An Overview of the NEXIS Ion Thruster Development Program

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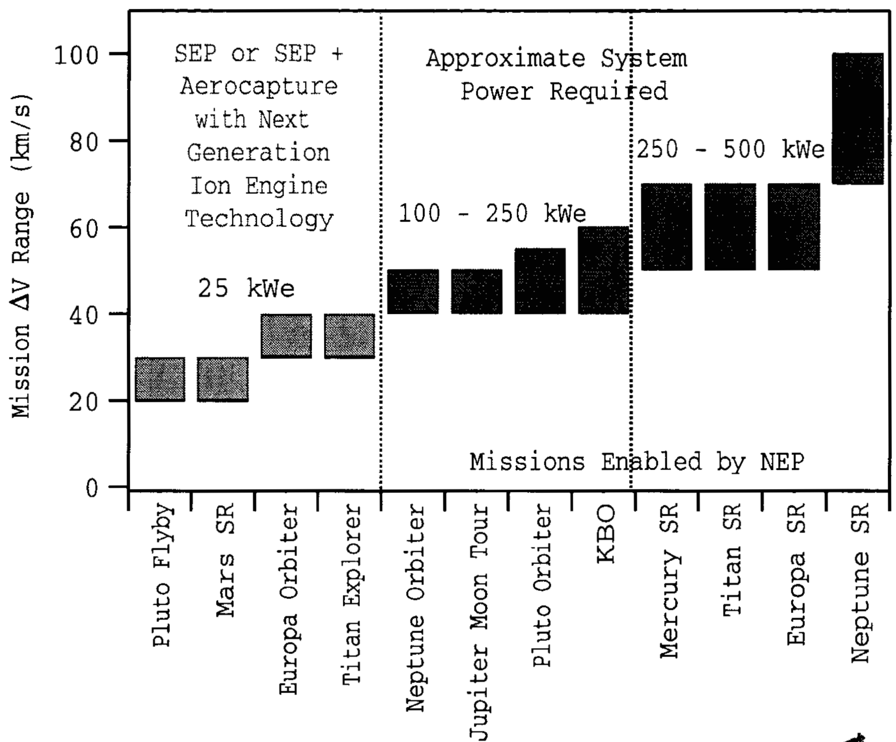
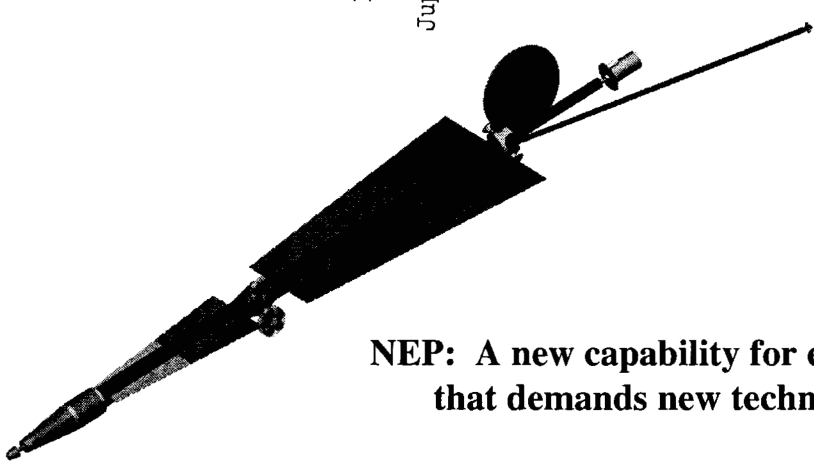
Proposed Future Missions Demand High Power, High Isp and Long Life

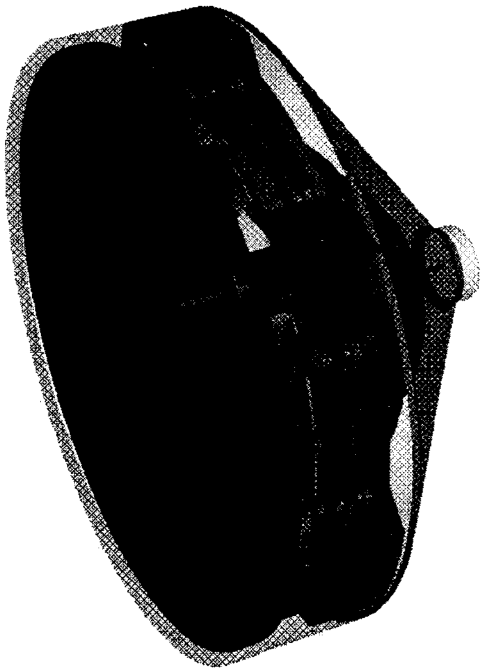


- **Near-term missions can be accomplished with advanced SEP**
- **More demanding proposed missions require NEP**
  - System power levels of 100 + kWe
  - Specific impulses ranging from 6000 to over 14000 s
  - Thruster burn times of up to 10 years
- **New technologies are required to meet these mission needs**
  - High power, high Isp operation
  - Long grid life
  - Long cathode life
  - High efficiency



NEP: A new capability for exploration that demands new technologies

Overview of NEXIS Program



Performance Metric	State-of-the-Art SEP Thrusters (NSTAR)	Proposed NEXIS Thruster	Baseline Gain Over SOA
Power (kWe)	2.3	20	9 X
Isp (s)	3170	7500	2.4 X
Thruster Efficiency	0.63	0.78*	1.25 X
Specific Mass (kg/kWe)	3.6	1.5	2.4 X less
Throughput (kg)	230	2000	8.7 X
Run Time (khrs)	30	93	3 X

Nuclear Electric Xenon Ion System (NEXIS)

Background: NEXIS was one of 3 high power EP proposals selected from 12 submitted to the 2nd In-Space Propulsion Program NASA Research Announcement (NRA). Now funded by the Project Prometheus Program.

Team Members: JPL (lead), Aerojet, Boeing, CSU, Ga. Tech, Aerospace Corporation, MSFC, Wayne Ohlinger

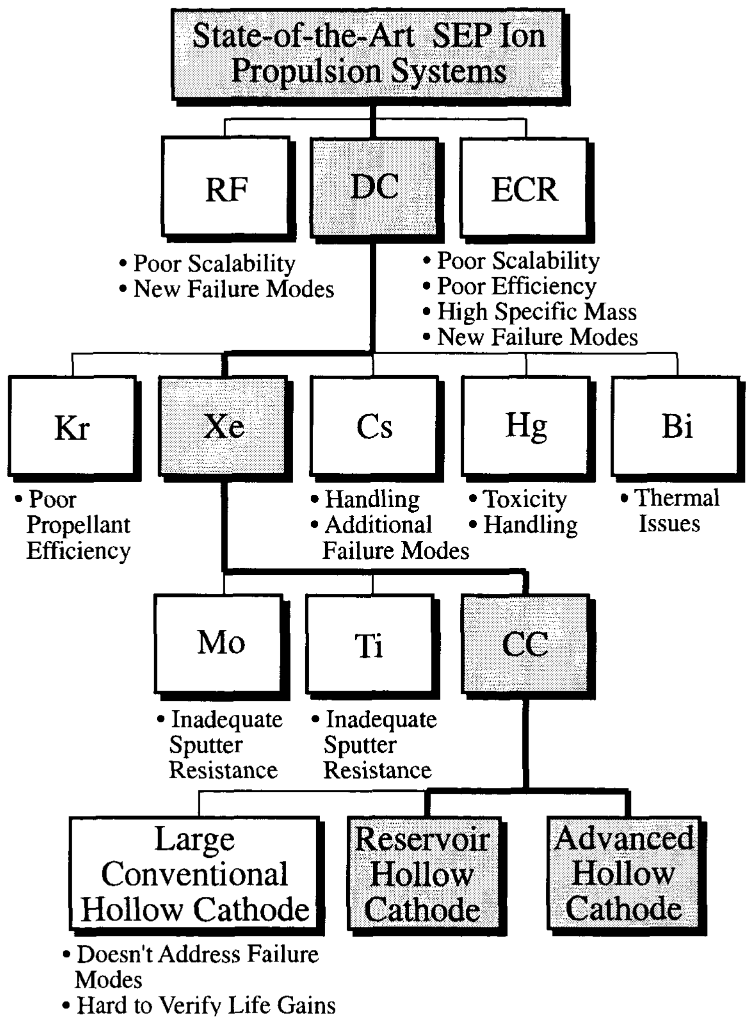
Current State-of-the-Art SEP Systems:

- NSTAR (DS1)
  2.3 kWe, 3170 s Isp
- Next Generation Ion Program
  6 kWe, 4050 s Isp

Objectives of the NEXIS Program:

- Demonstrate an ion engine capable of processing 20 kWe at an Isp of 7500 s with an efficiency of 78%
- Develop component technologies that essentially eliminate the wear-out failure modes
- Validate the service life capability through a combination of modeling, long duration testing, accelerated testing and in situ diagnostics

