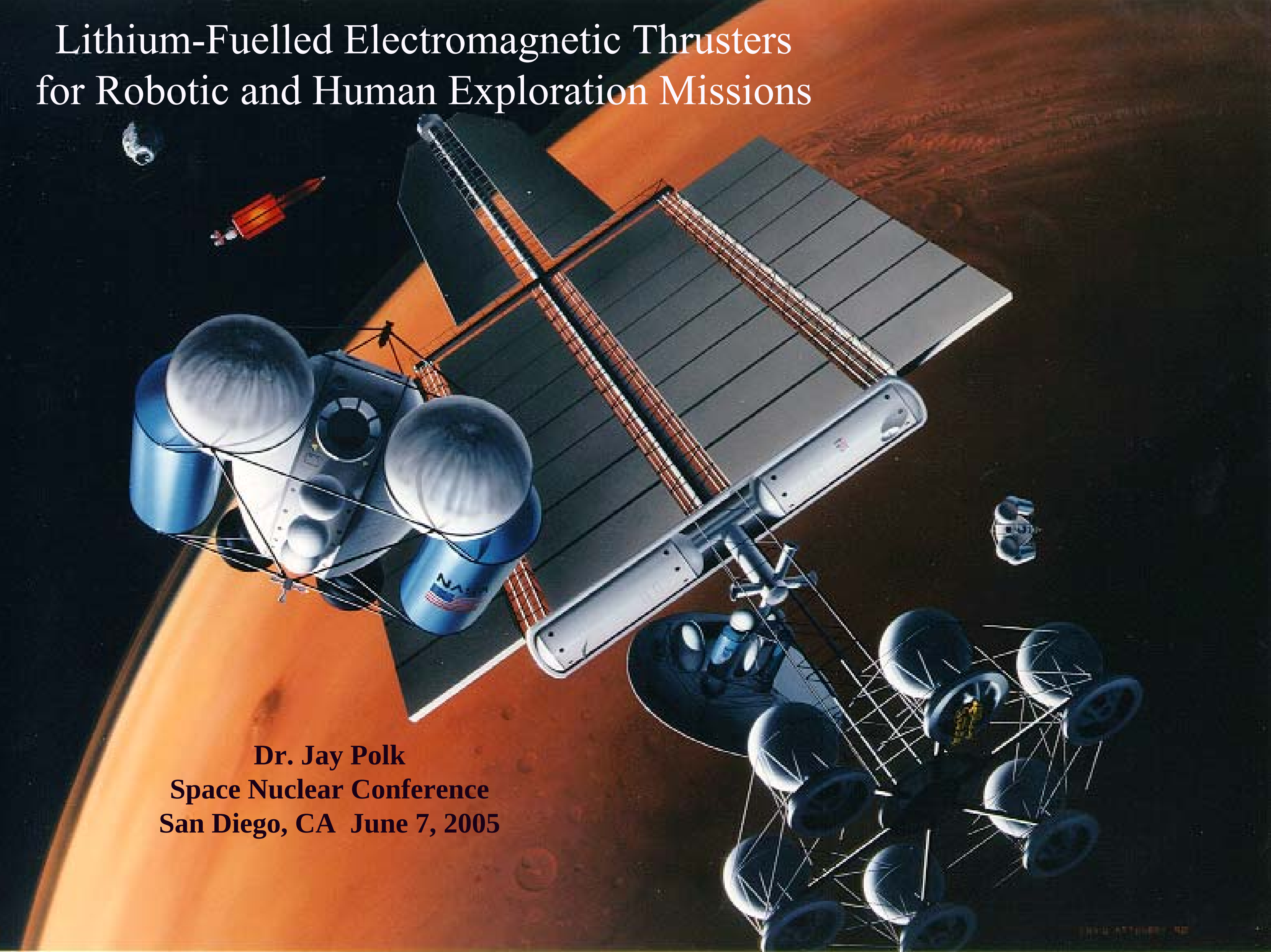
Lithium-Fuelled Electromagnetic Thrusters for Robotic and Human Exploration Missions

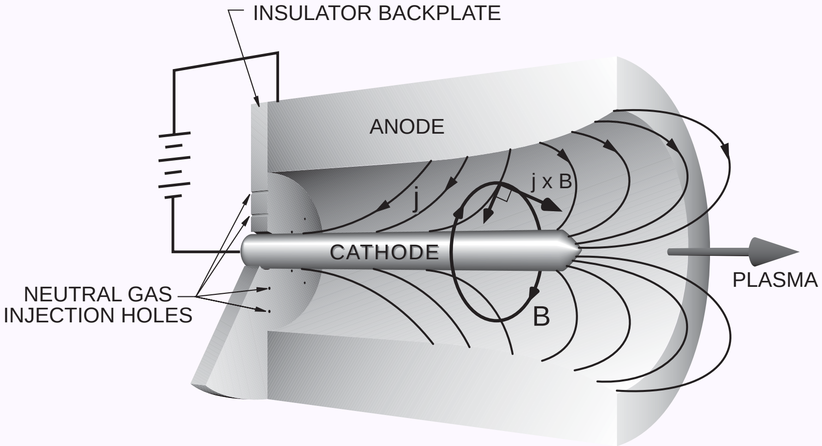


Dr. Jay Polk

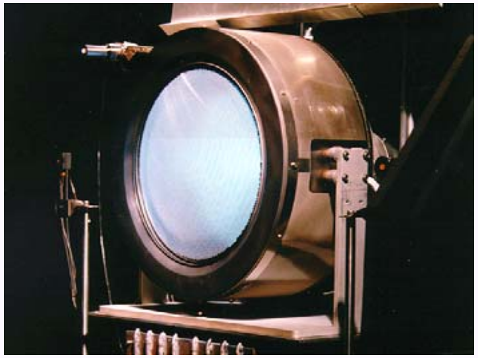
Space Nuclear Conference

San Diego, CA June 7, 2005

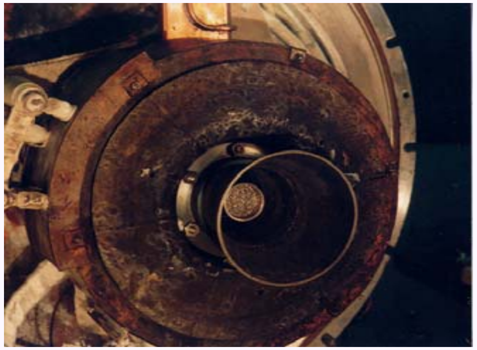
Lithium Lorentz Force Accelerators are Ideal for Very High Power Applications



J X B forces accelerate plasma axially and radially



2.3 kWe NSTAR Ion Thruster



200 kWe MAI Li- LFA

Electromagnetic acceleration allows >200 times the power of the NSTAR ion engine to be processed in the same volume

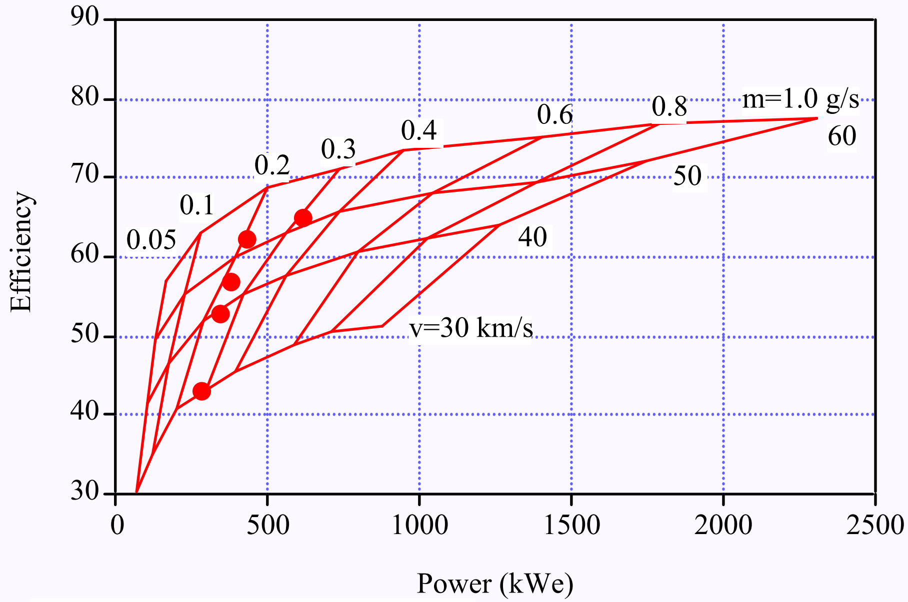
Lithium-fed Lorentz Force Accelerators (LFA's) are under investigation because:

