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INNOVATIVE ELECTRIC PROPULSION THRUSTER MODELING

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OUTLINE

- Introduction
  - Objective and Approach
  - Related Activities
- Concepts Selected for Modeling
  - C60 Electron-Bombardment Ion Thruster
  - Pulsed Inductive Thruster (PIT)
  - Lithium-Propellant MPD
- Other Concepts Modeled in Previous Studies
- Status and Plans

INTRODUCTION

JPL OBJECTIVES & APPROACH

- Objective
  - Model and evaluate advanced innovative electric propulsion concepts as an aid to performing NEP mission benefits studies
    - Provide scaling relationships for mass, power, efficiency, etc. as a function of Isp, propellant type, etc.
    - Identify technology status / needs
- Approach
  - Select concepts most appropriate for NEP Piloted / Cargo Mars Missions (MMW NEP emphasis)
  - Review relevant literature
  - Identify technology status / needs
  - Formulate scaling relationships
    - Use first-principals modeling approach

INTRODUCTION

JPL INNOVATIVE ELECTRIC PROPULSION RELATED ACTIVITIES AT JPL

- Advanced Propulsion Concepts Studies
  - High-Power Ion, MPD, and ECR Thruster Modeling
  - Microwave Electrothermal (MET) Thruster Modeling
  - MMW SEP / NEP - Ion / MPD Thruster PPU Modeling
- In-House Research in Advanced Electric Propulsion
  - Inert-Gas Ion Thrusters
  - C60 Ion Thrusters
  - Li-MPD Thrusters
  - Arcjets
  - ECR Thrusters (JPL/Caltech)
  - MET Thrusters
- Contract Research in Advanced Electric Propulsion
  - Variable-Isp Thruster Research (MIT)

JPL SUMMARY OF CONCEPTS CONSIDERED

Concept	Typical Isp (s)	Typical Eff. (%)	Typical Pe (MWe)	Likely Application Cis-Lunar	Likely Application Mars	Comments
High-Power Ion thruster	5,000-20,000	85	0.05-2	X	X	• Modeled in FY'91 (APC)
C60 Ion thruster	2,000-5,000	75	0.05-5	X	?	• THIS TASK • Good Eff. at Low Isp
Inert-gas MPD	5,000-9,000	60	1-10	X	X	• Modeled in FY'91 (APC)
Li-propellant MPD	5,000-9,000	80	1-10	X	X	• THIS TASK • Good Eff.
ECR	2,000-10,000	70	0.01-2	X	X	• Modeled in FY'91 (APC)
MET	1,000-2,000	60-70	0.001-0.1	X		• Modeled in APC RTOP • Not applicable to Mars
MIT Variable Isp Thruster	1,000-20,000	50	0.1-2	X	X	• Modest Eff.; Only ~ 10-20 % savings w/ variable Isp
TRW PIT	1,000-5,000	60	0.1-2.5	X	X	• THIS TASK • Omnivorous (ETRU ?)
Mass Drivers, Rail Guns	1,000-1,500	90 50	0.1-10	X		• Modeled in FY'89 (ASAO) • Omnivorous; pellet debris

JPL C60 ELECTRON BOMBARDMENT ION THRUSTER MODELING

- Electron-bombardment ion thruster analysis based on a model originally developed by Brophy
  - Propellants:
    - C60
    - Xenon
    - Krypton
    - Argon
  - Span-to-Gap Ratio: 500
  - Minimum Grid Separation: 0.6 mm
  - Maximum Electric Field between Grids: 3000 V/mm
  - Maximum Thruster Diameter: 1m
  - Losses considered:
    - Ion Production Cost
    - Propellant Utilization Efficiency
    - Beam Divergence Loss

C60 ELECTRON BOMBARDMENT ION THRUSTER MODELING

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PROCEDURE

- For a given specific impulse, maximize thrust (power input) of thruster
- Model two regimes:
  - Regime 1: Maximize grid diameter until 1-m limit is reached. Net-to-total voltage ratio R=0.2
  - Regime 2: Keep grid diameter fixed at 1 m, raise net-to-total voltage ratio R from 0.2 to 0.9
- Compute:
  - Total Power Consumption
  - Thrust
  - Thruster Efficiency
  - Thruster Mass
  - Specific Mass
  - Thrust-to-Power Ratio
  - Mass Flow Rate
  - Discharge Current
  - Beam Current
  - Grid Separation
  - Grid Diamenter
  - Beam Voltage
  - Total Voltage