Top Level Technology Trade Studies

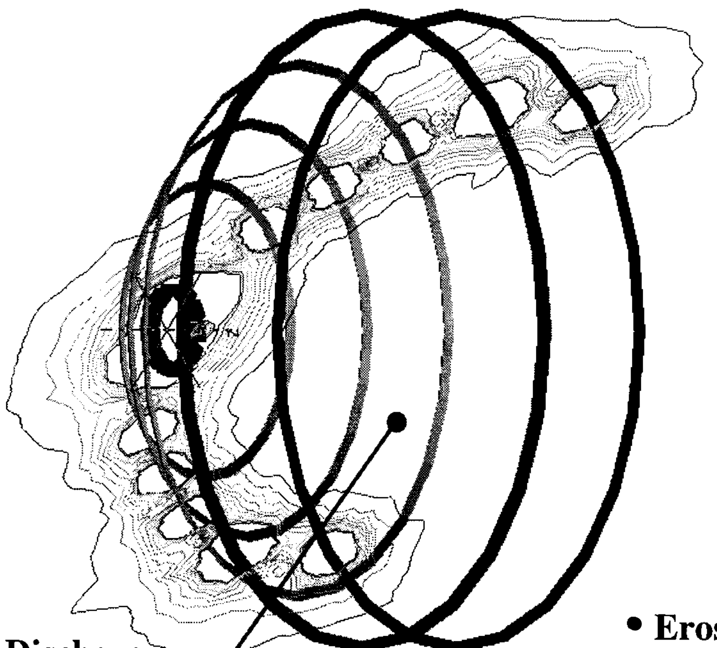


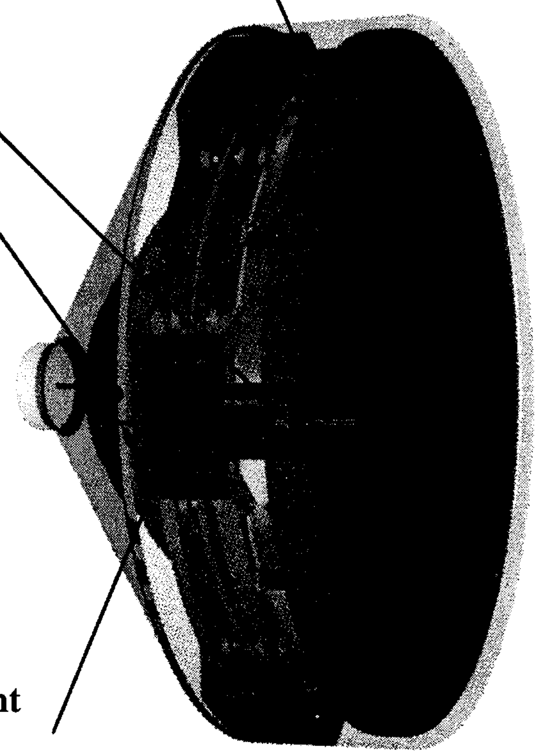
- **State-of-the-Art is represented by NSTAR and NEXT**
- **Selected DC discharge chamber**
  - ECR and RF are difficult to scale to large sizes
  - ECR suffers from poor performance
  - Chose to attack cathode life issue
- **Selected xenon propellant**
  - CSU life analysis trade shows Xe has best grid life characteristics
  - Kr has lower propellant efficiency
  - Cs and Hg have significant handling issues
  - Bi--good for TAL's, ion thrusters too big to keep hot
- **Selected CC grid materials**
  - Lowest erosion rate
  - Builds on significant development history
  - Leverages other programs
  - Chose to attack CC grid development issues
- **Selected reservoir hollow cathodes with W-Ir dispenser cathodes as backup technology**
  - Incorporates features to eliminate all known failure modes
  - Uniquely suited to life qualification
    - Can diagnose remaining life
    - Can develop accelerated test methodologies

The NEXIS Design Builds on NSTAR and XIPS Heritage

- Reservoir Hollow Cathode Incorporating:
  - -Advanced Emitter Material
  - -High Capacity Activator Supply Reservoir
  - -Improved Activator Transport
  - -Decoupled Emitter and Activator Source
- One Neutralizer Shared By Multiple Engines

- Beam Voltage > 5100 V
- New Grid Design Using Advanced Simulation Tools
- Erosion-resistant Carbon Carbon Grids
- High Perveance Margin Operation
- Grid Masking





- Large Discharge Chamber
- Advanced Ring Cusp Magnetic Field Configuration

- Erosion-resistant Carbon Keeper Electrode
- Operational Control of High Energy Ion Production

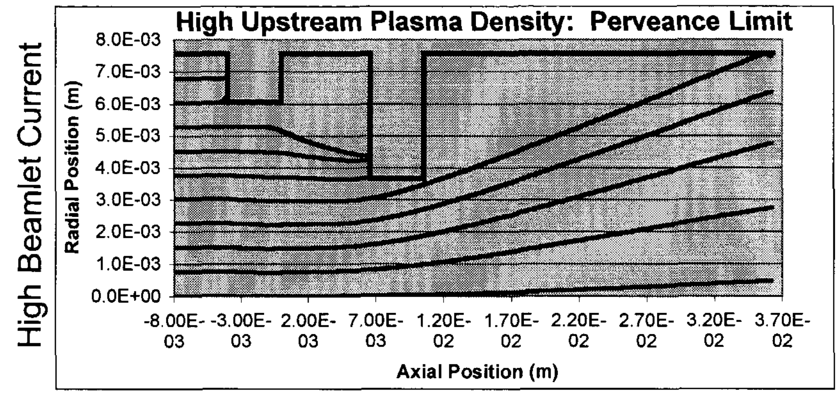
Modeling Tools Now Allow Rapid Grid Design

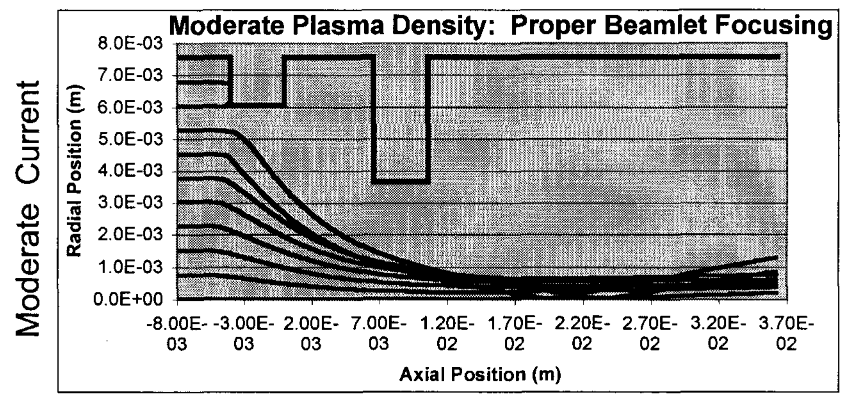
Challenges in the design of large, high Isp grids:

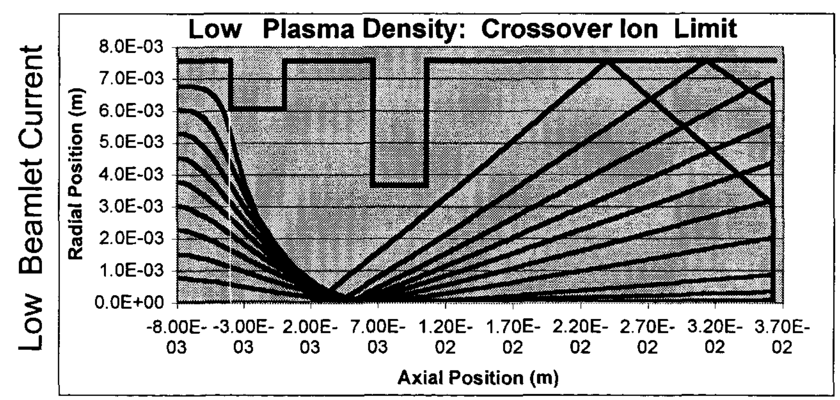
- Optimizing ion optics performance
  - Extracting the required current density
  - Tolerable electric fields
  - Proper focusing over the range of upstream plasma densities
- Managing charge exchange ion erosion
- Developing a sufficiently stiff structure to survive dynamic launch loads
  - Avoiding contact between grids
  - Controlling stresses due to displacement strains

Innovations enabling these challenges to be met:

- Discharge chamber design to yield very uniform plasma density profiles
- Operation at peak beamlet currents low compared to the perveance limit
- Grid dishing and stiff mounting structures to minimize stresses from dynamic loads







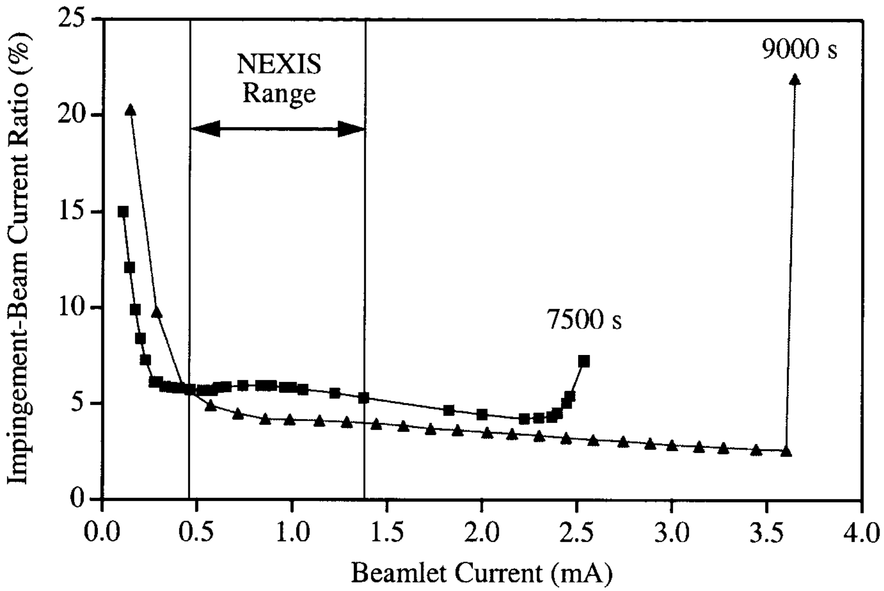
Ion Optics Design Methodology Rapidly Yields Optimum Configuration

