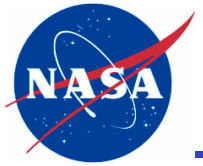

Evaluation of Radioisotope Powered Electric Propulsion for a Trojan Asteroid Orbiter

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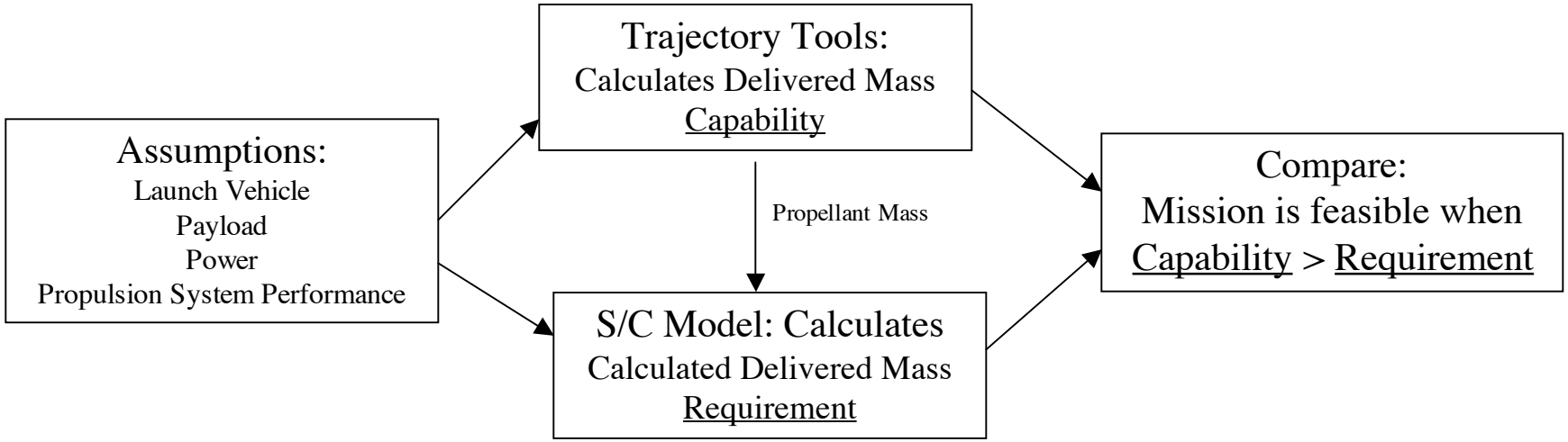
JPL

Overview

- **Objectives and Approach**
- **Chemical Propulsion Results**
- **SEP Results**
- **REP Propulsion Results**
  - 2nd Generation RPS (8 W/kg)
  - 1st Generation RPS (4 W/kg)
- **Conclusions**

Analysis Approach



- **Calculate capabilities using trajectory optimization tools**
- **Calculate requirements using spacecraft models**
- **Compare to find viable missions**

Chemical Spacecraft Uses Dawn Instrument Payload (Nominal Atlas 551 JGA case)

Nominal Transit Chem Propellant Mass	620	kg
RPS Alpha	8	W/kg
Power Degradation	1.15	% of BOL/year
Degradation Period	15	years
Max Power end of Degradation Period	330	W

- Payload = Instrument Suite from Dawn
- RPS oversized: 1.15% power degradation/year
- Chemical propulsion: 325 s Isp, 450 N thruster