C60 ELECTRON BOMBARDMENT ION THRUSTER MODELING

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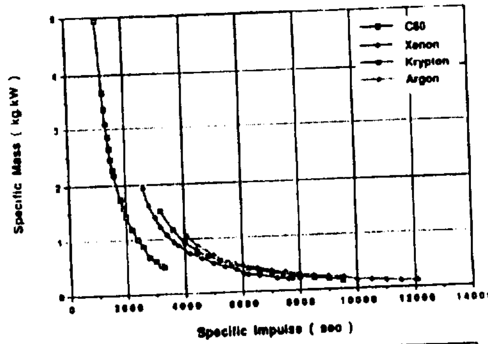
SAMPLE INPUT DATA

Propellant	C60	Xenon
Beam Divergence	0.95	0.95
Ion Production Cost	100 eV/ion	150 eV/ion
Propellant Utilization	0.9	0.9
Discharge Voltage	36 V	36 V
Neutralizer Coupling	20 V	20 V
Grid Open Area Fraction	0.75	0.75
Thruster Chamber Length	20 cm	20 cm

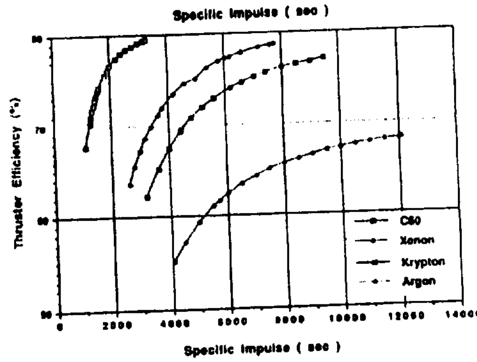
C60 ELECTRON BOMBARDMENT ION THRUSTER MODELING

JPL SPECIFIC MASS & EFFICIENCY vs Isp

- Specific Mass impacts vehicle sizing



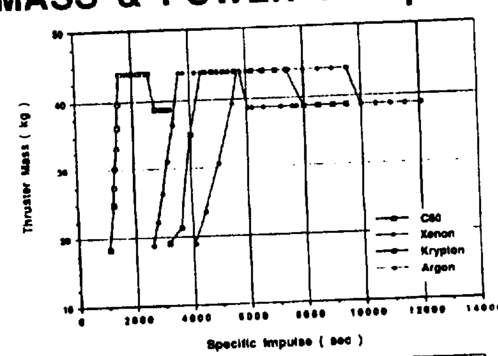
- Efficiency (Pjet/Pe) impacts "jet power" and thrust