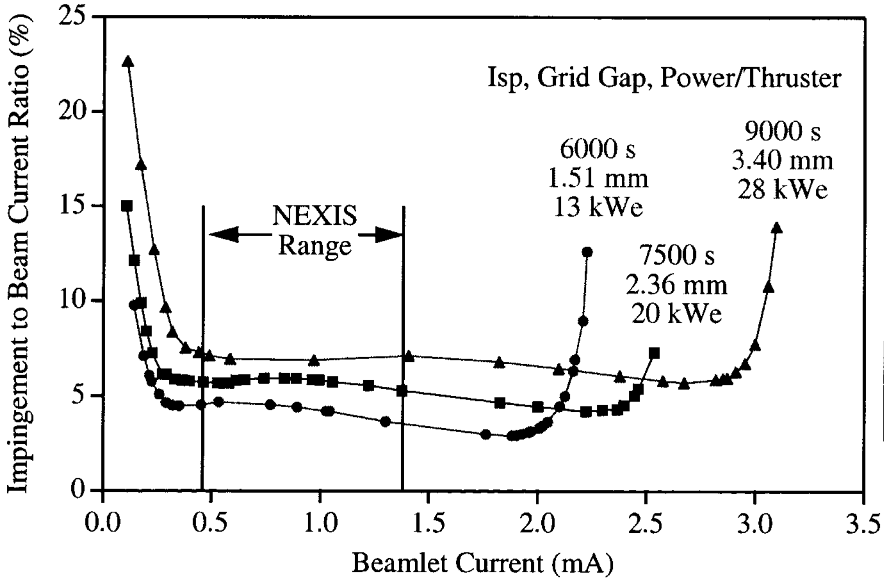
A systematic ion optics design methodology is evolving based on recent tool development and insights gained from the tools

- Preliminary optimization based on analytical tools to narrow trade space (John Brophy et al., "Numerical Simulations of Ion Thruster Accelerator Grid Erosion", AIAA-2002-4261)
- Hundreds of simulations to map effects of design parameters on optics performance and life
- Genetic algorithms to optimize design
- Subscale grid tests to validate designs
- Full-scale tests to demonstrate scalability and fabrication methods

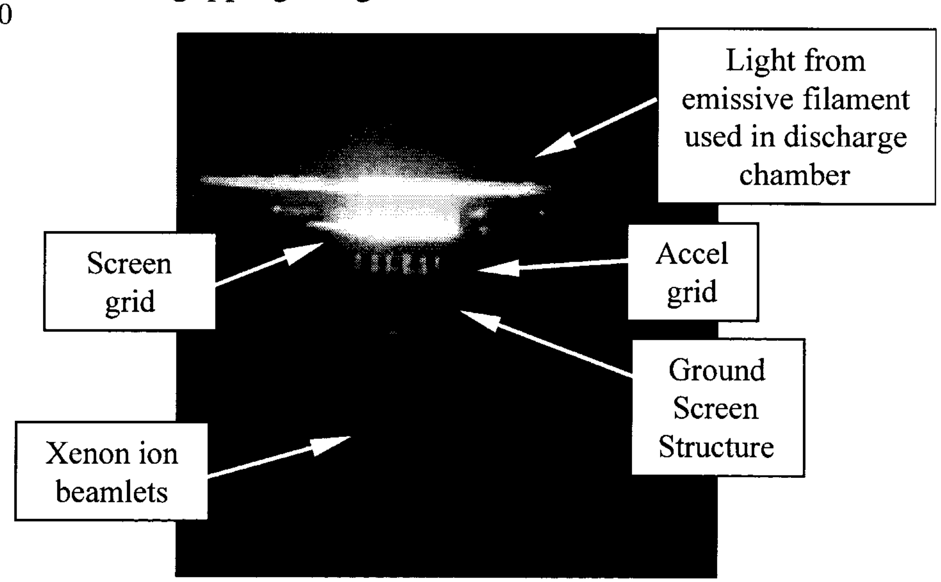
Parameter	NSTAR	NEXT	NEXIS
Thruster			
Power (kWe)	2.3	6.8	19.9
Isp (s)	3100	4050	7500
Propellant	Xe	Xe	Xe
Thrust (N)	0.092	0.233	0.42
Efficiency	0.63	0.67	0.75
Screen Grid			
Maximum Voltage (V)	1076	1800	4950
Thickness (mm)	0.36	0.36	2.00
Aperture Diameter (mm)	1.91	1.91	6.83
Minimum Webbing Width (mm)	0.30	0.30	1.12
Open Area Fraction	0.67	0.67	0.67
Ion Transparency	0.82	0.93	0.60
Accelerator Grid			
Minimum Voltage (V)	-180	-250	-560
Thickness (mm)	0.51	0.76	2.73
Aperture Diameter (mm)	1.14	1.14	4.10
Open Area Fraction	0.24	0.24	0.24
Assembly			
Active Beam Diameter (cm)	28.5	40	57
Peak Beamlet Current (mA)	0.26	0.18	1.38
Peak Current Density (mA/cm2)	6.0	4.1	2.51
Hole Spacing (mm)	2.21	2.21	7.94
Dish Depth (mm)	20.3	20.3	76.0
Grid Gap (mm)	0.66	0.66	2.36
Maximum Electric Field (V/mm)	1903	3100	2300

NEXIS Grid Design Validated in Subscale Tests





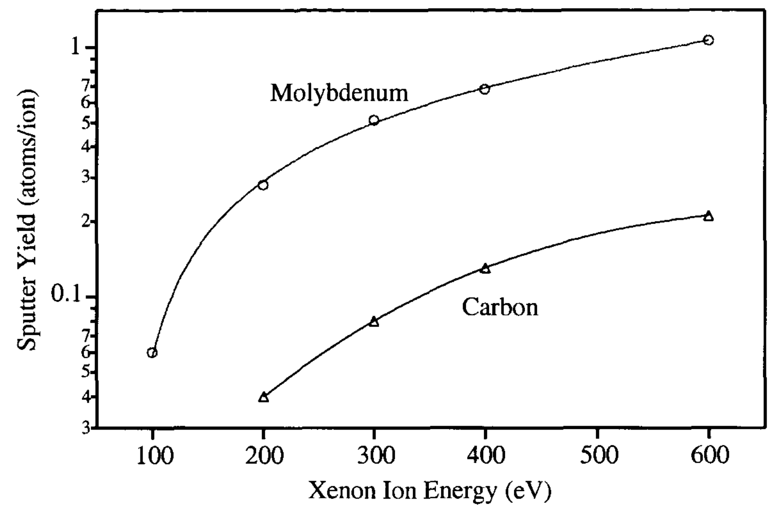
- Tests measure ion optics performance with subscale gridlets on a 10 cm diameter ion source at Colorado State University
- Results demonstrate that designs meet performance requirements for NEXIS applications
  - Dynamic range
  - Perveance margin
- The nominal 7500 s design will also work over a range of at least 6000 - 9000 s just by regapping the grids



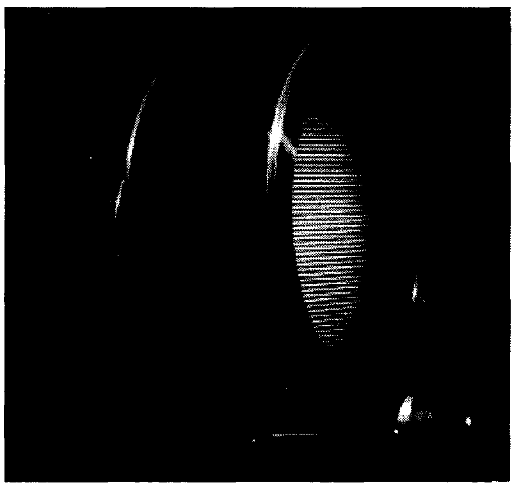
Gridlets operating at high Isp look remarkably like UFOs

Carbon Grids Represent a Major Advance In Ion Propulsion Technology

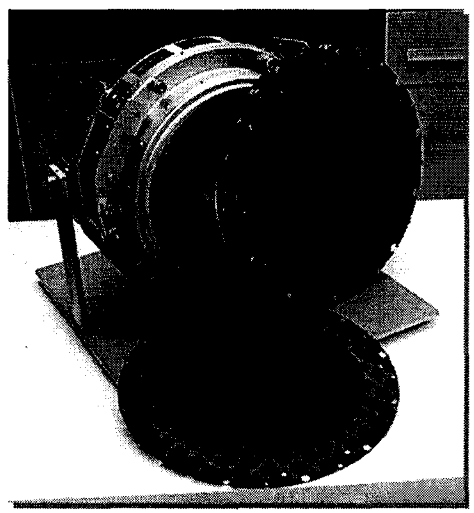
- **Advanced carbon grid materials offer dramatic improvements in ion engine technology**
  - Carbon erosion resistance essentially eliminates grid wearout failure modes
  - Light weight carbon materials yield factor of 3 savings in grid assembly mass
  - Near-zero CTE simplifies thermomechanical design