General Model	Mass, kg.	Mass Comments		Power (W)	Power Comments
Instruments	**42**	Same as Dawn CBE at Neutral Mass Review		**60**	~60% of Dawn Peak
ACS	**40**	Dawn:4 wheel+star tracker system		**30**	Dawn
C&DH	**25**	2 ACE's, 2 CEU's		**70**	Dawn
Comm	**30**	Dawn: 2 TWTA's		**12**	Dawn
Harness	**29**	Team X Harness model		**4**	Estimate: 1.5%
Mech/Structures	**127**	Team X structure model		**0**	NOTE: Power Budget is On Station
Thermal	**23**	Team X: thermal model		**38**	Team X: thermal model
Chemical Propulsion	**94**	Scaled from Team X 755 kg.		**5**	assumption
		Dual mode bipropellant, 12 MIT + 4 22 N + 1 main			
EPS	**71**			**30**	Team X: power model (250W bus)
Electronics	17	Team X: power model (250 W bus)			
Battery	6	Team X: minimum battery for bus stability			
RPS	48	350 W at 8W/kg.			
LV Adapter	**17**	1.5% of wet mass, no contingency			
Total Dry Mass, CBE	**497**		**Total Power, CBE**	**249**	
Contingency	149	30% contingency	**Bus Power, CBE**	249	
Total Dry Mass w/Contingency	**646**		**Bus Power w/Contingency**	324	30% contingency
Propellant, Chemical	**688**		**EP Power with Contingency**	0	5% contingency
Chemical Propellant, Nominal	620				
Chemical Propellant, ACS	15	half of Dawn			
Chemical Propellant, TCM	3	approx. 30 m/s			
Chemical Propellant, deltaV-Margin	15	approx 2% dV			
Chemical Propellant, Orbital Ops	15	approx 50 m/s			
Chemical Propellant, Residuals	20	Team X: 3%			
Xenon Propellant	0		**Total Power w/Contingency**	**324**	
Total Wet Mass w/Contingency	**1334**				
Total Delivered Mass to Asteroid	**714**				

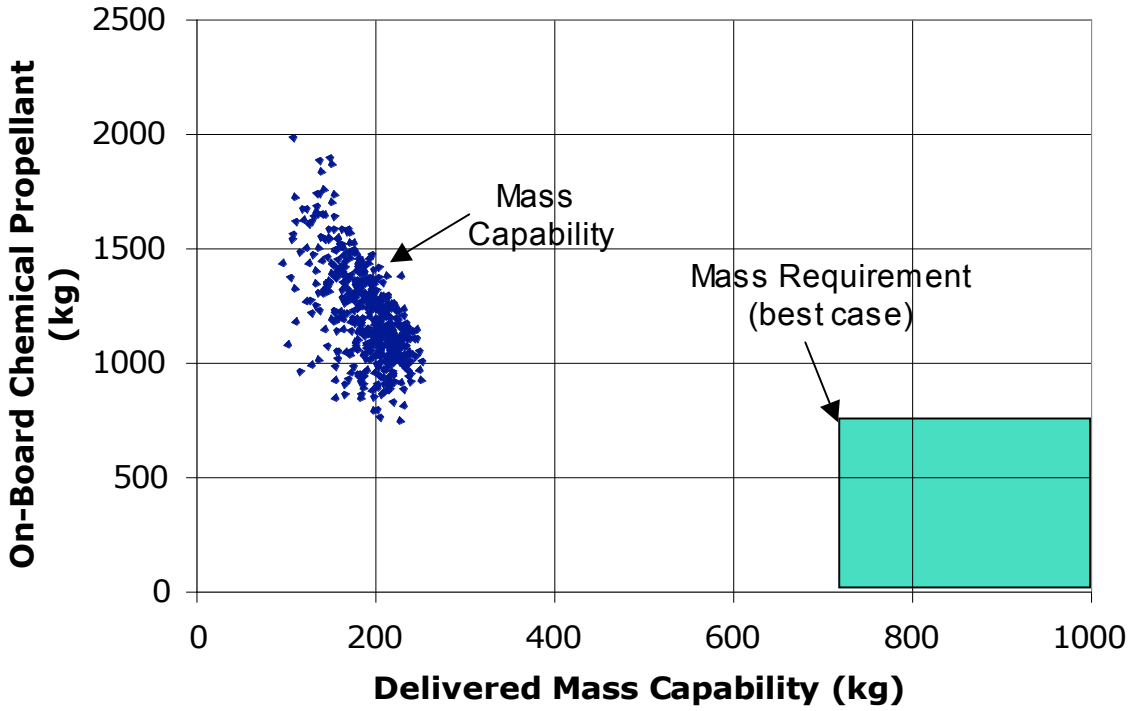
= From Dawn Mass Budget

= Team X Design Model

= Model Specific to this Study

All Chemical Direct Options are Infeasible

- Launch Vehicle: Atlas 551
- Launch C_3: 55-90 km^2/s^2
- ΔV: 4-10 km/s deep space and orbital insertion
- On-board I_{sp}: 325 s
- Flight Time: 3 to 5 years