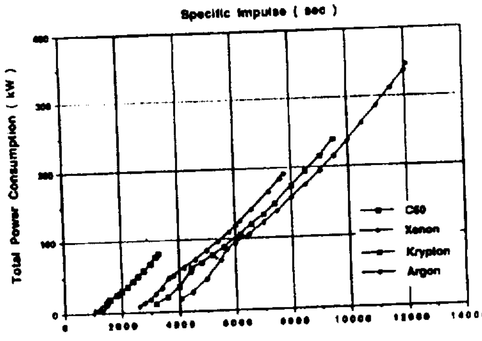
C60 ELECTRON BOMBARDMENT ION THRUSTER MODELING

JPL THRUSTER MASS & POWER vs Isp

- Mass-per-thruster impacts gimbal sizing



- Power-per-thruster impacts PPU sizing

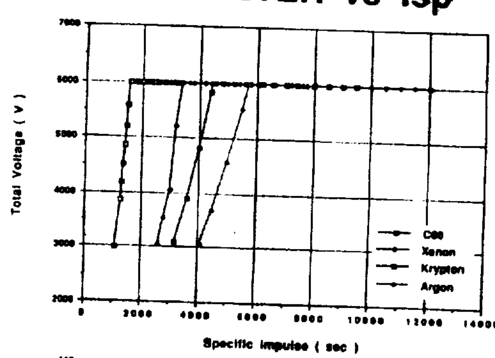


JPL C60/Xe/Kr/Ar-ION THRUSTER SUMMARY

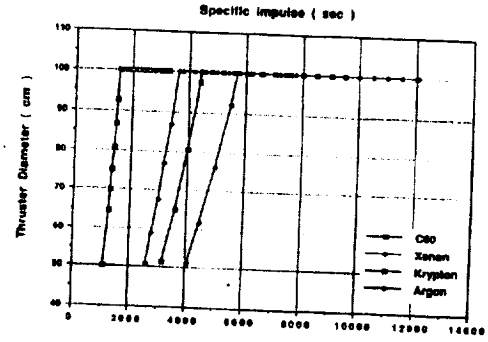
- C60 versus Xe/Kr/Ar
  - For Isp < 4000 lbf-s/lbm, C60 has lower specific mass and higher efficiency than Xe/Kr/Ar
  - Isp of C60 ideal for cis-lunar missions
- Xe vs Kr vs Ar
  - Xe/Kr/Ar have ~ same specific mass
  - Xe/Kr efficiencies higher than Ar
  - High cost of Xe and low eff. of Ar may favor Kr
  - High power-per-thruster (>0.1 MWe) possible

JPL MAX. VOLTAGE & DIAMETER vs Isp

- Maximum Voltage impacts PPU sizing



- Thruster Diameter impacts vehicle packaging / configuration



JPL PULSED INDUCTIVE THRUSTER (PIT) MODELING

- Concept
  - Current pulse in flat induction coil (1 m dia) induces ionization and drives plasma current
  - Magnetic (JxB) force accelerates plasma
  - Propellant injected with pulsing valve
- Advantages
  - Electrodeless (minimal errosion)
  - Can operate with a variety of propellants
    - Ammonia, hydrazine, argon, carbon dioxide demonstrated
- Technical Issues
  - Propellant valve lifetime
  - High rep-rate switch and capacitor life-time
  - System performance at high rep-rate

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Mark V Front View

PULSED INDUCTIVE THRUSTER MODELING

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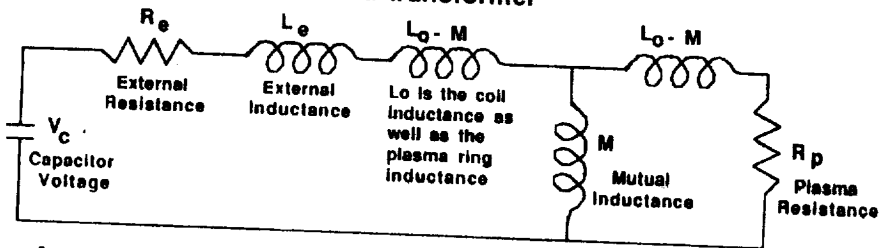
PIT MODEL DISCRIPTION

- PIT analysis based on a model originally developed by TRW
  - Thruster modelled as a transformer



- A system of coupled differential equations discribing the model is solved to estimate the specific impulse and efficiency
- Thruster paramaters input to the model are based on the TRWMark V design:
  - Mass = 150 kg
  - Coil diameter = 1 m
  - Total Vc = 30 kV DC
  - Applied Voltage (from PPU) = Vc / 2
- Plasma resistivity (related to Rp) is propellant dependent

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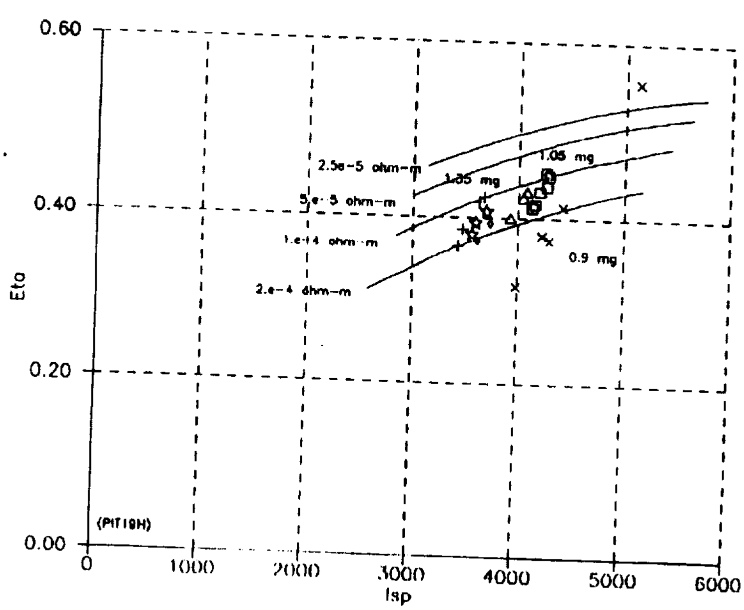
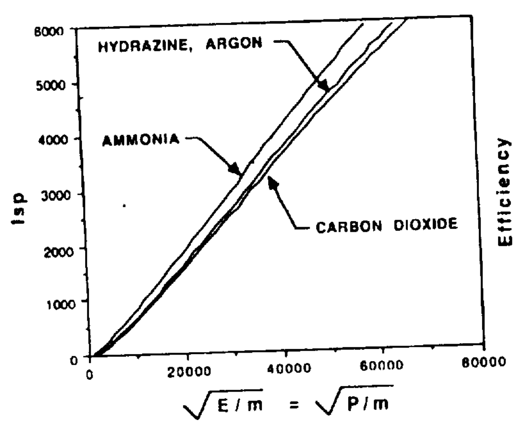
Comparison of N2H4 Data with Analytical Model