Carbon provides the lowest erosion rates

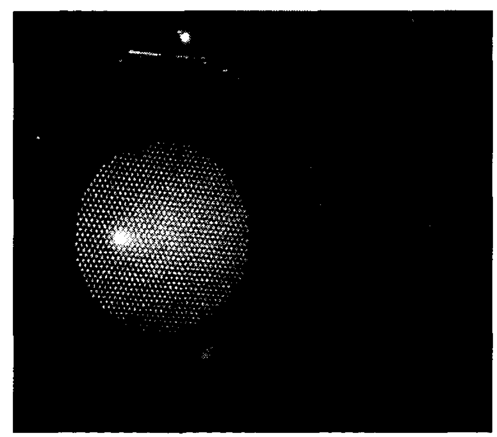


Advanced carbon-carbon grids on 15 cm ion engine

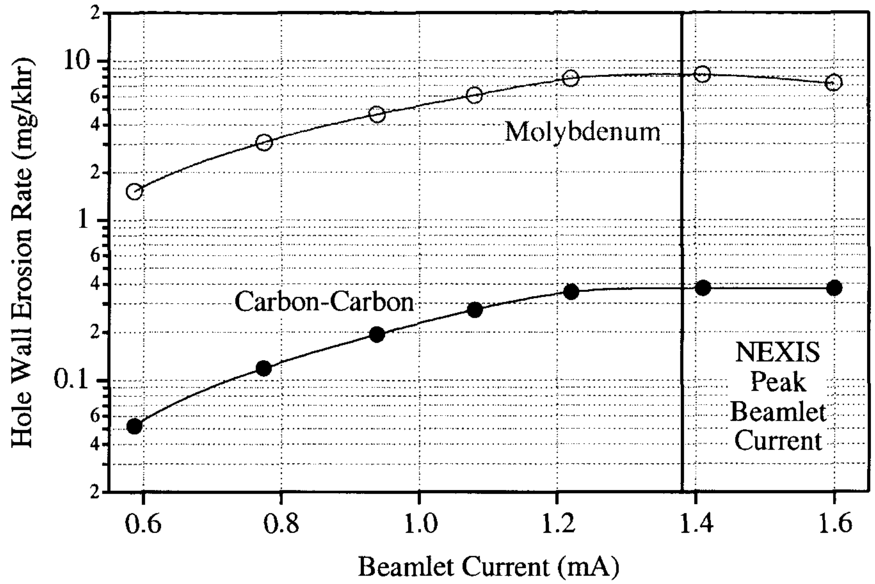


30 cm Carbon-Carbon Grids

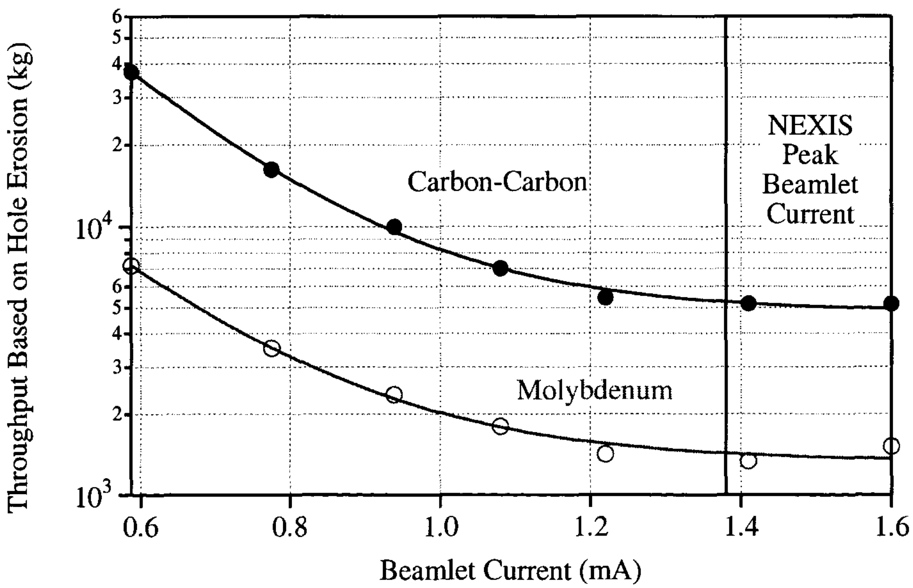
75 cm Carbon-Carbon Grids

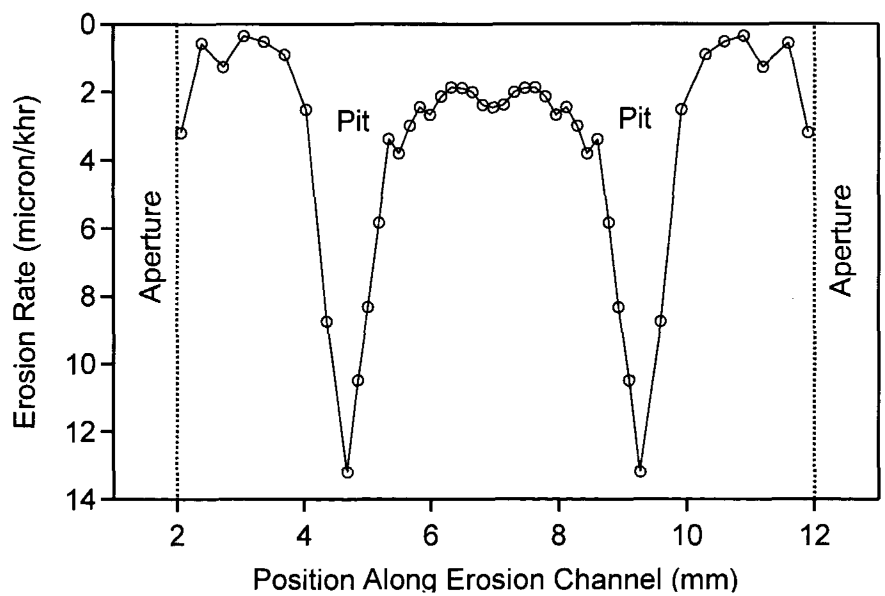


Erosion Modeling Shows Optics Design Eliminates Grid Erosion as a Credible Failure Mode



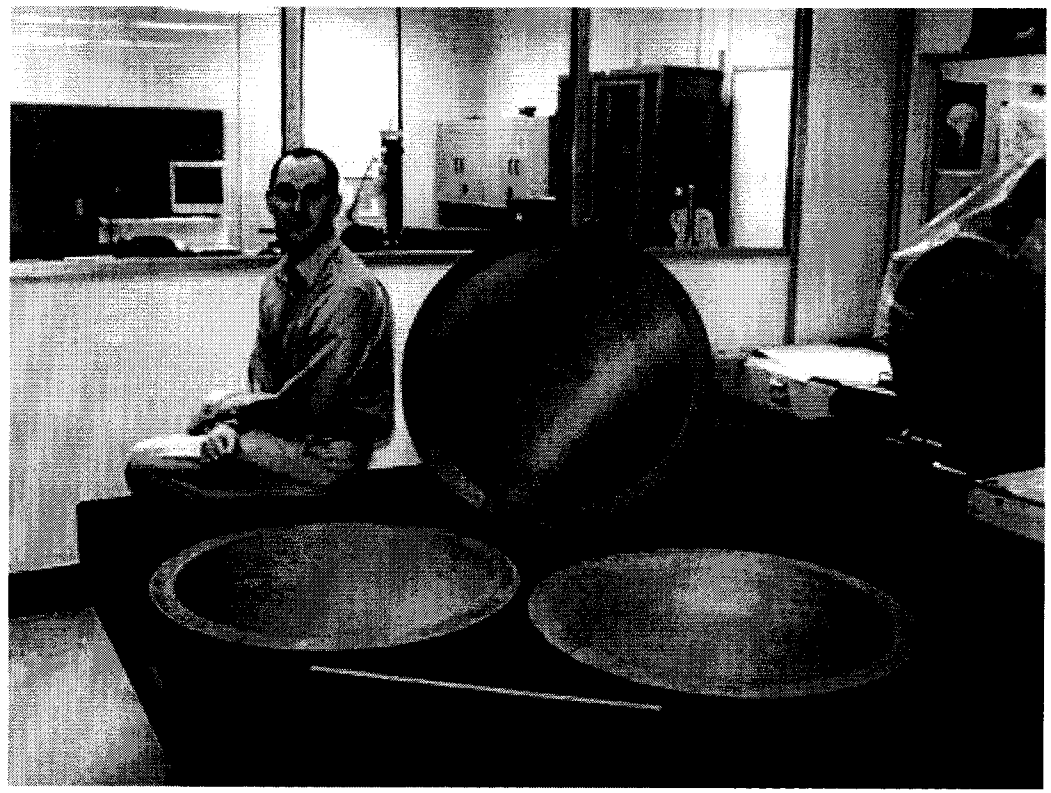
- **Hole wall erosion is virtually eliminated**
  - Low sputter yield
  - Low sensitivity to incident angle
  - Light species (more atoms/cc)
- **Pit and groove erosion on downstream surface is minimal**
  - Erosion rate implies >200,000 hours and >4800 kg throughput
- **Low discharge voltage and sputter-resistant grids eliminate screen grid erosion**