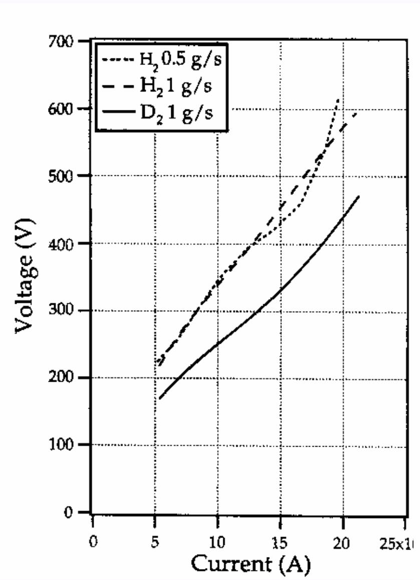
- Physics of operation yield high power processing capability
- Lithium propellant has potential for very high efficiency--low first ionization potential, high second ionization potential, and high first excited state of the ion yield low frozen flow losses

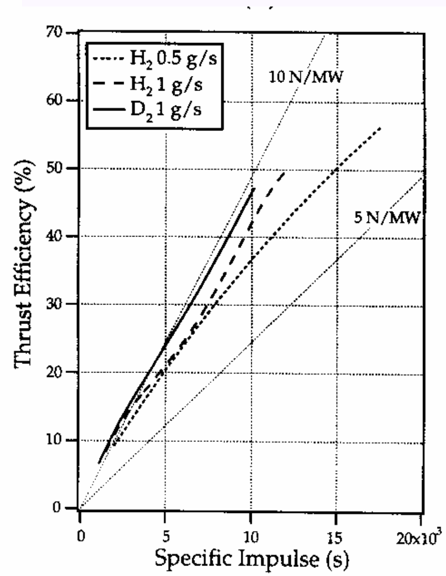
Very high power propulsion systems enable many far-term missions:

- Orbit-raising heavy payloads in Earth orbit
- Fast robotic outer planet missions
- Lunar and Mars cargo missions
- Piloted Mars missions
- Piloted outer planet missions

Propulsion Niches for High Power Lorentz Force Accelerators Define Evolutionary Path

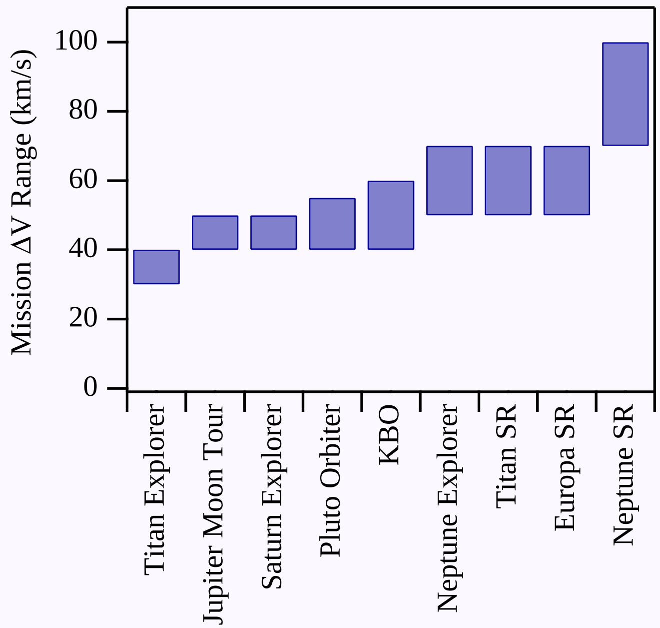




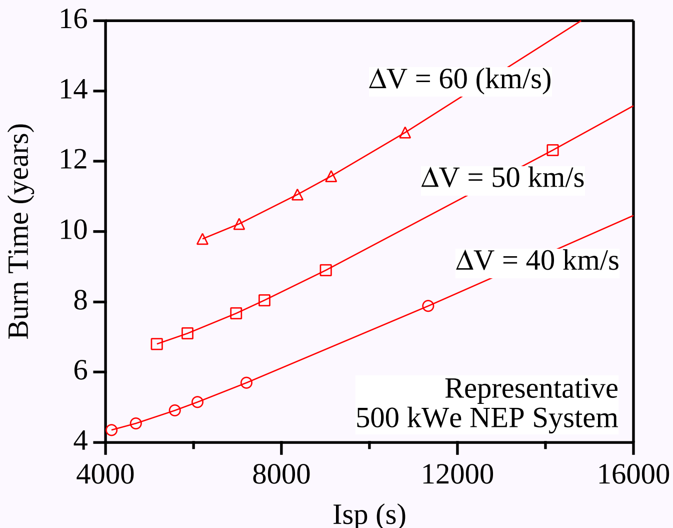


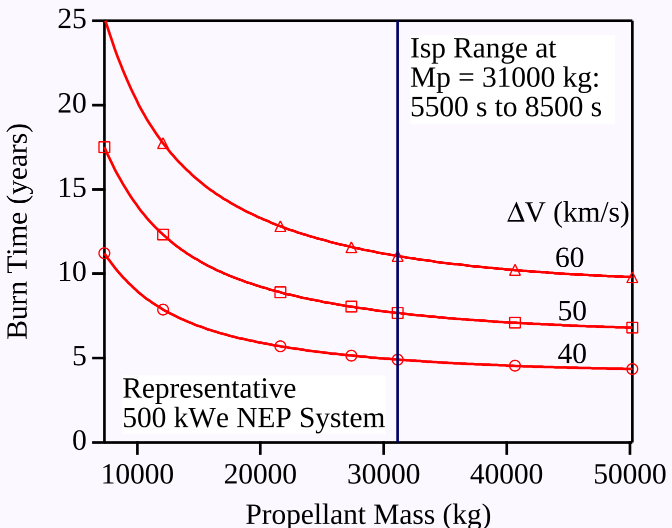
- **250 kWe applied-field thrusters are ideal for post-JIMO robotic missions**
  - Evolutionary power sources based on JIMO technology with up to 500 kWe system power
  - Specific impulse of 5500-8500 s
  - Fast robotic outer planet missions
- **0.5 -- 1 MWe lithium-fed thrusters give large mass savings for cargo missions**
  - First generation power sources with system power levels of 1-5 MWe
  - Specific impulse of 4000-6000 s
  - Orbit transfer and Mars cargo applications
- **1-- 5 MWe lithium thrusters fulfill mid-term propulsion requirements**
  - Second generation power systems at 10--30 MWe
  - Specific impulse of 4000-6000 s
  - Initial piloted Mars missions
- **5--10 MWe hydrogen or deuterium-fed thrusters open up the solar system**
  - Third generation (very low alpha) power systems at 100’s of MWe’s
  - Terminal voltage with lithium is too low to process very high power levels; hydrogen appears to provide required efficiency at Isp’s of 10000-15000 s
  - Piloted missions to Mars and the outer planets

Fast Robotic Outer Planet Missions Require Moderate Isp and High Power



- **Post-JIMO missions require ΔV's between 40 and 60 km/s**
- **Systems analysis for a 500 kWe-class robotic vehicle show:**
  - Burn time is proportional to Isp
  - Diminishing returns for propellant loads greater than 31000 kg
- **Fast trips are possible with 500 kWe systems and Isp's of 5500-8500 s**
  - Five year burn time for Jupiter
  - Eleven year burn time for outer planet sample return

