Evaluation of Radioisotope Electric Propulsion (REP) for Selected Interplanetary Science Missions

IEPC-2005-181
November 1, 2005

David Oh and Eugene Bonfiglio (JPL)
Mike Cupples and Jeremy Belcher (SAIC)
Kevin Witzberger (NASA Glenn)
Douglas Fiehler (QSS Group)
Gwen Artis (Gray Research)
Radioisotope Powered Electric Propulsion

- NASA In-space propulsion sponsored assessment of REP missions
  - New Frontiers Class Science missions (~$760 M FY04 cost cap)
  - Determine payload masses, mission times, costs for REP/REP hybrid missions
  - Compare REP, Solar Electric Propulsion (SEP) and Chemical Propulsion

<table>
<thead>
<tr>
<th>Mission:</th>
<th>Technology</th>
<th>REP (750W)</th>
<th>REP (1kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chemical</td>
<td>4W/kg</td>
<td>8W/kg</td>
</tr>
<tr>
<td>(Bipropellant ~325 lsp)</td>
<td>SEP Hall or Ion Thruster</td>
<td></td>
<td></td>
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<tr>
<td>Large Outer Planet Class</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Jupiter Polar Orbiter with Probes (JPOP)</td>
<td>0</td>
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<td>Comet Surface Sample Return (CSSR)</td>
<td>0</td>
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<td>Small Body Targets</td>
<td></td>
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4W/kg = 1st Gen RPS
8W/kg = 2nd Gen RPS
10W/kg = 3rd Gen RPS

- SOA spacecraft bus and instruments (unless otherwise indicated)
- REP and REP-Chemical spacecraft use Radioisotope Power System (RPS) technology
- All-Chemical propulsion options use 2nd Generation RPS for bus and instruments
Electric Propulsion Performance Models

- REP propulsion based on advanced gridded ion or Hall engine technology
  - Performance curves represent generic Hall / Ion thruster
  - Throughput at lower $I_{sp} >$ SOA Hall thrusters

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\eta = \frac{bb \ I_{sp}^2}{dd^2 + l_{sp}^2}
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Gridded Ion Regime

- $bb = 0.55479$
- $dd = 662.086$

Hall Regime

- $bb = 0.51493$
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- SEP propulsion based on Next Generation Electric Propulsion (NEXT) ion engine
Jupiter Polar Orbiter with Probes

• Mission objective: Deliver multiple deep atmospheric entry probes to Jupiter
  – 100-bars of atmospheric pressure
    (Galileo mission: 1 probe to 20-bars of atmospheric pressure)
  – 3 different latitudes between +/- 30 degrees

• Orbiter remains in near-polar orbit for at least 1 year
  – Very low perijove, 1.1 R_j, near equator
Jupiter Polar Orbiter with Probes Results

- To date, no feasible REP only solution found
- 1st Gen RPSs do not meet payload requirement
- 1 kW shows no benefit over 750 W

Fastest option is SOA chemical

SOA Chemical Delivers Required Mass with Shortest Trip Time
**JPOP Cost Summary**

Costs Estimated in FY04$M

- **All-Chemical mission is less expensive than REP/Chemical**
  - Multiple propulsion systems required for the REP/Chemical
  - Difference in # of RPSs (3 vs 8)

- **All-Chemical mission less costly than SEP/Chemical**
  - Multiple propulsion systems required for SEP/Chemical
  - 15 kW SEP power requirement

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**SOA Chemical Propulsion is Lowest Cost Option for Jupiter Polar Orbiter Mission**

* GDS/MOS, Science Team, and EPO
## Jupiter Polar Orbiter Summary

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(known issues with cost/flight time)  
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- **Star 48V would increase performance for high energy launches**
  - Essentially direct transfers - benefit all options
- **Optimal $I_{sp}$ for REP options: ~ 1,600 s**
- **If payload requirements increase, SOA chemical most likely to still offer better performance**
  - Gravity assist trajectories possible with an Earth flyby
  - Trip times on the order of 4 years
Comet Surface Sample Return Mission

**Mission Objective:**
- Return samples from Comet Tempel 1's surface to Earth
- Sample total mass ~1 kg

**Mission Description:**
- Earth Launch Date: 2008-2010
- Stay Time @ Target: 60 days

**Spacecraft Requirements**
- May be required to sample at multiple sites
- Sample collection system
  - Instruments to document geologic context
  - Sampling system
  - Sample return system

**Transportation Options**
- SOA chemical
- Solar electric
- Radioisotope electric

**Tempel 1 Orbit**
- Period = 5.51 years
- Semi-major axis = 3.119 AU
- Eccentricity = 0.52
- Inclination = 10.5 deg
- Radius perihelion = 1.5 AU
- Radius Aphelion - 4.7 AU

**Earth Orbit**
- Period = 1 year
- Semi-major axis = 1.0 AU
- Eccentricity = 0.02
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REP Trajectory Shown
Comet Surface Sample Return Results

**Fixed payload: 141 kg**

- **Launch Mass (kg):**
  - 2000
  - 1600
  - 1200
  - 800
  - 400

- **Chemical**

- **Launch Vehicle:**
  - Delta 4040
  - Atlas 401

- **Transfer Time:**
  - 8 years
  - 12 years

- **Trajectory:** Direct

**Propulsion Power:***
- **RPS Alpha (W/kg):** Infeasible
- **14.3 kW**

**Launch Vehicle:**
- **N/A**
- **Delta 4040**
- **Atlas 401**

**Transfer Time:**
- 8 years
- 12 years

**Trajectory:** Direct

**SEP has Faster Roundtrip and Smaller Launch Vehicle than REP**

*Total mass of stack larger than any available ELV can inject to the required C3*
CSSR Cost Analysis
Costs Estimated in FY04$M