Large Carbon-Carbon Grid Fabrication Processes are Being Established

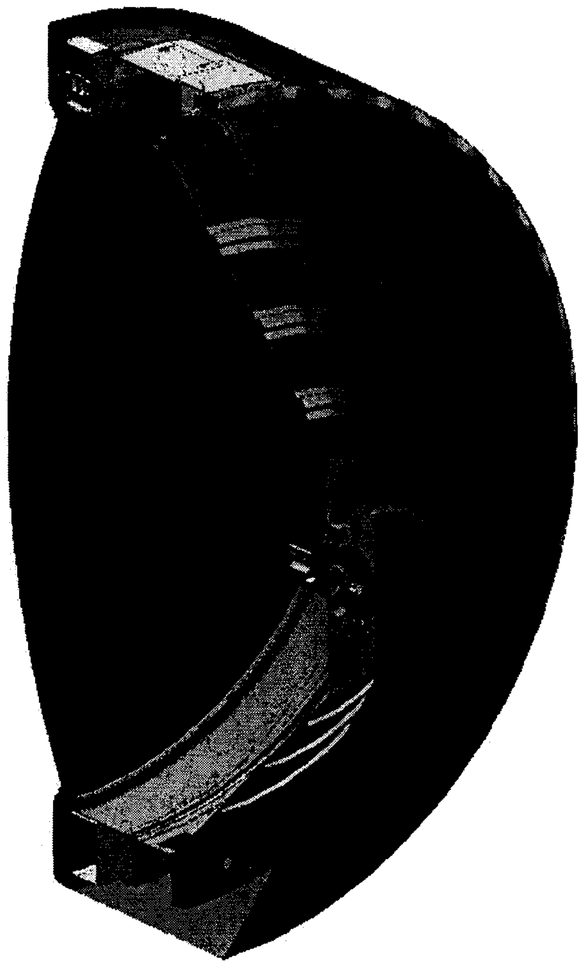
- **Flat grids fabricated and tested on laboratory model thruster**
- **Dished grid design complete and fabrication underway**
  - First time very large dished grids have been fabricated
  - Layup and cure went very well
  - Densification and high temperature heat treatment successfully completed
  - Grid blank tolerances are very good



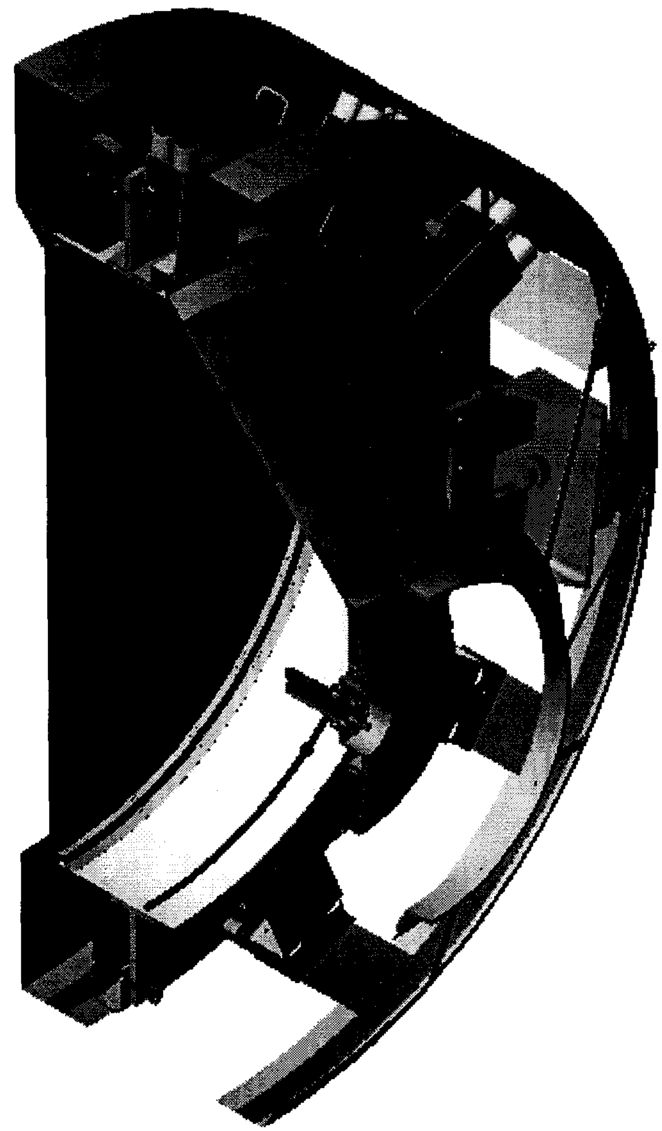
Dished grid blanks and cutaway view of assembly