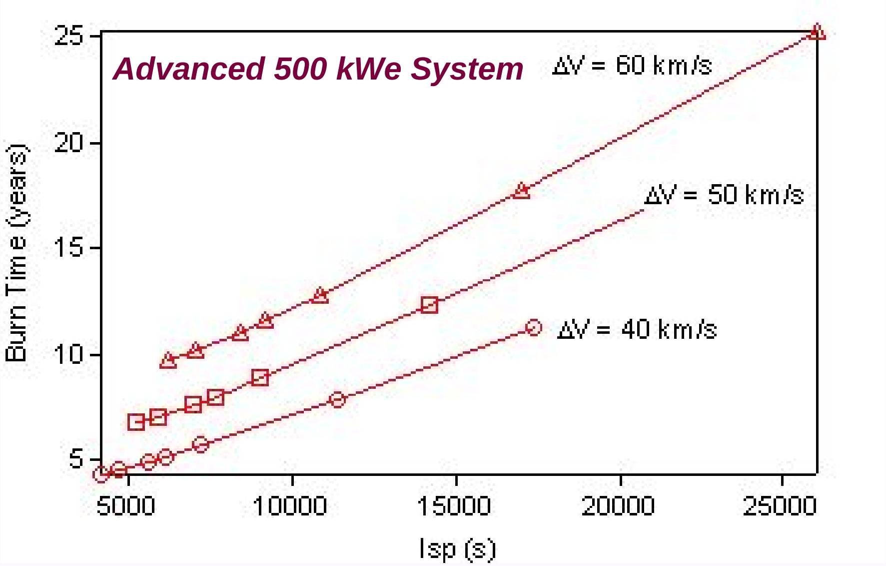




ALFA^2 Reduces Trip Time and System Complexity for Advanced NEP Missions

Problem Statement

- **Rapid outer planet missions require higher thrust**
  - Lighter, higher power nuclear systems
  - Moderate Isp thrusters
- **Current thruster technology is inadequate for high power missions**
  - Power per thruster is too low
  - Scaling to higher power at modest Isp is difficult



Modest Isp (higher thrust at a given power level) required for shorter trip times

Higher power thrusters reduce system complexity

CALIPPSO Is the Ideal Technology for Mass Savings in Lunar and Mars Cargo Missions

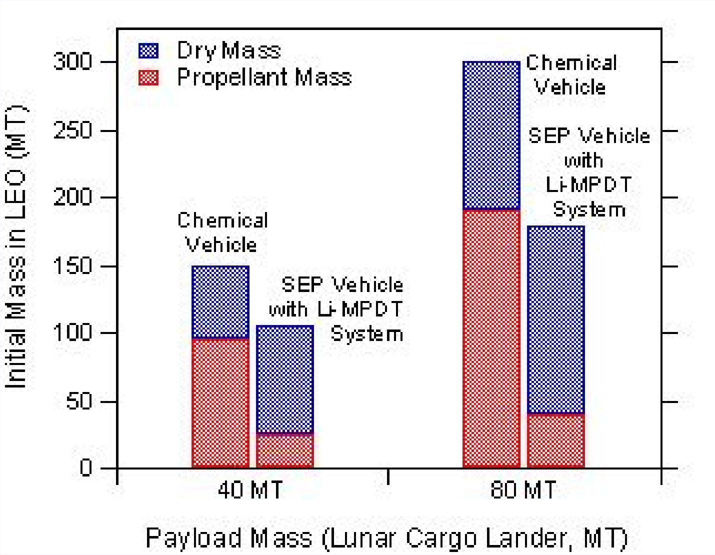
Problem Statement

The exploration program requires large payload masses

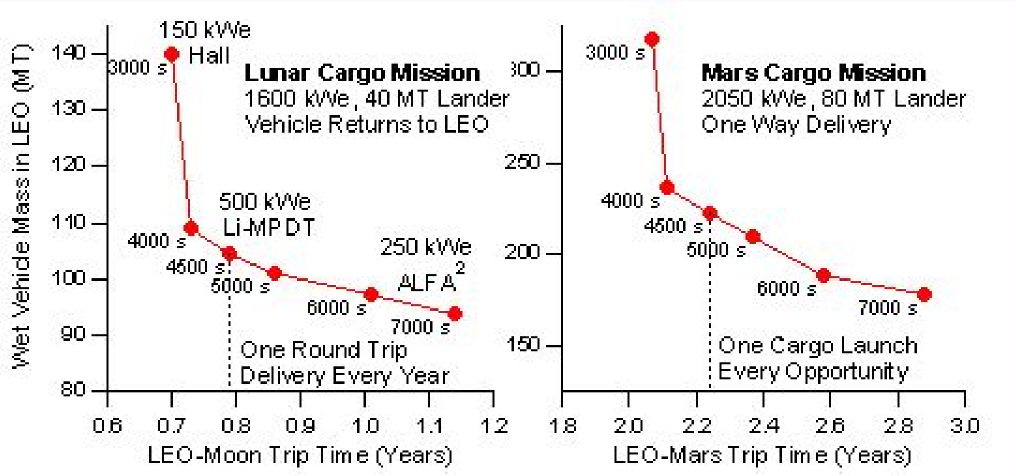
- Chemical propulsion suffers from large propellant fractions
- Cargo pre-deployment with EP offers huge mass savings

Current thruster technology is inadequate

- Power per thruster is too low
- Isp is either too low or too high



EP offers huge mass savings for cargo missions



High power, self-field Li thrusters provide the optimum Isp

Technical Approach

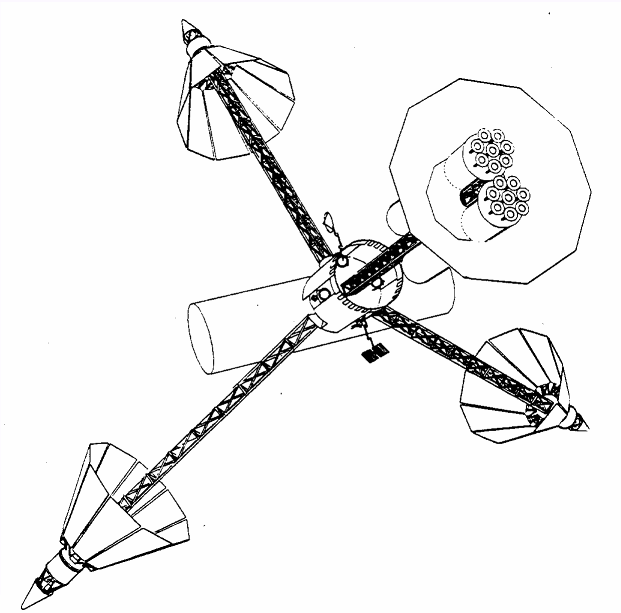
500 kWe thruster development

- Radiation-cooled
- All refractory metal construction
- Advanced cathode technologies
- Control of anode current conduction processes

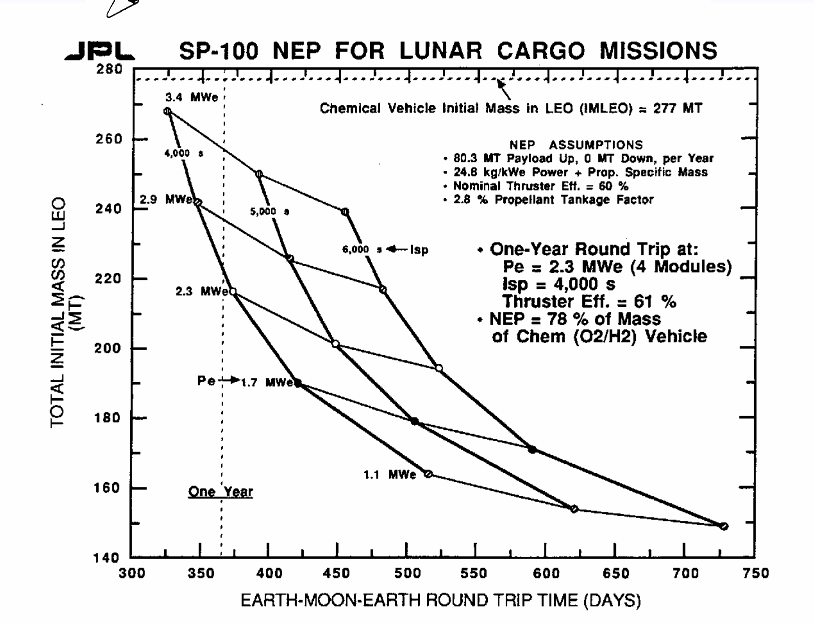
Experimental performance demonstration

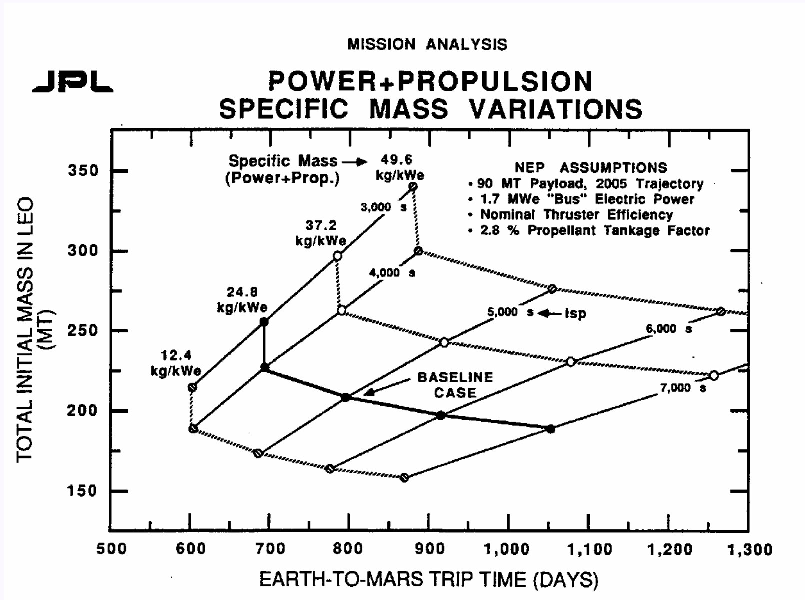
Life assessment using analysis and testing