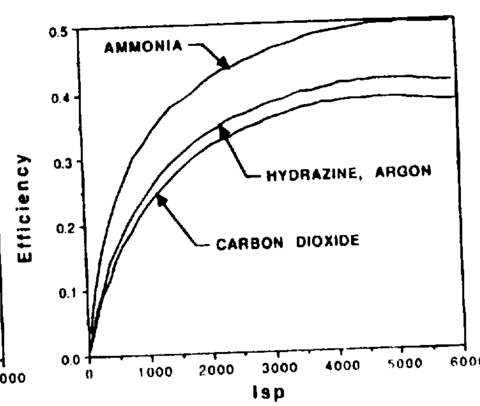


JPL PIT MASS AND POWER CONDITIONING

- Thruster Mass
  - Thruster mass is proportional to energy-per-shot (about twice capacitor mass)
  - To obtain a specific mass of 1 kg/kW requires rep-rate on the order of 100 Hz
- Power Conditioning
  - Switches needed to isolate power system from thruster circuit during shots
  - May need a dedicated Power Processing Unit (PPU) to charge capacitors between shots (supply ~15 kV DC)
  - It may be possible to use sychronous switching to charge capacitors directly from a dynamic nuclear electric power supply bus (typically 7-10 kV AC)

JPL PIT MODELING RESULTS





- For a given thruster (e.g., Mark V) and propellant type, efficiency and specific impulse are both functions of the square root of energy per shot divided by mass per shot (or square root of average power divided by average mass flow rate)

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PULSED INDUCTIVE THRUSTER MODELING

PIT SUMMARY

- Thruster efficiency varies from about 20 to 50 % at specific impulses between 2,000 and 6,000 lbf-s/lbm, respectively
- Thruster mass is proportional to energy per shot
- Specific mass is proportional to shot repetition rate
  - Shot rep rate ~ 100 Hz needed for ~ 1 kg/kWe
- Thruster has been operated on a variety of gases
  - Potential to utilize extraterrestrial propellants
- May have significant PPU needs for SEP or static-conversion NEP (~100 V DC source)
  - Dynamic-conversion NEP more attractive (~ 8 kV AC source)
- Propellant valve and capacitor switch lifetimes an issue

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LITHIUM MAGNETOPLASMADYNAMIC (MPD) THRUSTER MODELING

- Self-field steady-state MPD thruster analysis based on a model originally developed by Blandino
  - Propellants: - Lithium
    - Argon
    - Hydrogen
  - Axially-uniform radial current distribution, coaxially-uniform diameter tungsten electrodes
  - Geometry ratios fixed: Ra/Rc = 5, Lc/Rc = 9
  - Maximum cathode current density = 15 kA/cm^2 (to limit erosion)
  - Lithium heat pipe technology used for annular radiator
    - Max heat flux technology-limited to < 1000 W/cm^2
    - Max heat flux calculated < 500 W/cm^2
  - Losses considered: - Ohmic heating of plasma & electrodes
    - Sheath voltage drops
    - Anode heating

LITHIUM MPD THRUSTER MODELING

JPL SAMPLE INPUT DATA

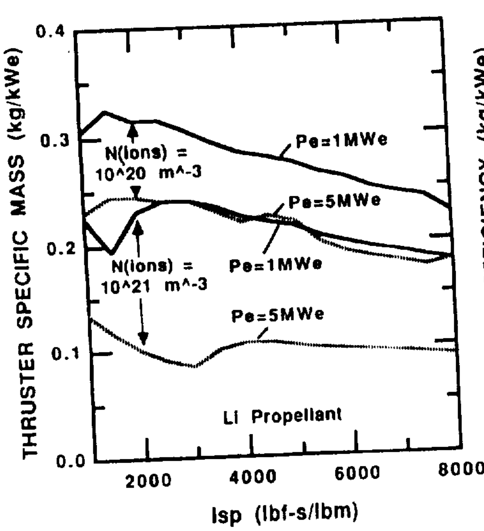
Propellant	Argon	Lithium
Ion Mass	39.9 amu	6.9 amu
Ionization Potential	15.76 eV	5.39 eV
T electrons	2 eV	2 eV
T ions	6 eV	2 eV
N ions	10^20 m^-3	10^20 m^-3