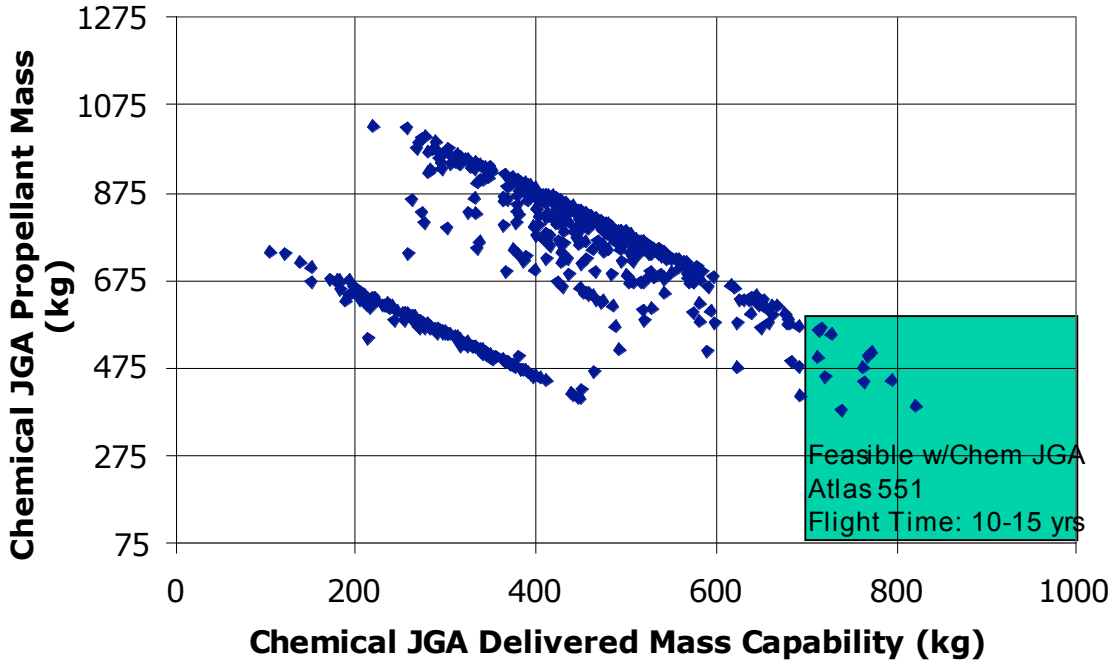


- Chemical-Direct trajectories run to > 500 Trojan-like asteroids

Mass capability always << Mass Requirement: clearly infeasible

Some Chemical-JGA Options are Feasible

- Launch Vehicle: Atlas 551
- Launch C_3: 75-90 km^2/s^2
- ΔV 1-7 km/s deep space and orbital insertion
- On-board I_{sp}: 325 s
- Power Source: 2nd Gen RPS



Limited number of targets can be reached using Chemical Propulsion with JGA

More aggressive design (i.e. advanced chemical) would increase range of feasible targets

SEP Spacecraft Model
(26 kW Atlas 541/551 case)