First Generation Power and Propulsion Systems Enable Cost Effective Earth Orbital, Lunar and Mars Cargo Missions

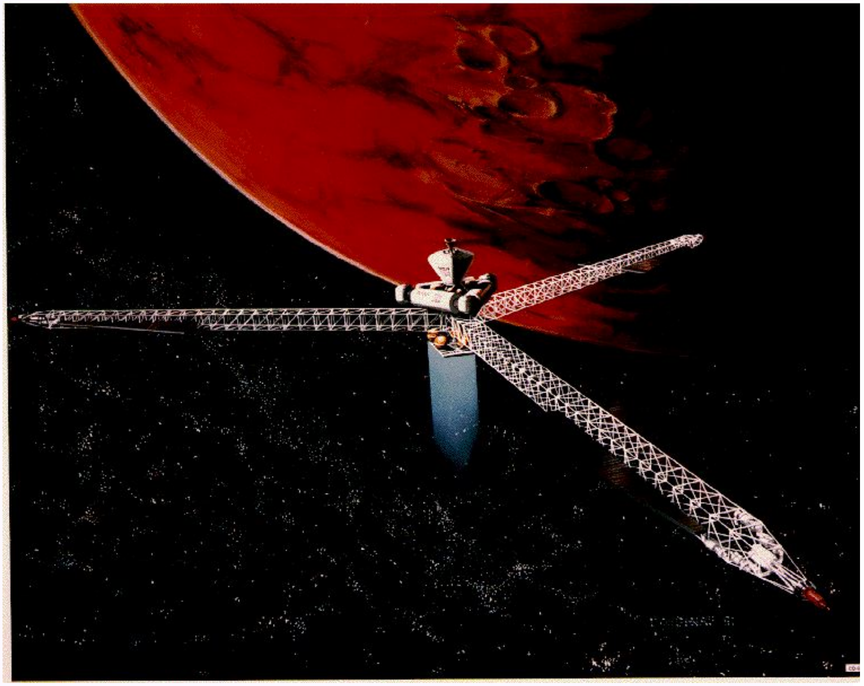


- 50% IMLEO reduction for 4540 kg payload delivered to GEO compared to chemical (250 kWe system with $\alpha = 31$ kg/kWe)
- 20% reduction in IMLEO for lunar cargo vehicle compared to chemical (2.3 MWe vehicle with $\alpha = 25$ kg/kWe)
- 55% reduction in IMLEO for Mars cargo vehicle compared to chemical (1.7 MWe vehicle with $\alpha = 25$ kg/kWe)



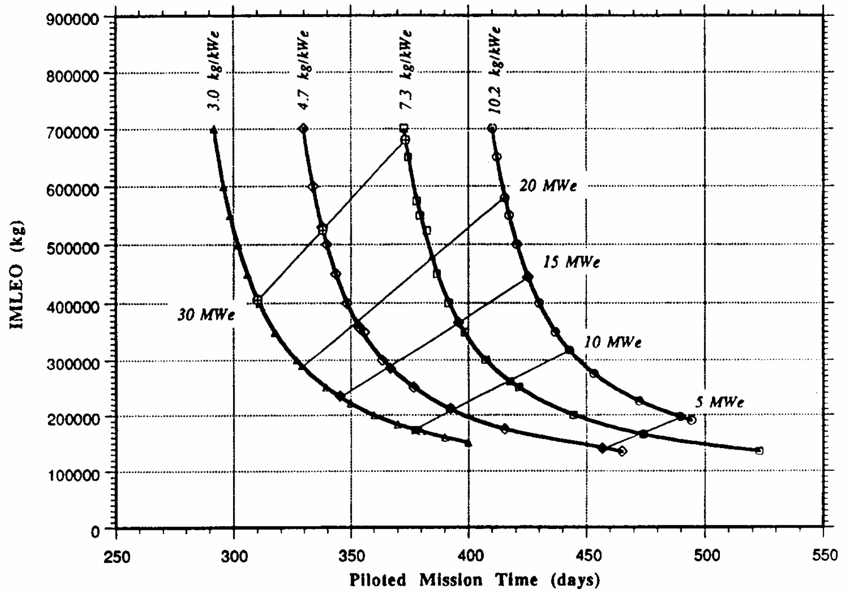


Second Generation Propulsion and Power Systems Enable Fast Piloted Mars Missions



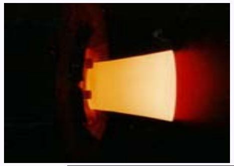
Effect of NEP Technology and Power Level on Piloted Mars Mission Performance

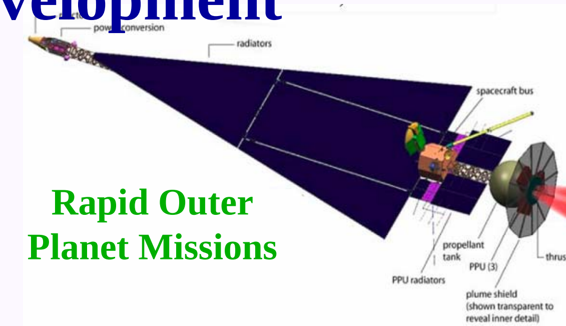
(2016 Split, 30 day stay, ECCV return, piloted vehicle mass only)



- 1 year round trip time possible with 20-30 MWe system
- All NEP missions consistently show the lowest IMLEO of all options

JPL's Programs Address the Key Challenges in Electromagnetic Thruster Development





POWER

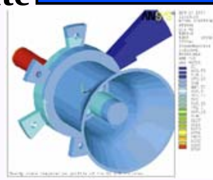
200 kWe
Steady State

- Anode Texturing/High Emittance Coatings
- Heat Pipes

250 kWe
Steady State

500 kWe
Steady State

Rapid Outer Planet Missions



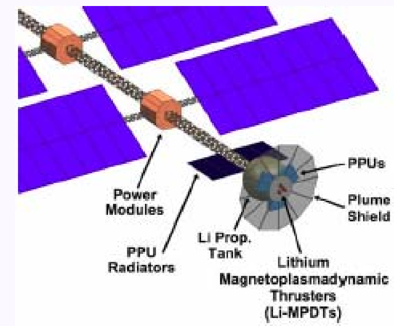
PERFORMANCE

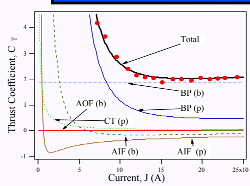
$\eta = 50\%$
Isp = 4000 s

- Lithium Propellant
- Onset Control
- Applied Field Optimization

$\eta \geq 60\%$
Isp = 6200 s

$\eta \geq 60\%$
Isp = 4500 s





LIFETIME

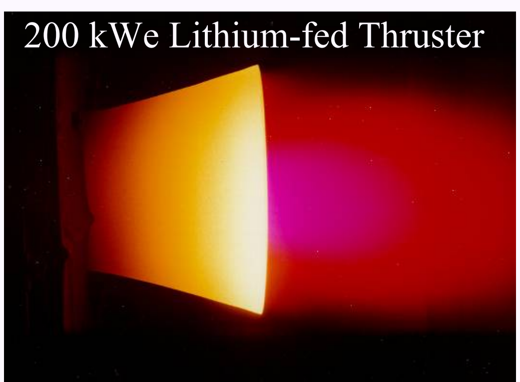
100's of Hrs
At 3000 A

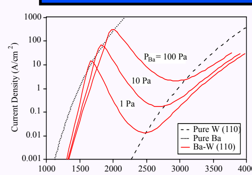
- Multi-Channel Hollow Cathodes
- Barium Addition

