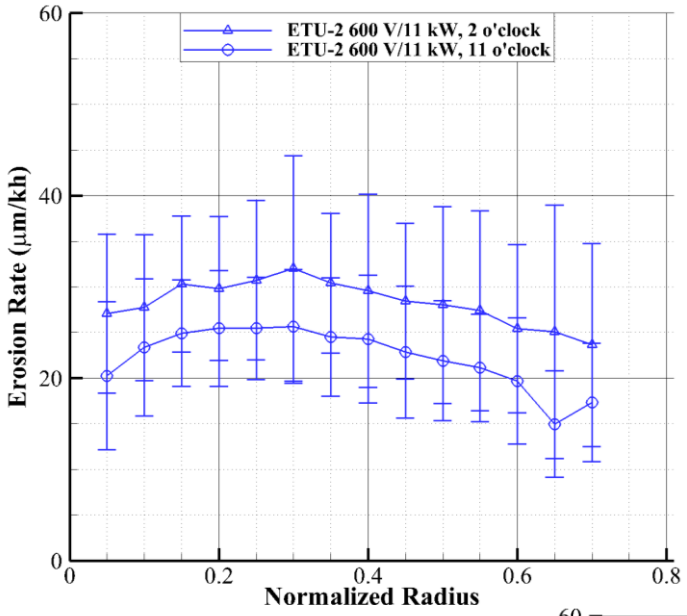

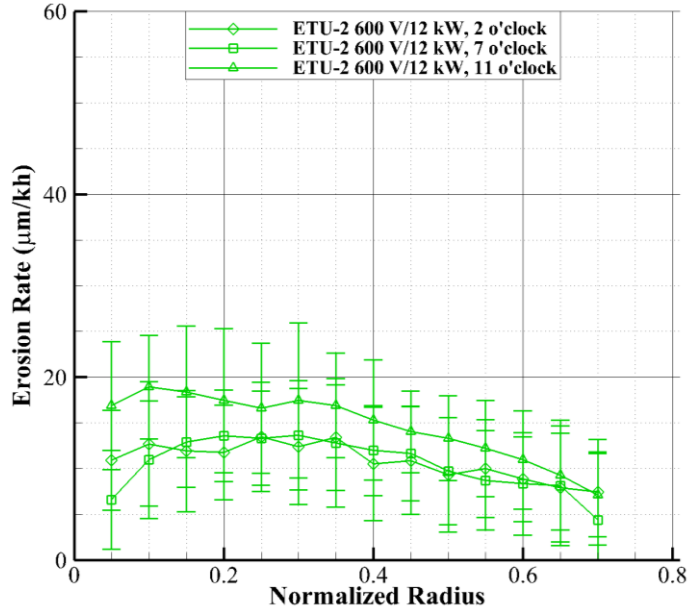

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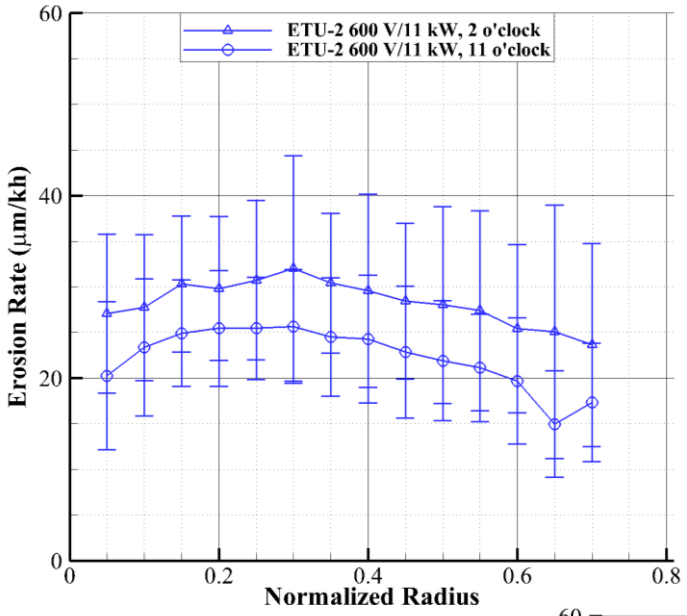

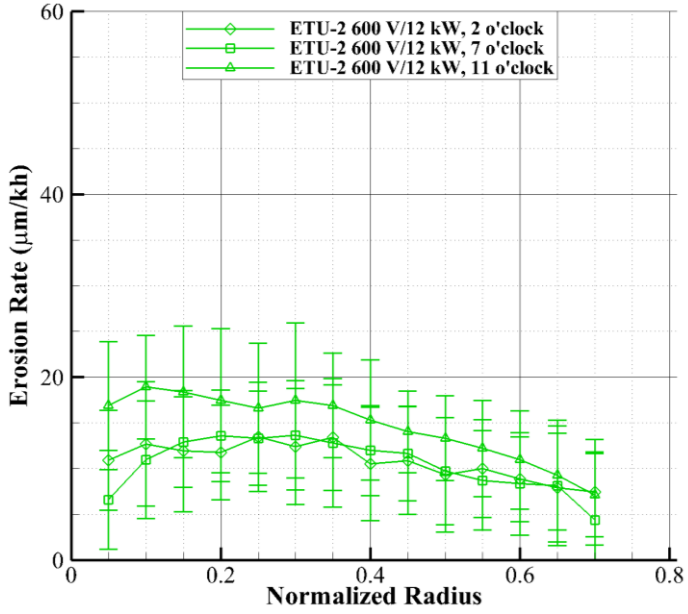

Conclusions

- The AR AEPS ETU-2 thruster was successfully operated for approximately 900 hours split across three wear test segments (600 V/9 kW, 600V/11 kW, and 600 V/12 kW)
- ETU-2 performance and stability were invariant with operating time and were equivalent to values measured in previous ETU-2 and HERMeS TDU testing
- Erosion rates of the IFPC at the 9 kW, 11 kW, and 12 kW conditions were equivalent to within the empirical uncertainty and matched rates previously measured at 600 V/12.5 kW
  - Same trends observed for OFPC erosion at 9 kW and 12 kW
- Elevated OFPC erosion rates were observed at 11 kW that were similar in magnitude to those observed on the IFPC
- Overall, all measurements indicate that the AEPS thruster has a high probability of meeting lifetime and performance requirements at all tested operating conditions as the design moves forward to flight production and qualification


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