Laboratory and Development Model Thrusters

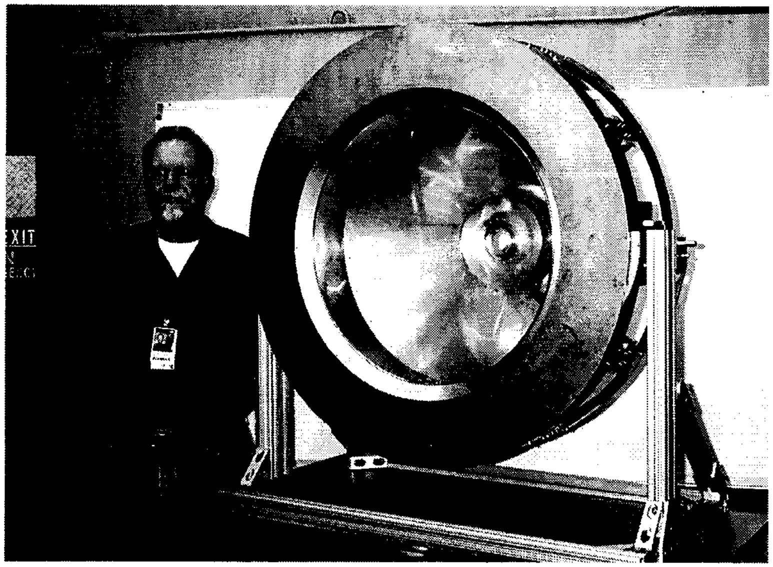
Development Model Thruster

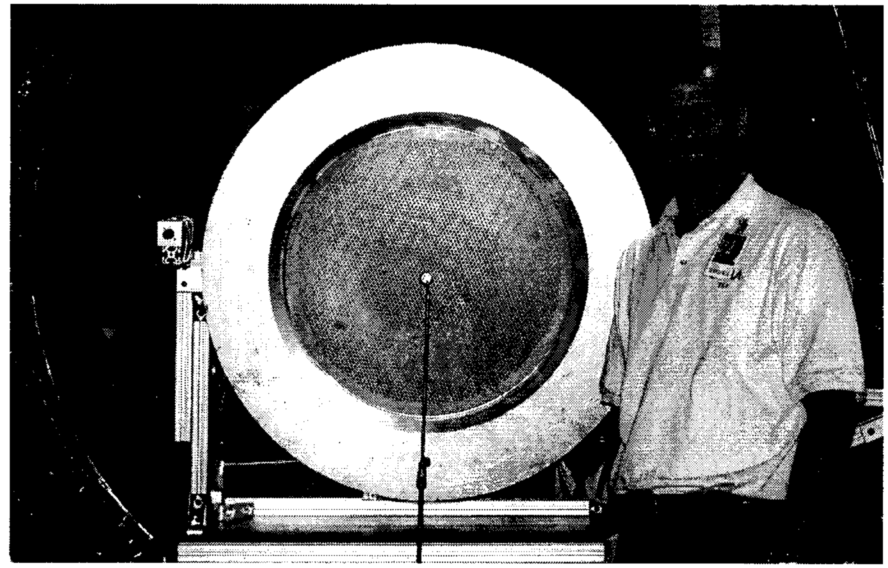


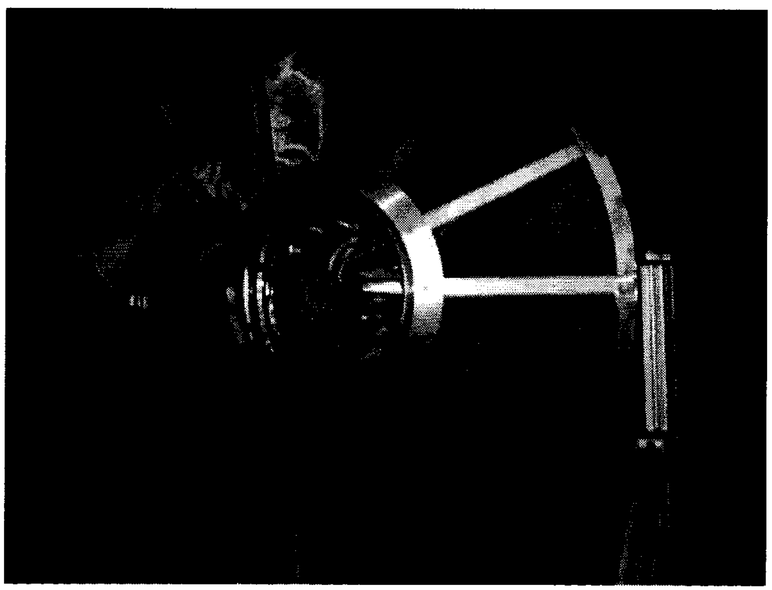
Laboratory Model Thruster

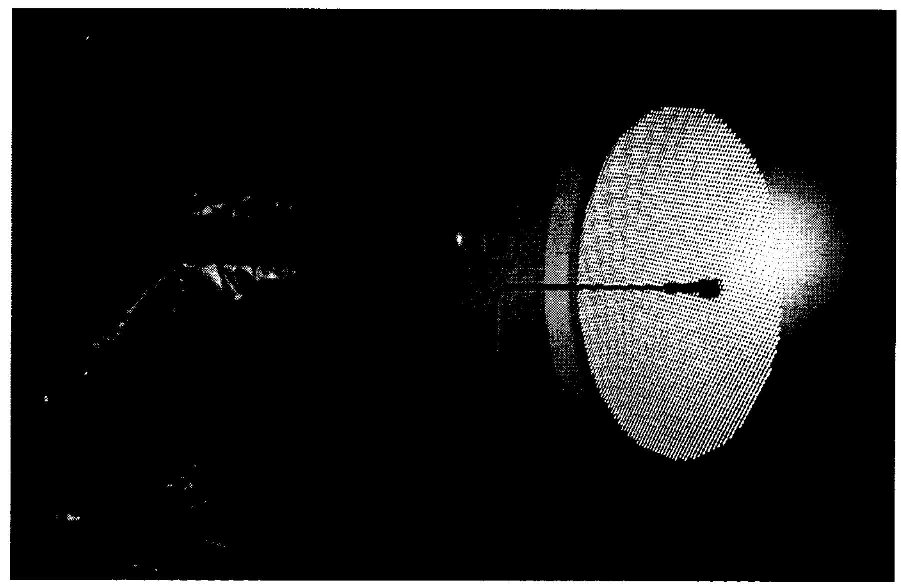


NEXIS Laboratory Model Thruster

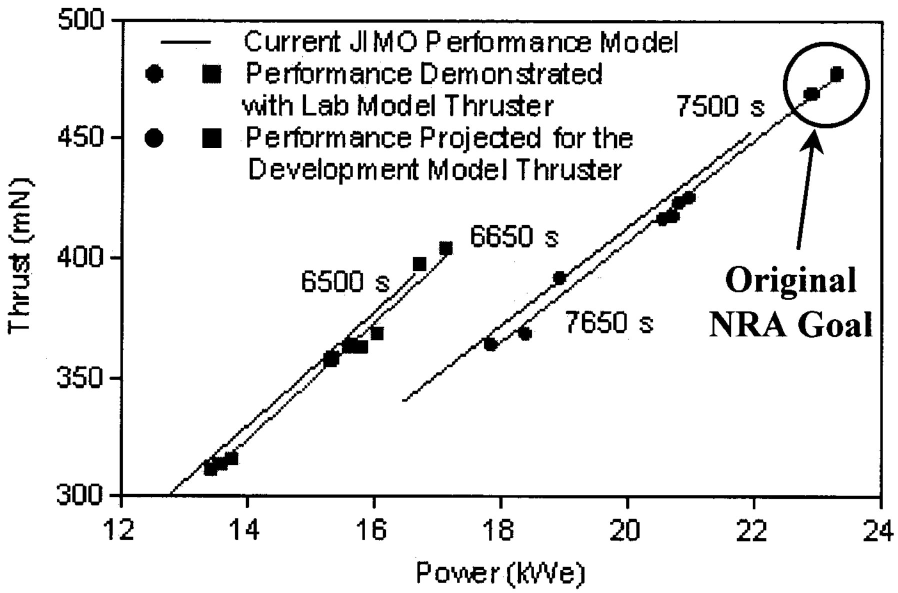


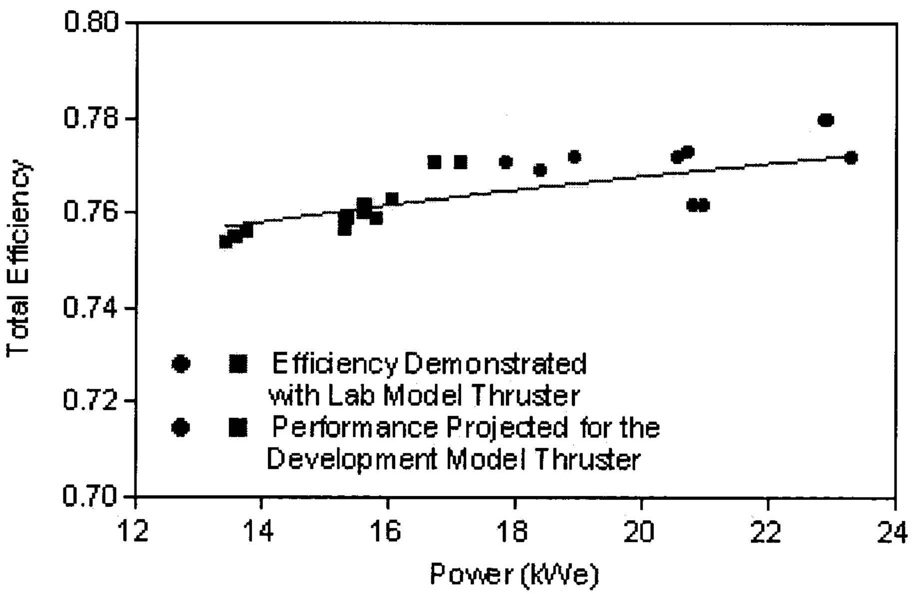






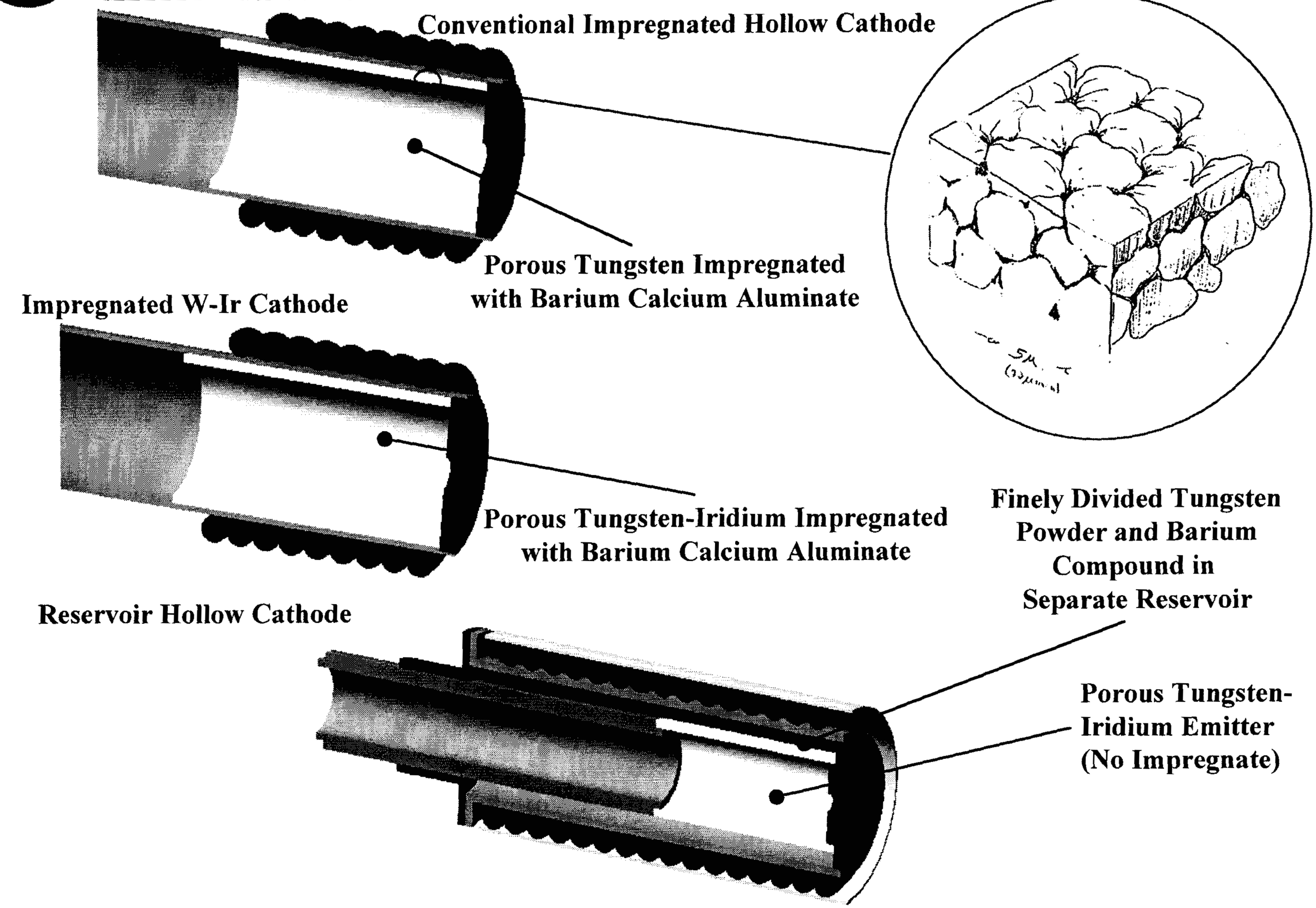
Initial Lab Model Thruster Tests Demonstrate Performance Adequate for Proposed JIMO Mission