- Ultraflex Array, 120 W/kg
- NEXT Electric Propulsion subsystem

Primary Transit Xenon Propellant 1100 kg

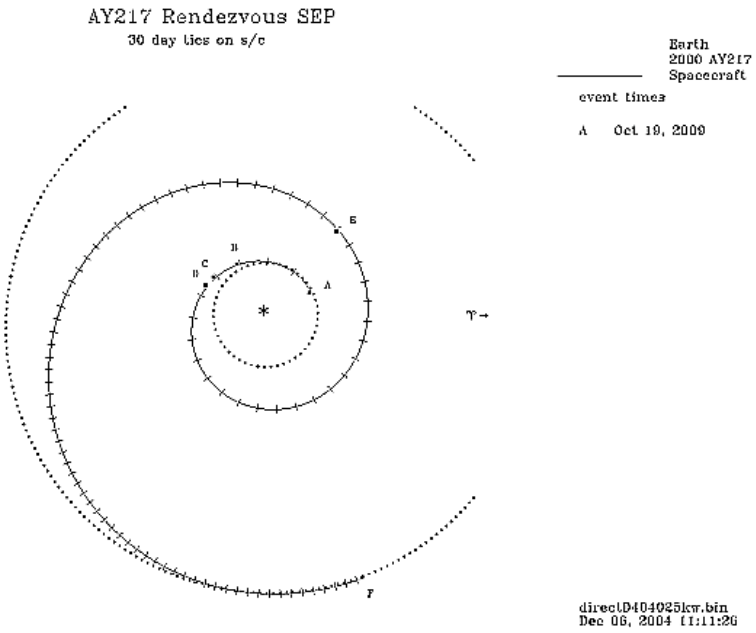
General Model	Mass, kg.	Mass Comments	Power (W)	Power Comments
Instruments	**42**	Same as Dawn CBE at Neutral Mass Review	**30**	Dawn
ACS	**40**	Dawn:4 wheel+star tracker system	**30**	Dawn
C&DH	**25**	2 ACE's, 2 CEU's	**70**	Dawn
Comm	**30**	Dawn: 2 TWTA's	**12**	Dawn
RCS / Prop	**14**	Dawn: 12 thruster hydrazine	**2**	Dawn
Mech/Structures	**217**	Scaled from REP Team X Model	**0**	NOTE: power budget for EP ON
Thermal	**100**	Titan Orbiter SEP Module	**150**	Titan Orbiter SEP Module
Electric Propulsion	**275**		**24750**	assumption
Xenon Tank	50	Scaled using Dawn Tank Mass Fraction (4.5%)		
EP Subsystem	225	Discovery Analysis Model: 5 thruster NEXT system		
EPS	**291**		**15**	Team X: power model (250W bus)
Electronics	36	Dawn EPS		
Solar Array Drive	8	Titan Orbiter SEP Module		
Battery	27	Dawn Battery		
Solar Array	220	Ultraflex Array (120 W/kg)		
Harness	**45**	Titan Orbiter SEP Module Harness	**15**	Guess: 1.5%
LV Adapter	**34**	1.5% of wet mass, no contingency		
Total Dry Mass, CBE	**1113**		**Total Power, CBE** **25074**	
Contingency	334	30% contingency	**Bus Power, CBE** 324	
Total Dry Mass w/Contingency	**1447**		**Bus Power w/Contingency** 421	30% contingency
Propellant, Chemical	**33**		**EP Power with Contingency** 25988	5% contingency
Chemical Propellant, Nominal	30	From Dawn		
Chemical Propellant Margin	3	Dawn margin 10%		
Propellant, Xenon	**1182**			
Xenon Propellant, Primary Transit	1100			
Xenon Propellant, Contingency/Residuals	77	Dawn equivalent 7%	**Total Power w/Contingency**	**26409**
Xenon Propellant, Orbital Operations	5	generous guess		
Total Wet Mass w/Contingency	**2662**			
Total Delivered Mass to Asteroid	**1562**			

= From Dawn Mass Budget
= Team X Design Model
= Model Specific to this Study

SEP Model is less detailed than Chemical/REP Spacecraft Models
SEP Architecture can accommodate mass uncertainty by using slightly larger launch vehicle

All-SEP Solution Uses 26 kW Solar Array

- **26 kW (1 AU) Solar Array produces about 900 W of power at Jupiter orbit**
  - Power roughly equivalent to REP
  - Enables SEP orbit insertion at target
- **Launch Vehicle: Delta 4040**
- **Flight Time: 7.5 years**
- **Launch C3: 7.5 km^2/s^2**
- **Throughput: 1100 kg Xenon**
- **Thrusters: Five NEXT ion engines**
  - Up to 3 thrusters operate simultaneously
- **Power Source: Ultraflex solar arrays (120 W/kg)**



All-SEP Architecture Requires Very High power and Xenon Throughput

26 kW array is 2.5 times larger than Dawn
Configuration must accommodate 5 x 40 cm ion thrusters

SEP Architecture is not extensible to Centaur Objects

REP Spacecraft Model
(nominal 750 W Atlas 541/551 case)