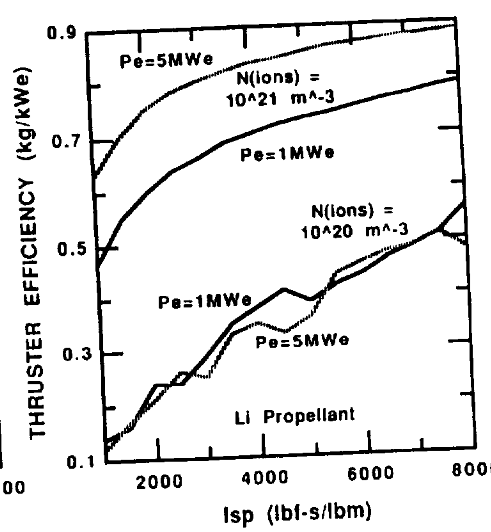
- Modeling still in early stages
- Results shown following are preliminary only
  - Still in process of de-bugging model
    - Example - output sensitive to assumed ion number density (N ions)

LITHIUM MPD THRUSTER MODELING

JPL SPECIFIC MASS & EFFICIENCY

- Thruster power, Isp, and N (ions) used as inputs to model





- Onset limits Isp to 7000 lbf-s/lbm for I/M-DOT < 300 kA/(g/s)

LITHIUM MPD THRUSTER MODELING

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Li-MPD SUMMARY

- Model still being tested / verified
- In general, correct trends observed
  - Specific mass decreases and efficiency increases as Isp, power, and N(ions) increase
- But - - -
  - Efficiency & specific mass a strong function of N(ions)
    - Experimental values of N(ions) ~ 10^20 - 10^21 m^-3 for megawatt-class MPDs
    - Possible solution - convert N(ions) to a dependant variable using the Saha equation

$$\frac{N(ions)}{(\, N(total) - N(ions)\,)} = \frac{3.0x10^{\wedge}27 \cdot T(ions)^{\wedge}3/2 \cdot \exp\,(\, I.P. / T(ions)\,)}{N(ions)}$$

N = m^-3, T and I.P = eV, and I.P. = Ionization Potential

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OTHER EP CONCEPTS

- Numerous electric propulsion thrusters and subsystems have been modeled in past and current studies:
  - Rail Guns and Mass Drivers
  - Variable-Isp Plasma Thruster (MIT)
  - Electron-Cyclotron Resonance (ECR) Plasma Engine
  - Power Processor Units (PPUs)
  - Refrigerators for Active Thermal Control of Cryogenic Propellants

OTHER EP CONCEPTS

JPL THRUSTERS MODELED IN PREVIOUS STUDIES

- Rail Guns and Mass Drivers
  - Medium-Isp (1200 lbf-s/lbm) ideal for cis-lunar orbit raising
  - Can use extraterrestrial-produced propellants (e.g., O2)

Rail Gun Mass = 126.2 MT, η_{total} = Pjet / Pe = 0.45

Mass Driver Specific Mass (total) = 2-20 kg/kWe (=MT/MWe), η_{total} = 0.80

Refrigerator (for liquid-O2 propellant storage) [MT] = 0.022 · (Mp [MT])^2/3

Freezer (for solid-O2 pellet production) [MT] = 4.18 · η_{total} · Pe [MWe]

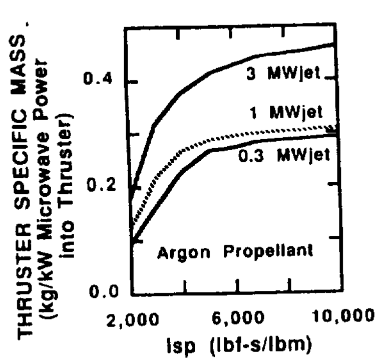
- ICRF-Heated Variable-Isp Plasma Thruster
  - NASA-supported on-going research program at MIT
  - Vary Isp (800-35,000 lbf-s/lbm) in flight to optimize trajectory
    - Potential 10-20 % savings in mass, and trip time
  - Preliminary estimates by MIT of specific mass and efficiency