$760M NF Cost Cap

FY04 $, Million

600

500

400

300

200

100

0

Power:

GaAs Array

2nd Gen RPS

Total Operations
Program Mgt/Sys Intg
Science Instruments
Total Spacecraft
Phase A/B/C/D other*
Total RPS
Total LV
Reserves

* GDS/MOS, Science Team, and EPO

SEP costs less than REP because Solar Array power is significantly less expensive than an RPS

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**Observation**: analyses performed for one comet only

- Further work needed to characterize REP over wider range of comets
Trojan Asteroids

- Trojan Asteroids sit near Jupiter’s L4 and L5 Lagrange Points
  - Primitive body targets of interest for solar system exploration
- **Mission Objective:** place scientific instrument payload into orbit around Jovian Trojan Asteroid
- **Reference Payload:** Dawn Instrument suite (42 kg / 100 W peak)
Some Chemical-JGA Options are Feasible

- Launch Vehicle: Atlas 551
- Launch C₃: 75-90 km²/s²
- ΔV 1-7 km/s deep space and orbital insertion
- On-board Iₚ: 325 s
- Power Source: 2nd Gen RPS
- Trip time: 10-15 years

Fixed payload: 42 kg

Limited number of targets can be reached using Chemical Propulsion with Jupiter Gravity Assist

More aggressive design (i.e. advanced chemical) would increase range of feasible targets
2nd Generation REP (8 W/kg) vs. Chemical JGA

- 2nd Generation REP (8 W/kg) options overlaid on Chemical JGA results
  - Fixed payload: 42 kg
- Launch Vehicle: Atlas 541/551
- Launch \( C_3 \): 78-95 km\(^2\)/s\(^2\)
- Specific Impulse: 1450-1700 s
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- Flight Time: 5 to 10 years

REP with 2nd Generation RPS (8W/kg) enables a wide range of targets compared to chemical propulsion
1st Generation REP (4 W/kg) vs. Chemical JGA

- Launch Vehicle: Atlas 551
- Launch C₃: 71.5 km²/s²
- Specific Impulse: 1780 s
- Power Source: 1st Gen RPS
- Flight time for feasible case is 6 years

* Assumes custom spacecraft structure/C&DH systems and lightweight xenon tank

REP with 1st Generation RPS (4W/kg) is marginal for this application
Customized lightweight spacecraft can reach a limited range of targets
Trojan Asteroid Orbiter Cost Summary

Costs Estimated in FY04$M

NOTE: costing based on Dawn instrument suite

Chemical missions are lowest cost, but capture only small percentage of asteroids

REP missions cost more, capture much larger percentage of asteroids

SEP missions have highest cost: large power requirements to match REP missions
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**Feasible** = can deliver Dawn-like payload within New Frontiers cost-cap

Red = infeasible  
Yellow = feasible to limited range of targets  
Blue = possibly feasible  
(known issues with spacecraft configuration)  
Green = probably feasible

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**Enabling technologies for REP Trojan asteroid mission**

Advanced RPS ($\alpha > 6$ W/kg?)

Advanced Hall Thruster (throughput $> 300$ kg)
Overall Summary

- **Three mission classes analyzed**
  - Small Body Targets (Trojan Asteroids)
  - Medium Outer Planet Class (Jupiter Polar Orbiter with Probes)
  - Main Belt Asteroids & Comets (Comet Surface Sample Return)

- **Mission opportunities to small body targets (Trojan asteroids) show**
  - Marginal benefit with use of 1st generation RPS
  - Significant benefit with 2nd generation RPS and enhanced throughput Hall Thruster
  - Effectively enabled by Advanced RPS ($\alpha > 6 \text{ W/kg}$?) and Advanced Hall

- **SOA chemical offered best performance for medium outer planet class missions (JPOP). No viable REP-only option found.**

- **SEP was better performer for Comet Surface Sample Return.**
  - No solution found using SOA chemical
  - REP requires larger launch vehicle and longer transfer time.

**REP appears to be best applied to small body missions beyond main asteroid belt**
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- **Mission objective:** Deliver multiple deep atmospheric entry probes to Jupiter
  - 100-bars of atmospheric pressure
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  - 3 different latitudes between +/- 30 degrees
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Fastest option is SOA chemical

Fixed Payload 272 kg
55 kg science instruments
72.3 kg x 3 probes

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<tr>
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<th>SOA chemical</th>
<th>SEP+chem</th>
<th>REP+chem 750 W 1st Gen</th>
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<tr>
<td>Trip time (yrs)</td>
<td>2.2</td>
<td>3.1</td>
<td>3.8</td>
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<td>$C_3$ (km²/s²)</td>
<td>85.6</td>
<td>38.2</td>
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  - Difference in # of RPSs (3 vs 8)

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  - Multiple propulsion systems required for SEP/Chemical
  - 15 kW SEP power requirement

SOA Chemical Propulsion is Lowest Cost Option for Jupiter Polar Orbiter Mission

* GDS/MOS, Science Team, and EPO
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• **Mission Objective:**
  - Return samples from Comet Tempel 1’s surface to Earth
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• **Mission Description:**
  - Earth Launch Date: 2008-2010
  - Stay Time @ Target: 60 days

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- Total Operations
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- Science Instruments
- Total Spacecraft
- Phase A/B/C/D other
- Total RPS
- Total LV
- Reserves

FY04 $, Million

Power:

- GaAs Array
- 2nd Gen RPS

* GDS/MOS, Science Team, and EPO

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Note: costing based on Dawn instrument suite

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- Advanced Hall Thruster (throughput > 300 kg)
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