RPS Alpha	8	W/kg
Power Degradation	1.15	% of BOL power/year
Degradation Period	6.9	years
Max Power end of Degradation Period	1068	W

- Payload = Instrument Suite from Dawn
- RPS oversized: 1.15% power degradation/yr

	Mass, kg.	Sources	Power (W)	Power Comments
Instruments	**42**	Dawn CBE, Neutral Mass Review	**30**	Dawn
ACS	**40**	Dawn:4 wheel+star tracker system	**30**	Dawn
C&DH	**25**	2 ACE's, 2 CEU's	**70**	Dawn
Comm	**30**	Dawn: 2 TWTA's	**12**	Dawn
RCS / Prop	**14**	Dawn: 12 thruster hydrazine	**2**	Dawn
Harness	**28**	Team X: structure model	**15**	Estimate: 1.5%
Mech/Structures	**111**	Team X structure model (no LV adapter)	**0**	
Thermal	**25**	Team X: thermal model	**42**	Team X thermal model
Electric Propulsion	**55**		**750**	REP Assumption
Xenon Tank	21	Scaled using Dawn Tank Mass Fraction (4.5%)		
EP Subsystem	34	REP EP Mass Model 1.1 w/ADVANCED HALL		
EPS	**166**		**15**	Team X: power model
Electronics	17	Team X: power model (250 W bus)		
Battery	6	Team X: minimum battery for bus stability		
RPS	144	Calculated		
LV Adapter	**16**	1.5% of wet mass, no contingency		
Total Dry Mass, CBE	**552**	**Total Power, CBE**	**966**	
Contingency	166	30% contingency **Bus Power, CBE**	216	
Total Dry Mass w/Contingency	**718**	**Bus Power w/Contingency**	281	30% contingency
Propellant, Chemical	**33**	**EP Power with Contingency**	788	5% contingency
Chemical Propellant, Nominal	30	From Dawn		
Chemical Propellant Margin	3	Dawn margin 10%		
Propellant, Xenon	**509**			
Xenon Propellant, Primary Transit	471			
Xenon Propellant, Contingency/Residuals	33	Dawn equivalent 7%	**Total Power**	**1068**
Xenon Propellant, Orbital Operations	5	Generous Estimate		
Total Wet Mass w/Contingency	**1260**			
Total Delivered Mass to Asteroid	**789**			

= From Dawn Mass Budget
= Team X Design Model
= Model Specific to this Study

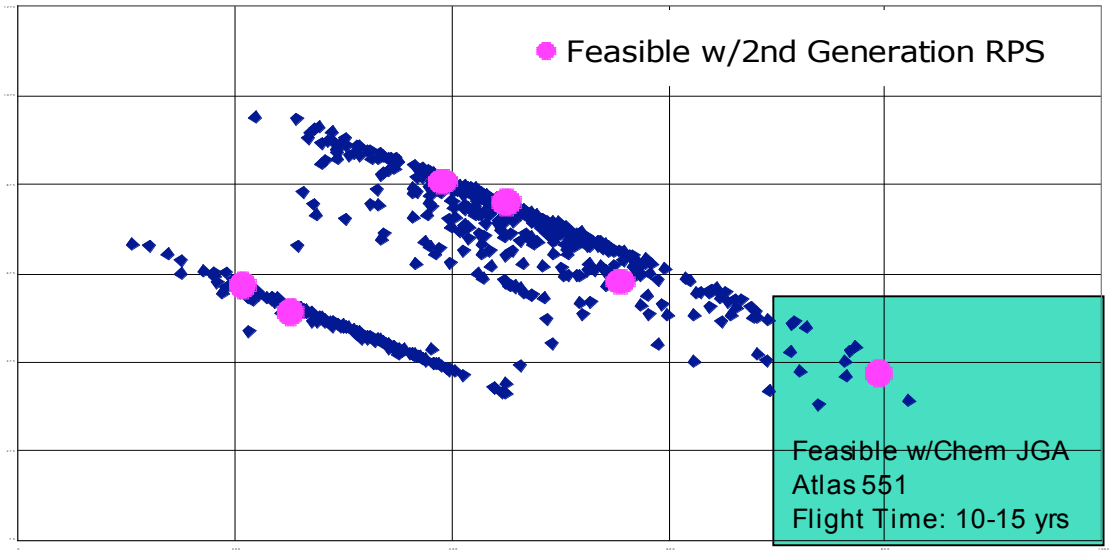
NOTE: Electric Propulsion assumes advanced Hall thruster

3 advanced Hall thrusters (2 primary + 1 redundant) = 7 SOA Hall thrusters - infeasible option!