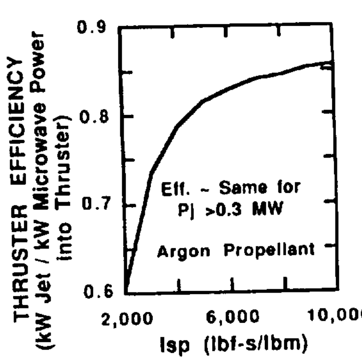
Specific Mass (total) = 4.04 kg/kWe, η_{total} = Pjet / Pe = 0.5-0.7

OTHER EP CONCEPTS

JPL THRUSTERS MODELED IN PREVIOUS STUDIES - CONT'D

- Electron-Cyclotron Resonance (ECR) Plasma Engine
  - Use on-board or remotely-transmitted microwave power
  - Electrodeless thruster (potential long life)
  - Can use extraterrestrial-produced propellants





Remote Beamed Microwave Power Source:
  1-km Diameter Inflatable Optics & Waveguides = 23.6 MT
On-Board Microwave Power Source:
  Magnetron Specific Mass = 0.2 kg/kW Microwave Power, η = Pmicrowave / Pe = 0.9

JPL POWER PROCESSOR UNITS (PPUs) MODELED IN PREVIOUS STUDIES

- Power Processing Unit (PPU) design depends on :
  - Power source output (high-voltage AC for NEP w/ dynamic conversion vs low-voltage DC for SEP or NEP w/ static conversion)
  - Thruster input (high-voltage DC for ion/PIT vs low-voltage DC for MPD, and power-per-thruster)
  - PPU system topology (switching, redundancy, devices)

Mass of SEP/NEP(Static)-Ion Thruster PPU (kg) = { 138.36 · (Pe [kWe] / 62)^0.71 · (K+M) + 1.02 · (2·(K+L) + 3·(K+M)) } · { 1 + 0.025 · (Max. Voltage - 3 kV) } and η = 0.955

Mass of NEP(Dynamic)-Ion Thruster PPU (kg) = 1.0867 · { 617 · (K · Pe [MWe] / 4.97)^0.75 + (16.86 + 10.57 + 14.29) · (K+M) · (Pe/0.71) + 3.5 · ((K+L) + (1+K) · (K+M)) } · { 1 + 0.025 · (Max. Voltage - 6 kV) } and η = 0.992

where Pe = power (electric) per thruster (but PPU limited by transformer to 5 MWe per PPU)
K = number of operating thrusters = number of operating PPUs
L = number spare thrusters
M = number of spare PPUs
and Thruster redundancy typically ≥25 %, PPU redundancy ≥12.5 %

- SEP-Ion PPU significantly heavier, less eff. than dynamic-NEP-ion PPU
  - DC-to-AC inverter required for SEP or static-NEP PPU
  - Economy-of-scale for common transformer in dynamic-NEP PPU
  - Lower eff. of SEP PPU contributes significantly to waste-heat rejection requirements (4.5 % vs 0.8 % of Pe as waste heat)

JPL REFRIGERATORS FOR ACTIVE THERMAL CONTROL OF CRYOGENIC PROPELLANTS MODELED IN PREVIOUS STUDIES

- Active thermal control may be needed for long missions
  - Trade Refrigerator mass against boiloff

PROPELLANT	PROPELLANT TEMP. (K)	TANK COOLING LOAD (Wcool)	REFRIGERATOR MASS (kg)
Xe	165	0.005 · Mp^2/3	0 + 13 · Wcool
Kr	121	0.008 · Mp^2/3	15 + 16 · Wcool
Ar	88	0.011 · Mp^2/3	31 + 18 · Wcool
O2	90	0.012 · Mp^2/3	
N2	77	0.016 · Mp^2/3	
H2	21	0.083 · Mp^2/3	46 + 21 · Wcool

Mp = PROPELLANT MASS (kg)

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STATUS & PLANS

- Status
  - C60 EB ion thruster modeling complete
  - Completion of C60 Radio Frequency Ion Thruster (RIT) modeling (mass breakdown) awaiting reply from Prof. Loeb, University of Giessen, Germany
  - PIT modeling complete
  - Li-MPD modeling underway
- Plans
  - Complete C60-RIT ion thruster modeling
  - Complete Li-MPD thruster modeling
  - Complete final report (including summary of high-power ion, MPD, ECR, Variable-Isp, and Rail-Gun/Mass-Driver thrusters, and MET thruster modeling under APC RTOP)