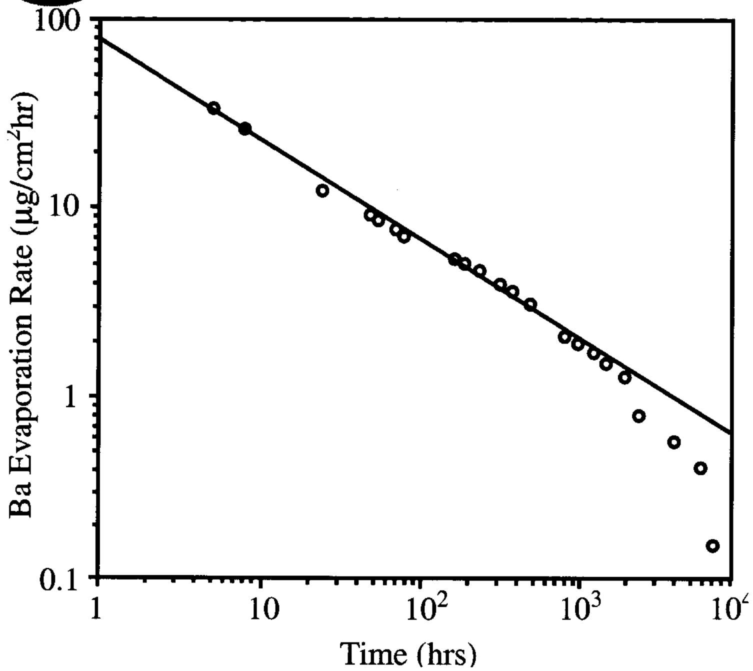


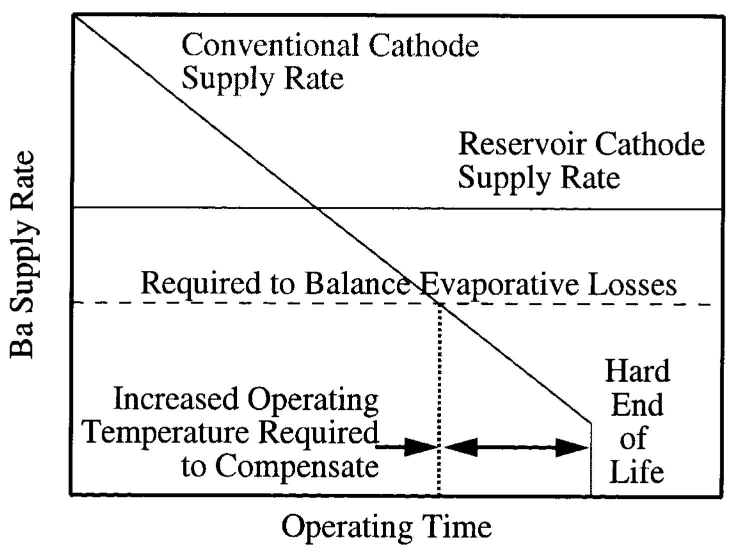
- **Original NRA goal met in first tests of lab model thruster**
- **Results agree well with JIMO performance model**
  - Approximately 200 W more required for a given thrust than assumed in model
- **Development model thruster performance expected to be very similar**
  - Dished grids will increase beam divergence loss
  - Lower neutralizer flow rate and reduced discharge loss from thinner screen grid will compensate
- **Peak performance: 0.517 N of thrust at 27 kWe and 8700 s, propellant utilization efficiency of 0.95, total efficiency of 0.81**

Cathode Technology Options



Life-Limiting Processes in Hollow Cathode Inserts





- **Low cathode operating temperature is achieved by establishing a Ba-O absorbate complex on the surface of the tungsten emitter**
- **Hollow cathodes rely on supply of Ba and BaO from the interior of the insert to replenish material lost from the surface by evaporation**
- **Hollow cathode life is limited by 4 processes:**
  - Depletion of barium
  - Build-up of reaction products
  - Inadequate transport of barium and barium oxide through the tungsten matrix
  - Closure of the pores by deposition of tungsten
- **Conventional impregnated dispenser cathodes have a limited supply and a time dependent supply rate**
- **Reservoir cathodes provide a much larger supply of source material and a fixed flow resistance that yields a constant supply rate**

Reservoir Cathodes Are the Best Performers in Vacuum Device Life Tests

- **Reservoir cathodes have a long history**
  - Reservoir cathode concept predates the impregnated cathode (Lemmens patent, 1948)
  - Fell into disfavor based upon long processing times and risks associated with use of carbonate-based barium source materials
- **Modern reservoir cathodes solved the problems encountered in early devices**
  - BaO and W - solved problems of carbonates, but still environmentally sensitive
  - Barium calcium aluminates - same material as impregnated cathodes
  - Alternate materials - 10 candidates identified in Phase 1

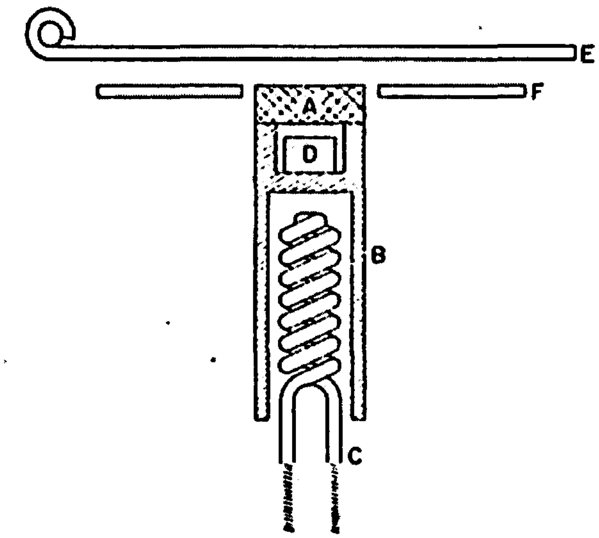
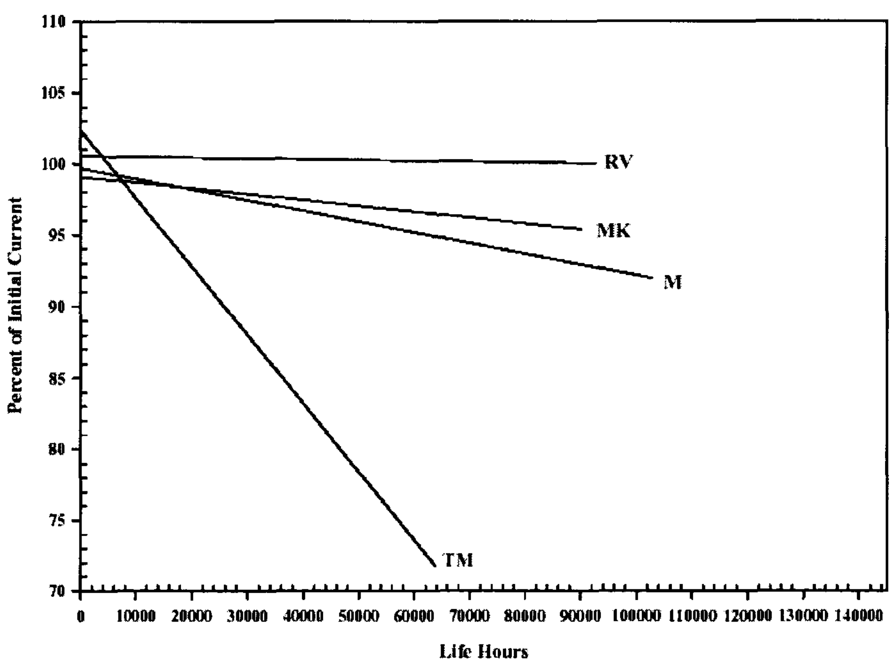
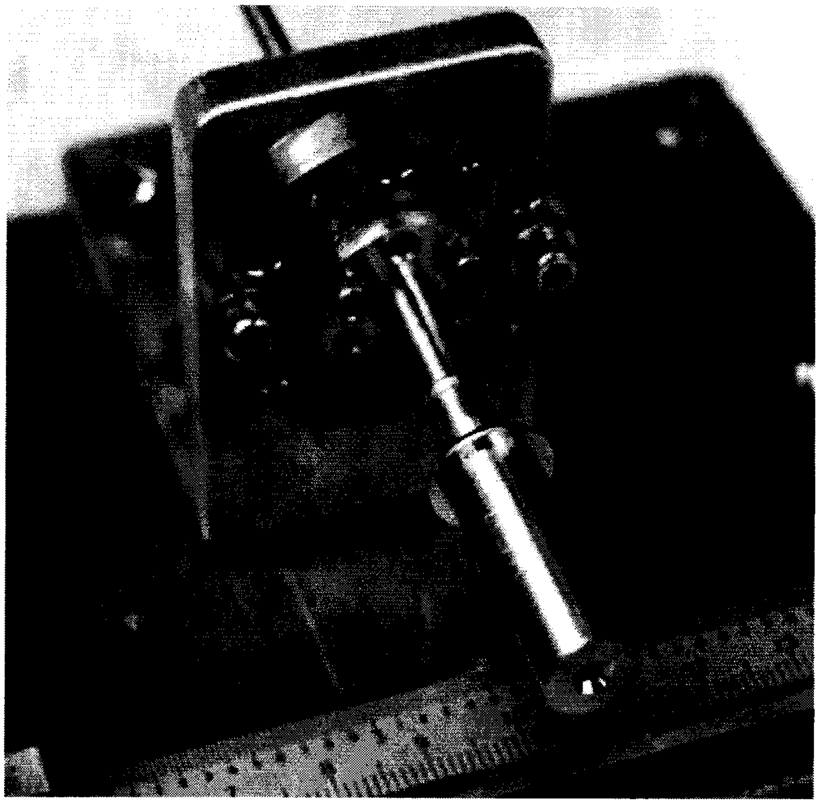