28000 Hrs
At 2750 A

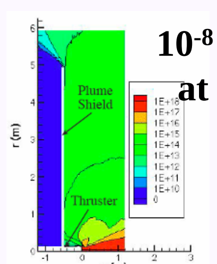
8800 Hrs
At 10000 A

Lunar and Mars Cargo Missions





PLUME CONTAMINATION



10^{-8} g/cm^{2}s
at 0.3 m

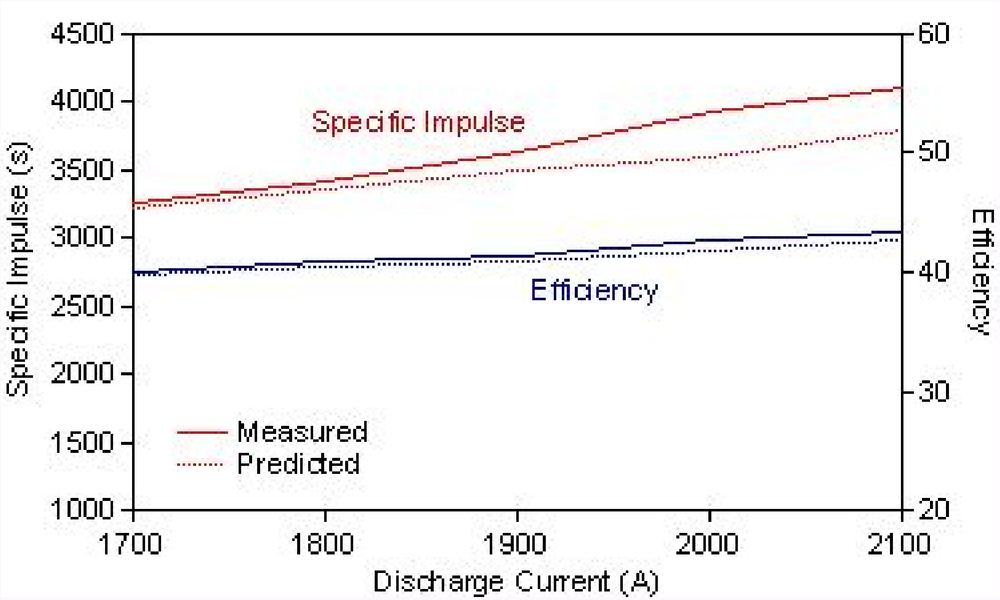
- Plume Shields
- Booms

10^{-10} g/cm^{2}s
at 30 m

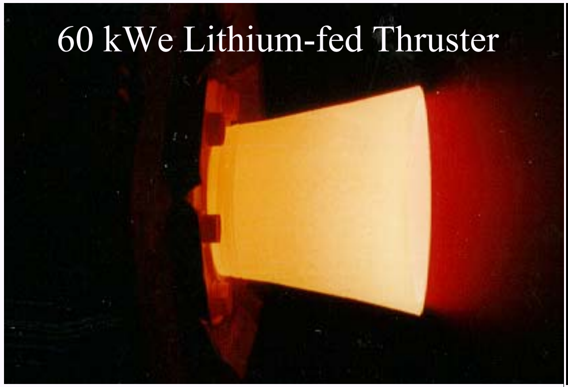
STATE OF THE ART

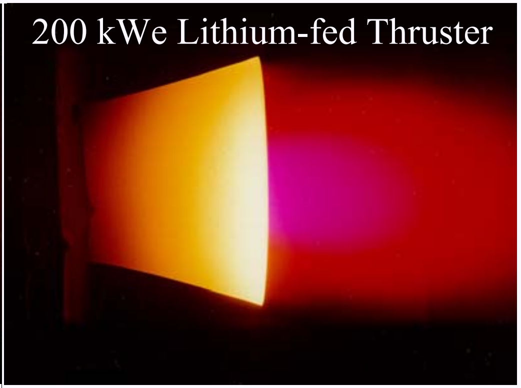
250 kWe Applied Field Thruster Design Based on Russian Experience

Comparison between model and experiments at 120 kWe



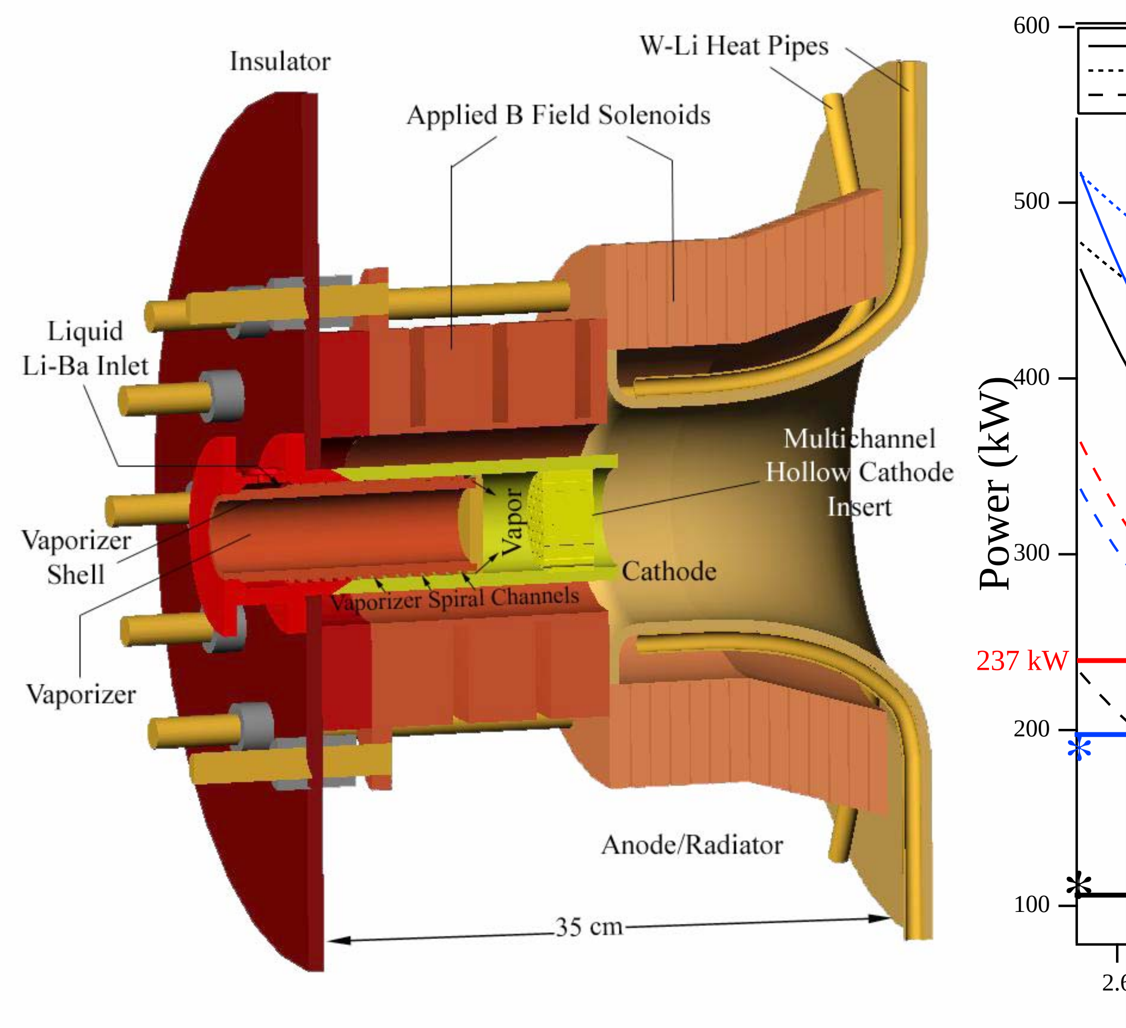
Two of MAI's family of applied field Li LFAs