2nd Generation REP vs. Chemical JGA

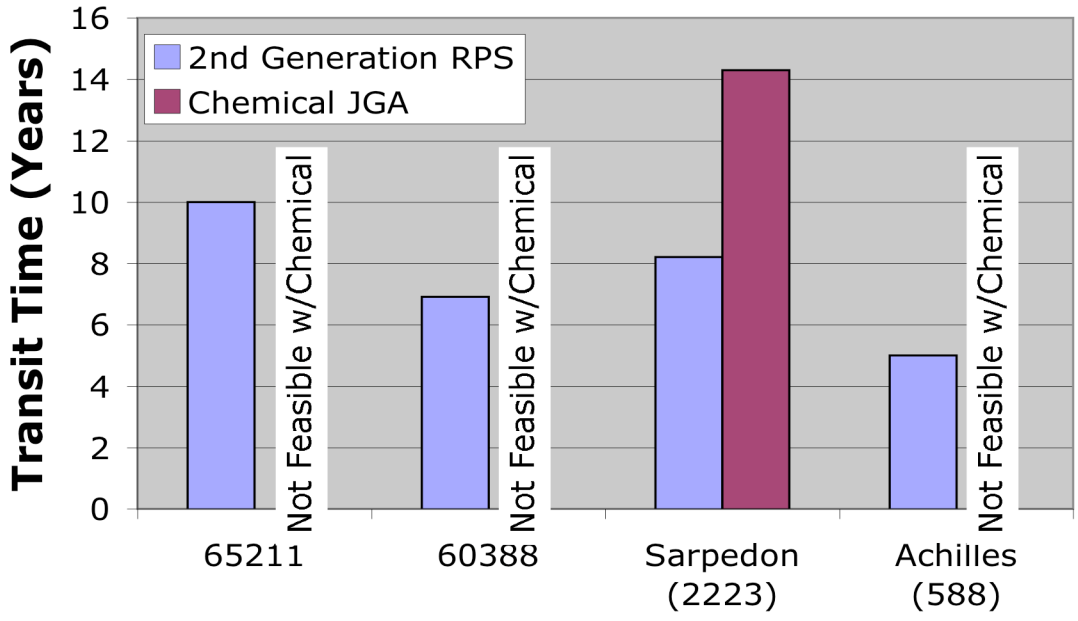
- **2nd Generation REP options are overlaid on Chemical JGA results**

- **Launch Vehicle: Atlas 541/551**
- **Launch C_3: 78-95 km^2/s^2**
- **Specific Impulse: 1450-1700 s**
- **Power Source: 2nd Gen RPS**



REP with 2nd Generation RPS enables a wide range of targets compared to chemical propulsion