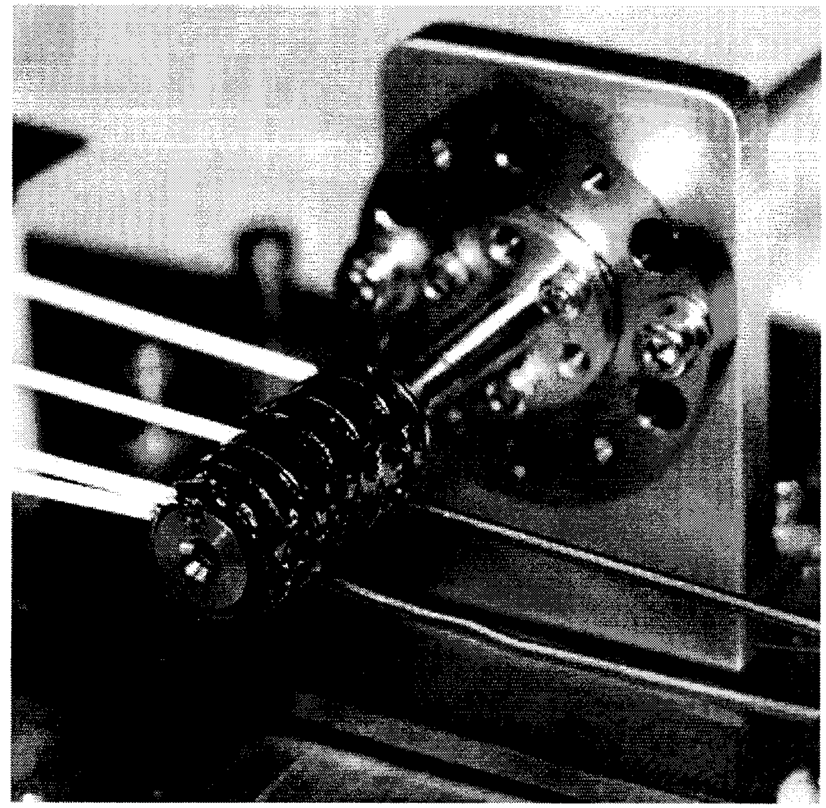
FIG. 1. Cross section of *L* cathode in planar diode. *A*-porous W plug, *B*-Mo supporting body, *C*-heater, *D*-tablet of $BaCO_3$ or $(Ba,Sr)CO_3$, *E*-Mo anode, *F*-guard electrode.



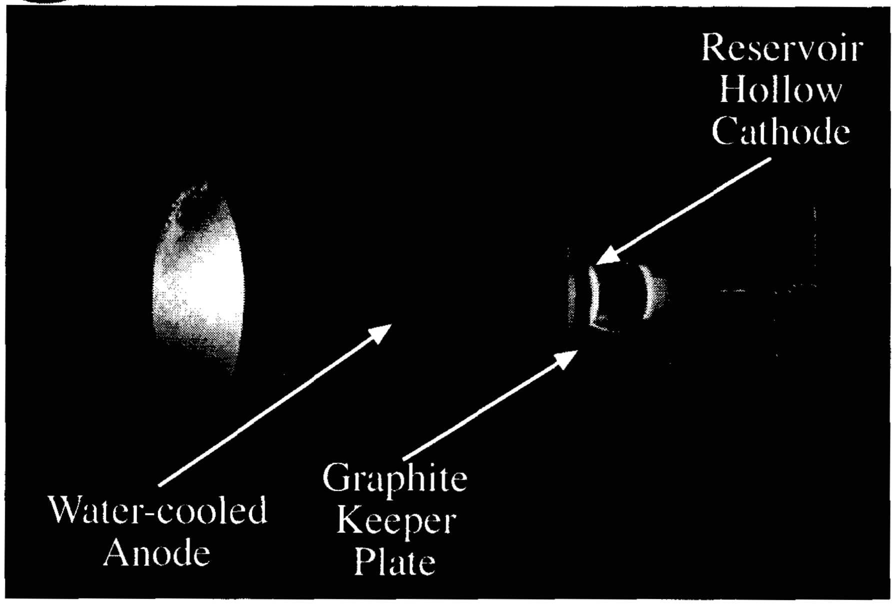
Data from the 2002 TriService/NASA Cathode Life Test Facility Annual Report show the reservoir cathode (RV) emits like new after 90,000 hours of operation.

Proof-of-Concept Reservoir Hollow Cathode





Tests of the First Reservoir Hollow Cathode

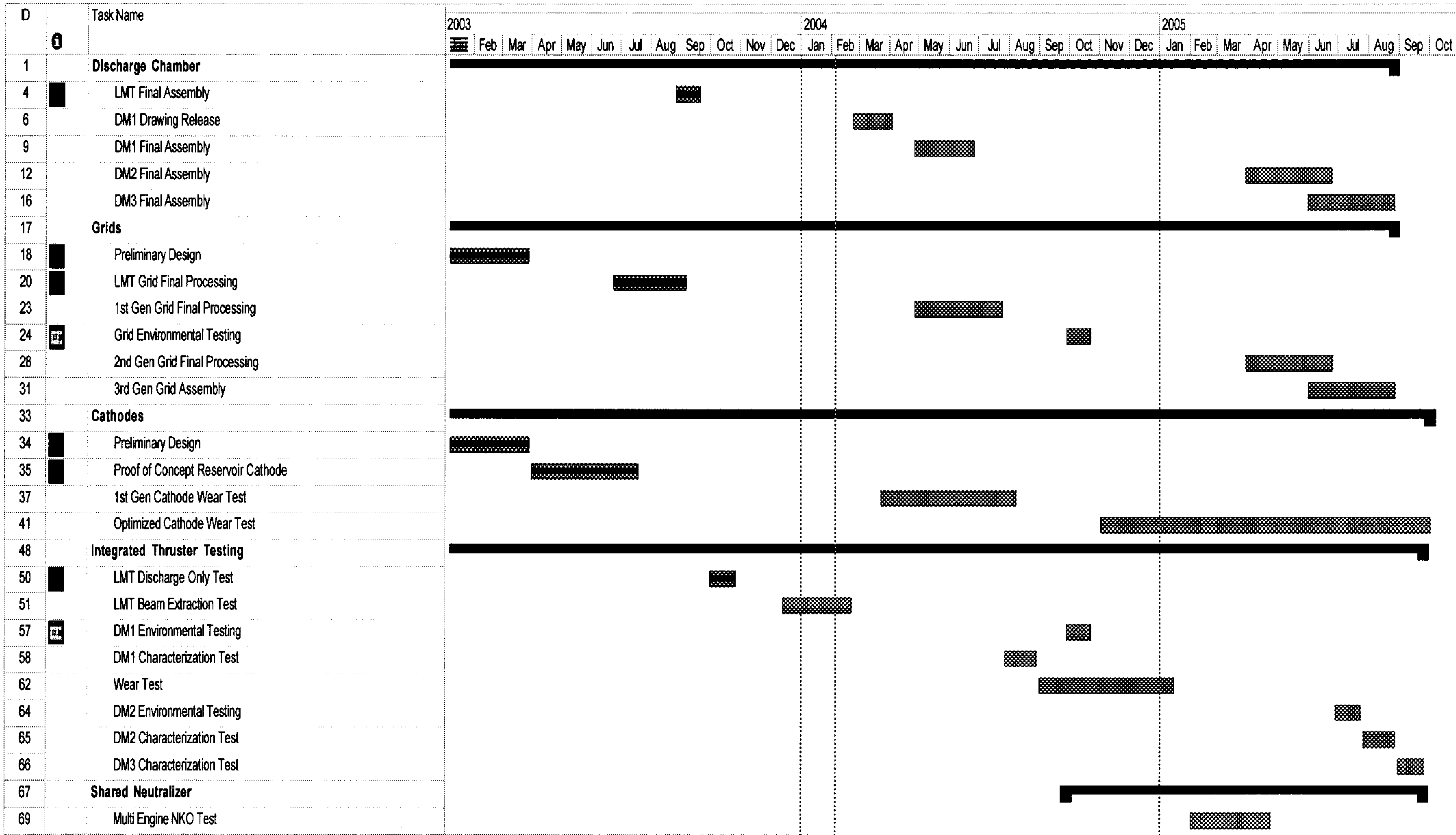


- **Preliminary tests of the proof-of-concept cathode demonstrated:**
  - Sound fabrication methods
  - Successful cathode conditioning
  - Reliable ignition
  - Stable operation from 12-37 A total emission current
- **Thermal and mass flow characteristics were excellent:**
  - Stable operation at flows as low at 3 sccm for 12 A
  - Stable operation at flows as low as 5.5 sccm for 37 A
  - Reservoir tube temperatures varied from 960 to 1150 °C over range of currents (downstream and mid-reservoir temperatures)
  - Orifice plate temperatures ranged from 1100 to 1230 °C

These results demonstrate the feasibility of the reservoir hollow cathode concept

Project Prometheus-The Nuclear Systems Program

NEXIS Ion Thruster Development Schedule



PRE-DECISIONAL - For planning and discussion purposes only

Conclusions

- **The NEXIS technology program is designed to develop technologies for NEP applications**
  - High power, high Isp operation
  - Long grid life
  - Long cathode life
  - High efficiency
- **Key technologies look very promising**
  - Large, robust carbon-carbon grids eliminate optics erosion as a credible failure mode
  - Reservoir hollow cathodes eliminate known hollow cathode insert failure modes
  - Recent tests of both technologies demonstrate feasibility
- **The NEXIS development plan focuses on demonstrating performance and life**
  - Laboratory model thruster in fabrication; first tests started in September 2003
  - Current plan calls for 3-5 development model engines in 3 design cycles
    - Performance testing (underway)
    - 2000 hour wear test
  - Life validation will rely on a combination of testing and analysis
    - Wear tests to identify failure modes
    - Accelerated tests where applicable
    - Probabilistic failure analysis based on models of failure mechanisms
    - Focused tests to validate failure models and characterize inputs