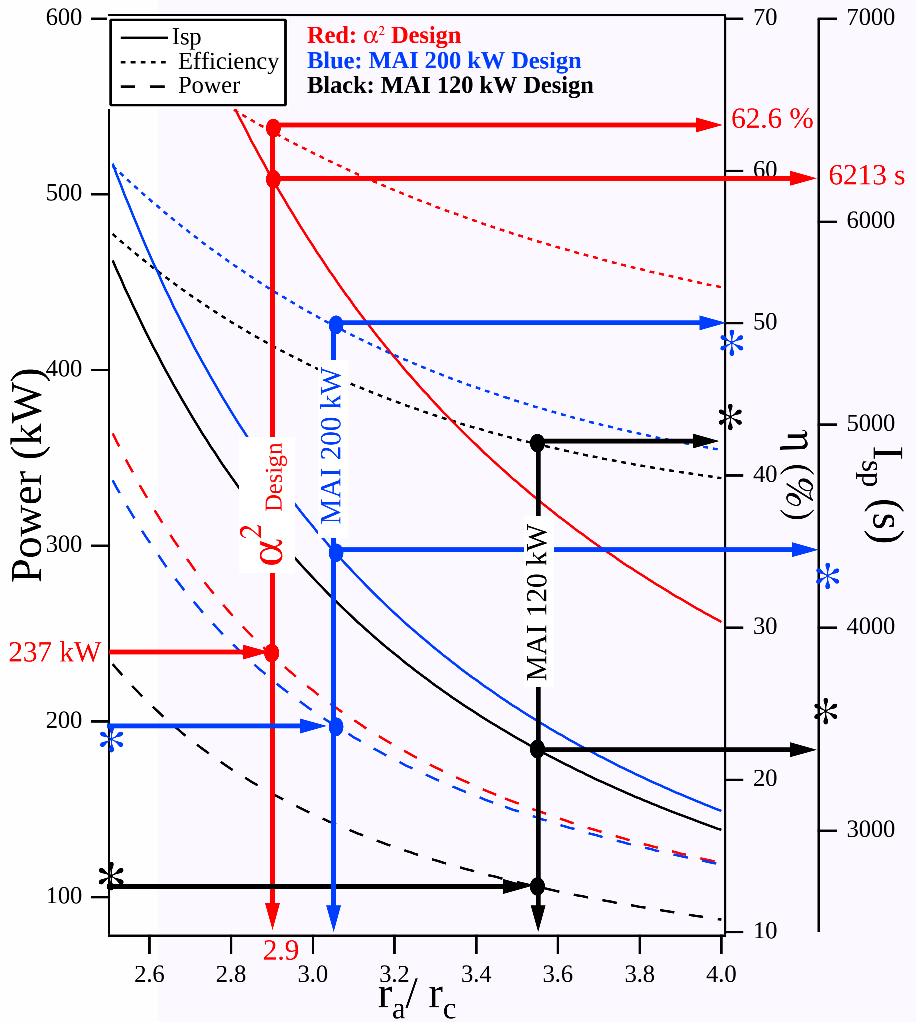




- The Moscow Aviation Institute has validated a performance model with a family of applied-field thrusters developed under JPL sponsorship
- The semi-empirical model includes:
  - Thrust equation
  - Voltage model
  - Onset current model
- Data from thrusters with power levels of 60 - 200 kWe show excellent agreement
- Model was used to design a 250 kWe thruster for post-JIMO robotic missions.

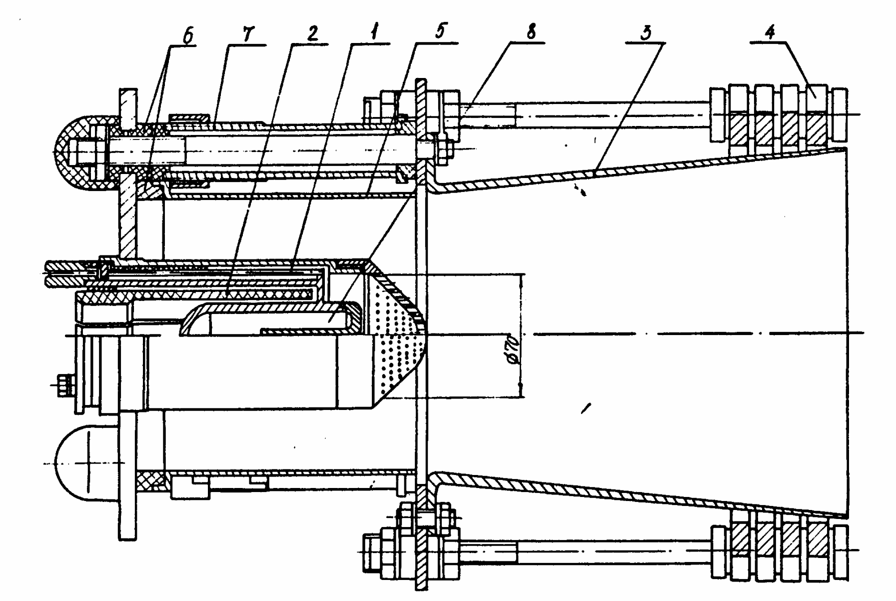
250 kWe Design Yields Performance Required for Post-JIMO Robotic Missions





Large Russian Experience Base For Very High Power Self-Field MPD Thrusters

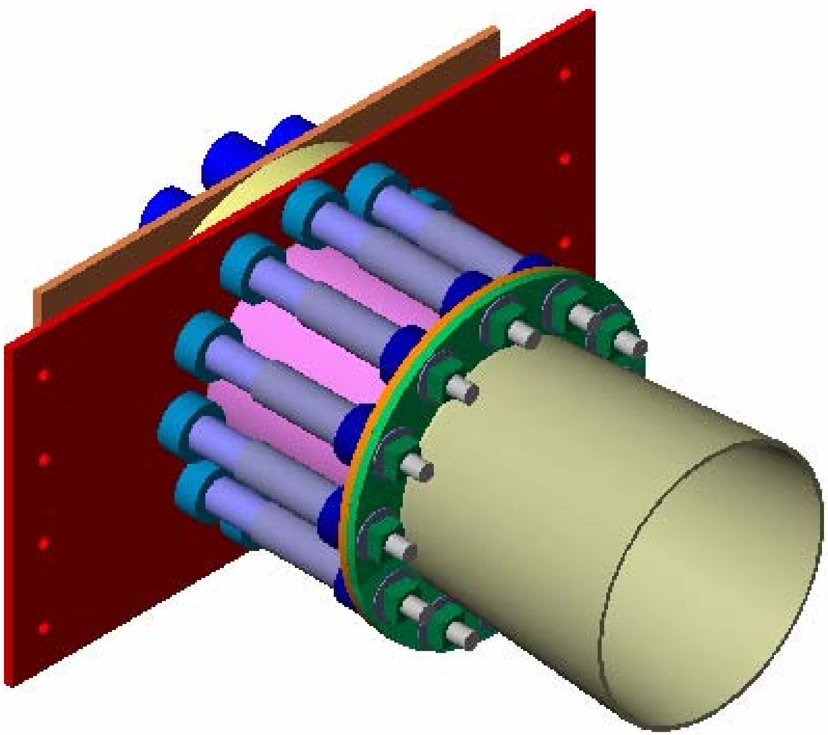
Organization	Power (kWe)	Current (kA)	Specific Impulse (s)	Efficiency	Typical Operating Period	Notes
NIITP	300-1000	6-15	3500-5000	40-60	5 min	NIITP design
Fakel	300-500	6-9	3500-4500	40-60	30 min	Energiya design
Energiya	300-500	6-9	3500-4500	40-60	30 min	Energiya design
Energiya	500	9	4500	55	500 hours	Endurance test of Energiya design
Energiya	250-500	5-8	3000-4500	35-55	30-60 min	Coaxial thruster with long cathode. Stopped because of cathode failure
MAI	300-500	6-9	3500-4500	40-60	30 min	Energiya design

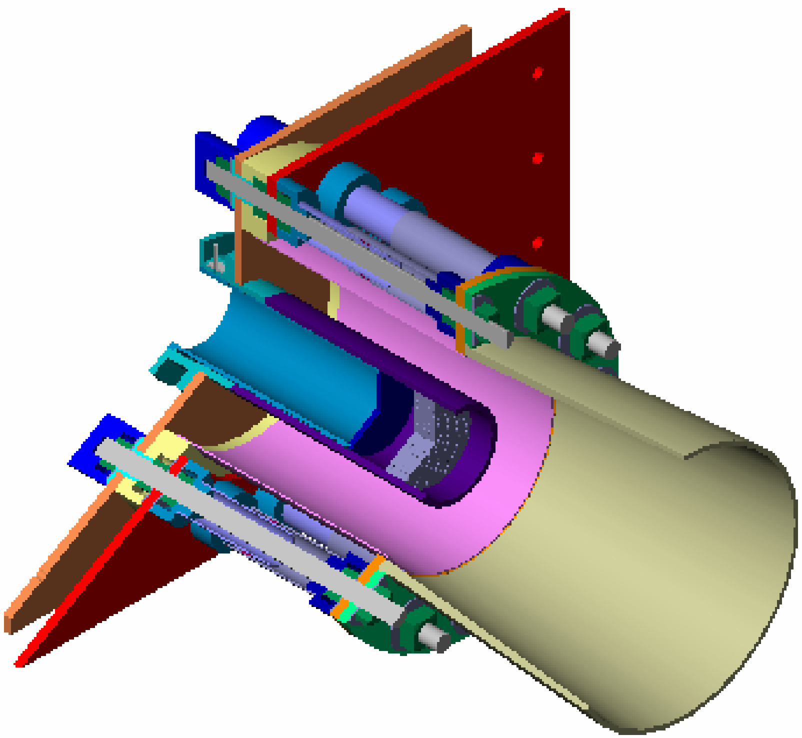


Energiya 500 kWe thruster design.