2nd Generation REP vs. Chemical JGA

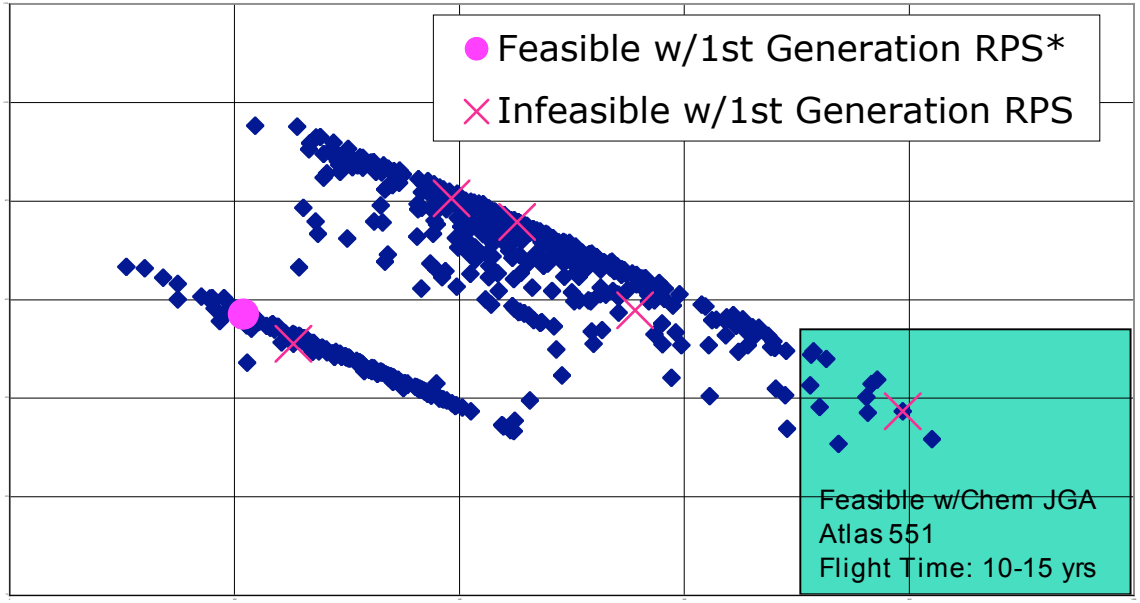


	65211	60388	Sarpedon (2223)	Achilles (588)
Power:	750 W	750 W	750 W	1000 W
Isp:	1700 s	1535 s	1660 s	1440 s
Propellant:	485 kg	580 kg	600 kg	665 kg
Trip Time:	10 yr	6.9 yr	8.2 yr	5.0 yr

REP with 2nd Generation RPS can substantially lower trip time compared to Chemical Propulsion

1st Generation REP vs. Chemical JGA

- **Launch Vehicle: Atlas 551**
- **Launch C_3: 71.5 km^2/s^2**
- **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 is marginal for this application

Customized lightweight spacecraft can reach a limited range of targets

REP Mission Characteristics

- **Identical 42 kg/100 W payload used in REP/chemical comparison**
  - Apples to apples - but does not fully utilize REP capability
- **REP spacecraft provides much more power at destination than chemical spacecraft**
  - REP: 1100 W total power vs. Chem: 350 W total power
  - Allows higher instrument duty cycle
  - Potentially allows higher power instruments (if mass available for high power instrument)
  - Potentially allows higher data rates (if mass available for high power amp)
- **Optimum REP I_{sp}: ~1500 s - ~1700 s**
  - Range typical for Hall Thrusters
- **REP propellant throughput requirements are very high**
  - Total throughput typically > 500 kg.
  - Thruster throughput assumption: 300 kg
  - Current SOA Hall thrusters are not feasible at this throughput
- **Better performance may be achievable with a Star 48 upper stage**

Comparison of Architectures

Architecture	Trojan Asteroid Mission Feasibility
Chemical Direct	Infeasible
Chemical with JGA	Feasible to limited number of targets
SEP-Chemical	No feasible solutions found - Further work needed
REP, Generation 1	Marginally feasible to limited number of targets
All-SEP	Feasible to unknown number of targets with very large solar array
REP, Generation 2	Feasible to most targets

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

- **Feasible = can deliver Dawn-like payload within New Frontiers cost-cap**
  - Technology development risk is not considered in this chart
  - "Science floor" payload may not provide sufficient science for NF

Conclusions and Future Work

- **REP with 2nd Generation RPS enables a wide range of targets compared to chemical propulsion**
  - REP substantially lowers trip time in some cases
- **REP with 1st Generation RPS is marginal for this application**
  - Customized lightweight spacecraft can reach a limited range of targets
- **All SEP architecture requires very high power and xenon throughput**
  - 26 kW array is 2.5 times larger than Dawn
  - Architecture not extensible to Centaur Objects
- **Further work is needed on SEP-Chemical architecture**
  - There is probably a viable solution between 15 kW and 25 kW
- **Use of Star 48 upper stage may increase performance on all options**

- **Enabling technologies for REP Trojan asteroid mission**
  - Advanced RPS (α > 6 W/kg?)
  - Advanced Hall Thruster (throughput > 300 kg)