- Development of high power Li-fed thrusters also occurred in Russia.
- Capabilities required for human exploration missions largely attained.
  - High performance verified at 3 different institutions.
  - 500 hour lifetest at 500 kWe successfully completed.
  - Several thousand hour life projected.

JPL's 500 kWe Thruster is Designed to Recapture High Power Capability



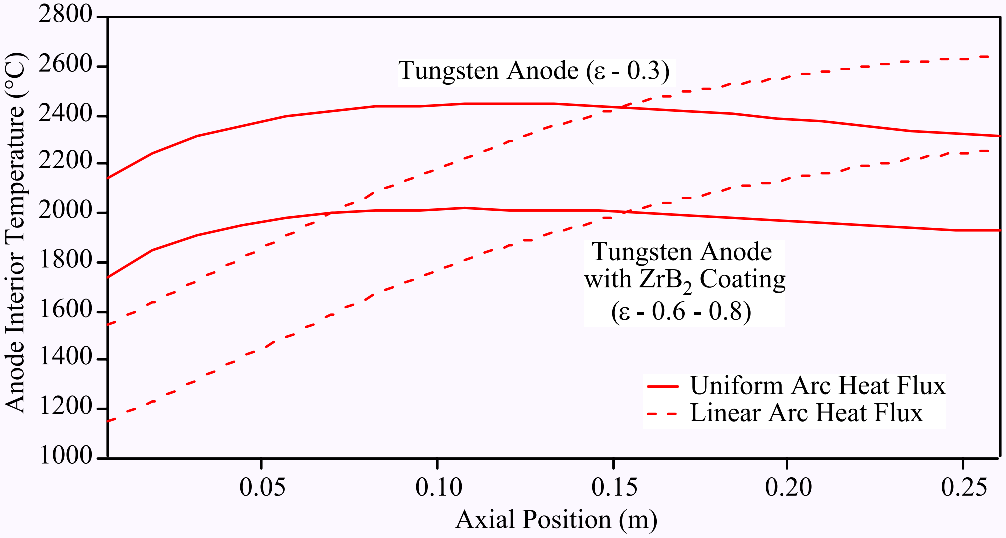


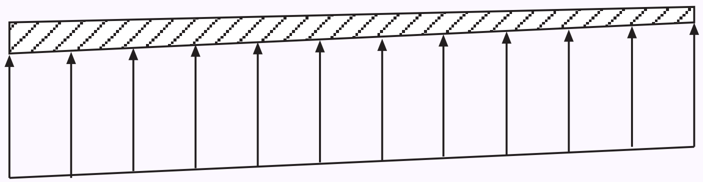
Unique Attributes:

- Steady state operation at up to 500 kWe
- Radiation-cooled
- All refractory metal construction

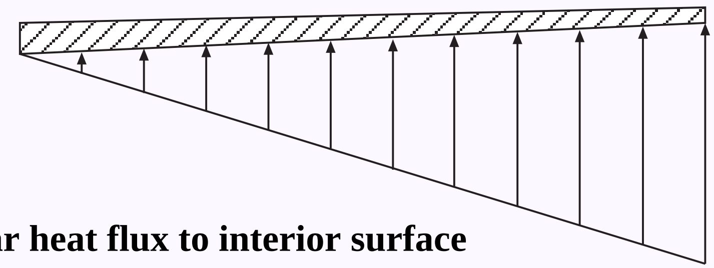
Results Indicate Tolerable Temperatures with High Emissivity Coatings

Marshall Space Flight Center
Thermodynamics and Heat Transfer Group





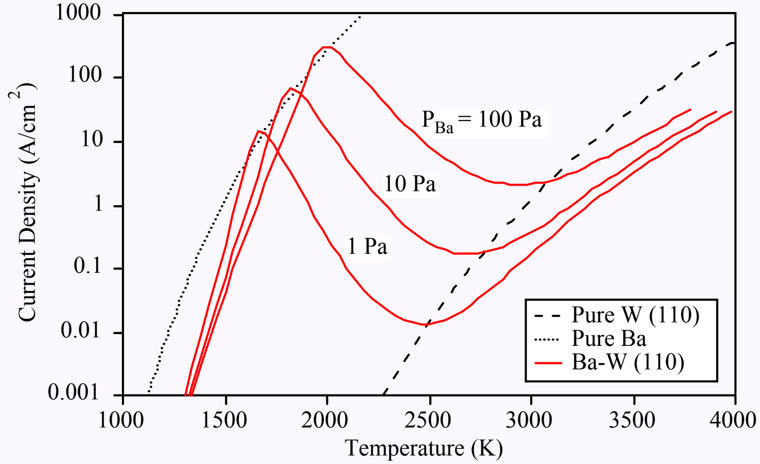
Uniform heat flux to anode interior surface



Linear heat flux to interior surface

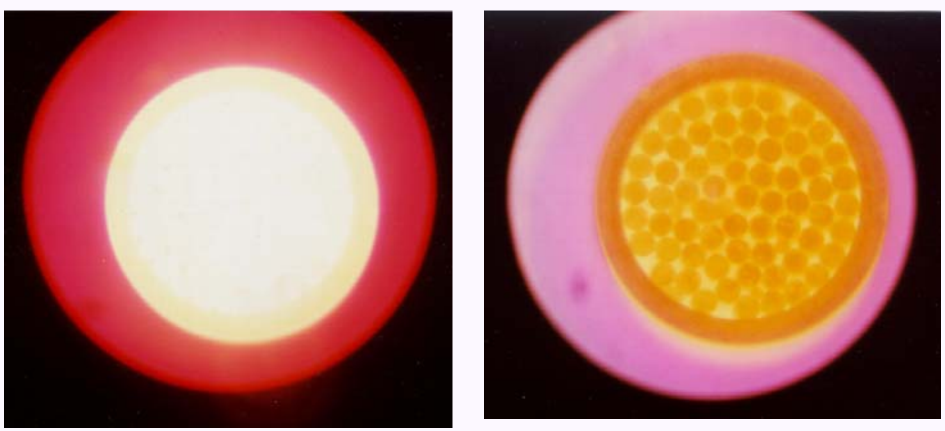
- 200 kW total arc heat load assumed as realistic upper bound for 500 kWe operation
- Anode heat flux distribution is not known; two distributions modeled to determine sensitivity
- Emissivity of anode exterior surface treated parametrically to study effect of high emissivity coatings
- Peak temperatures with ZrB_2 plasma-sprayed coatings developed in JPL 30 kWe ammonia arcjet program are 2000-2200 °C

Barium Addition Appears to be the Key to Long Cathode Lifetime



Higher current density capability enabled by addition of barium vapor to propellant flow through cathode

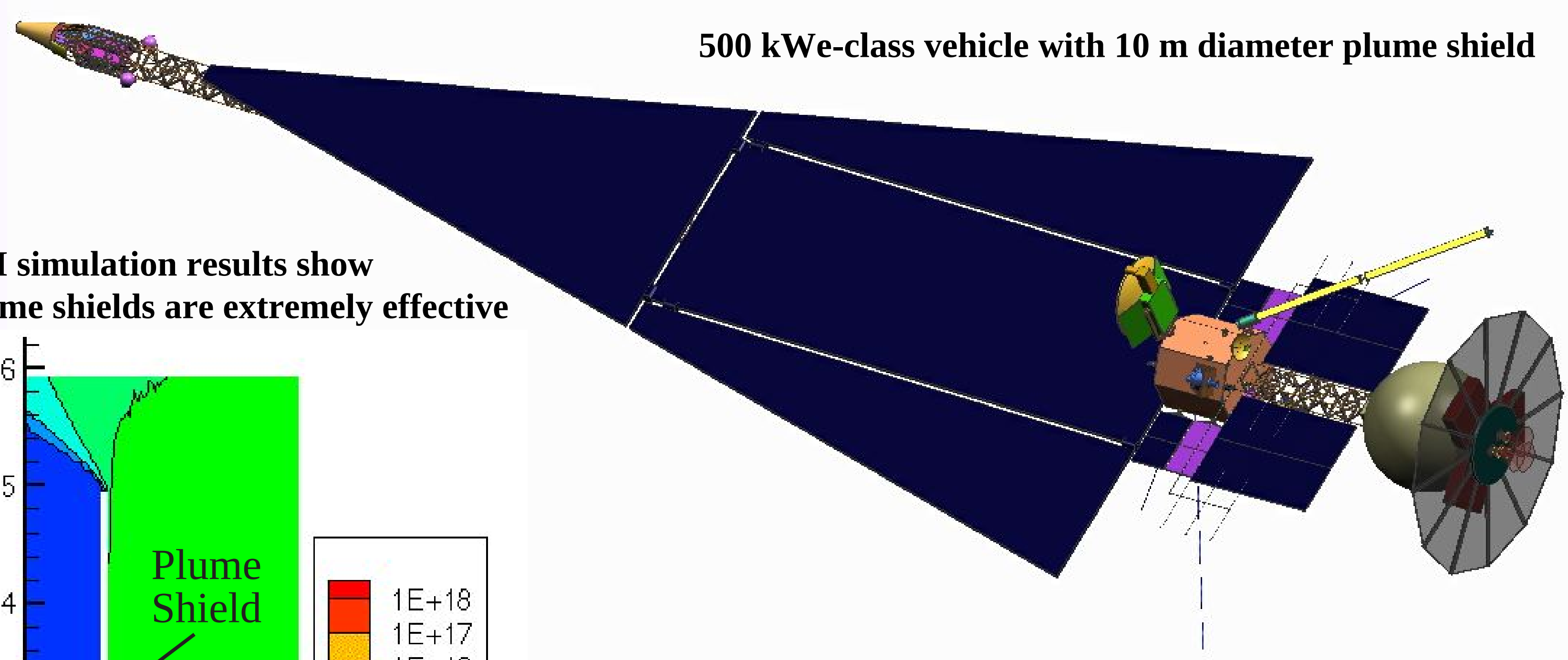
Preliminary experiments at MAI show 300-400 °C decrease in cathode temperature with barium addition



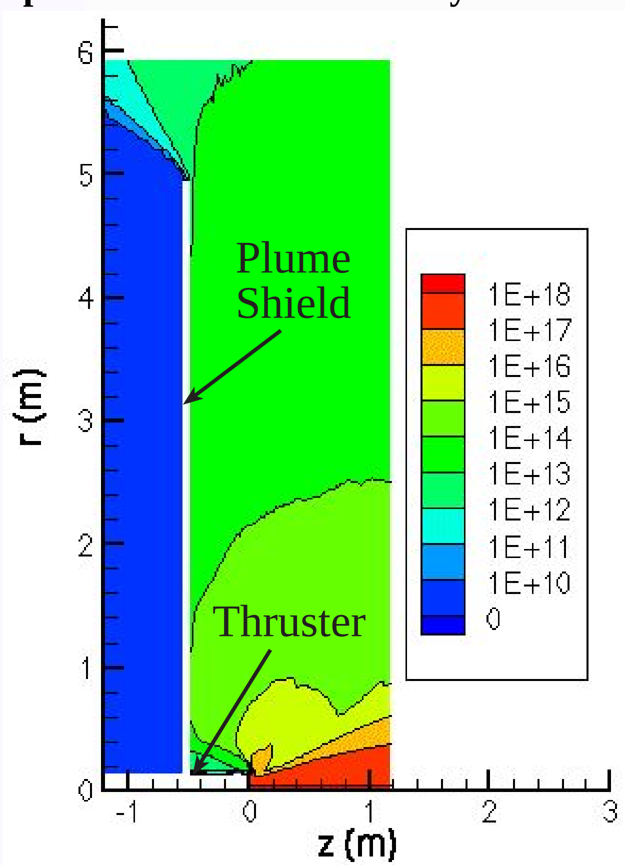
- Increasing engine power places greater stresses on cathode
  - Increased current density requirements
  - Radial temperature gradients caused by magnetic pinching
- JPL models of surface kinetics suggest that modest amounts of barium in propellant stream reduce the work function and lower cathode temperatures
- Preliminary experiments at MAI verify temperature decrease
  - Up to 300-400 °C drop in temperature observed in tests with uncontrolled flows of Ba
  - Very high barium flow rates actually limit achievable discharge current
- Additional experimentation and modeling required to understand and control radial variations and optimize barium flow

Modeling and Experiments Indicate that Contamination Hazards are Manageable

500 kWe-class vehicle with 10 m diameter plume shield



UM simulation results show plume shields are extremely effective

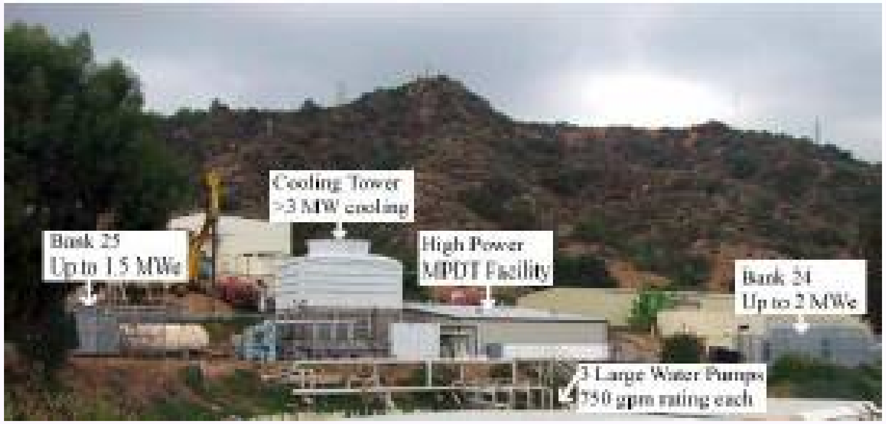


- The scale of high power vehicles offers opportunities to isolate engines from sensitive surfaces
- Preliminary measurements of lithium backflow in the MAI thruster yielded estimates of the near-field fluxes
- Plume modeling at University of Michigan and MIT show that plume shields are effective in reducing backflow

Electrical Power and Cooling Capability for Testing Up to 2 MWe Thrusters

The JPL High Power Thruster Testing Complex

The JPL High Power Test Facility--A Unique Asset for High Power Thruster Development



- The only facility in the country for high power metal propellant testing
- 3 m diameter x 8 m long
- Over 2 MWe of power-handling capability
- Safety approval for handling reactive Li propellants

The JPL High Power Test Facility: A Unique Asset for MWe-Class Thruster Development

- 3 m diameter x 8 m long stainless steel vacuum chamber
- Custom-designed, cooled stainless steel liner to absorb up to 2 MW thermal load from plume of thruster and facilitate handling of reactive propellants
- Pumping plant sufficient to maintain 10^{-6} Torr with condensable propellants

Lithium LFA's Show Great Promise for Ambitious Future Missions

- **Exciting results continue to support the conclusion that Li LFA's have the potential to meet the performance and lifetime requirements of high power missions**
  - Performance of 49% at 4100 s and 185 kWe with MAI applied-field device
  - Applied-field and self-field engine models support high performance claims
  - Approaches to achieving required cathode lifetime have been identified
  - Spacecraft contamination issues appear tractable
- **LFA's fill unique niches in high power propulsion**
  - Lithium-fed thrusters are the only propulsion option for near- to mid-term applications that require high power/thruster in the Isp range of 4000--6000 s
  - Hydrogen- or deuterium-fueled thrusters may meet the requirements of far-term systems with 10's of MWe's per engine at Isp's above 10000 s
- **Application of unique capabilities can resolve many of the remaining issues in the next few years**
  - Demonstration of performance at 500 kWe and further development of performance models
  - Better understanding of multi-channel hollow cathode thermal behavior
  - Further experimental characterization and modeling of lithium plumes