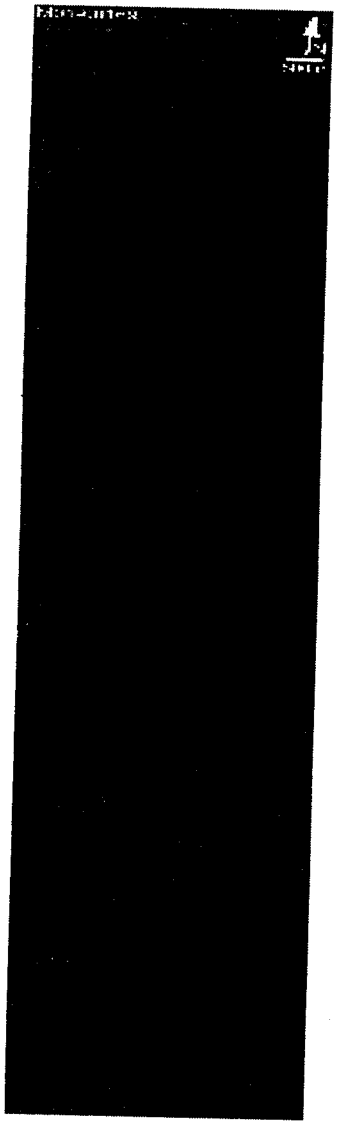
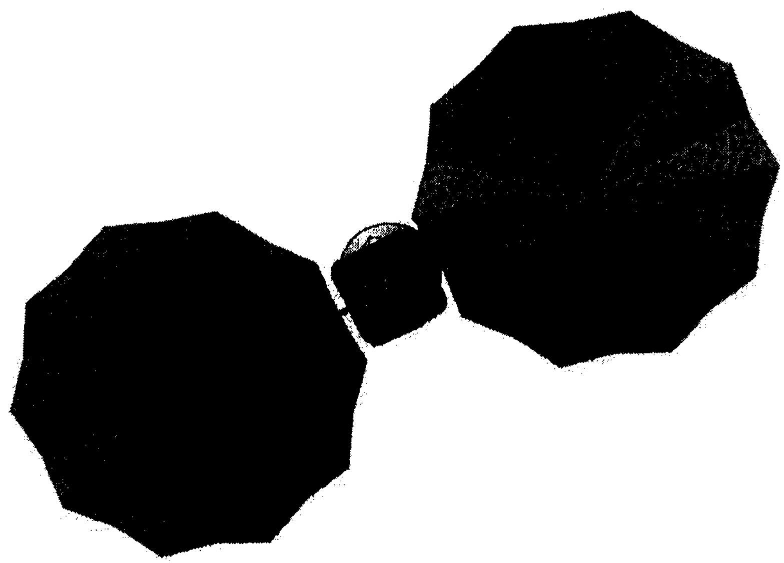


In-Space Propulsion Options for Mars Sample Return Missions

Benjamin Donahue – Boeing

Michael Cupples, Shaun Green – SAIC

Victoria Coverstone, Byoungsam Woo – University of Illinois Unbana-Champlaign



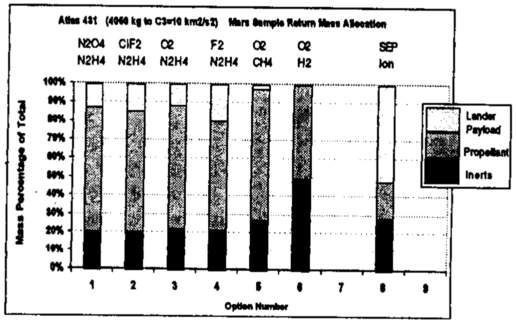
Briefing Agenda

- Review of Analyses Goal
- Analyses Introduction: Summary, approach & global assumptions
- Systems Analysis: Propulsion technologies investigated
- Analysis Results: Mission and performance analyses
- Cost Analysis
- Comparison of Propulsion Technologies
- Conclusions

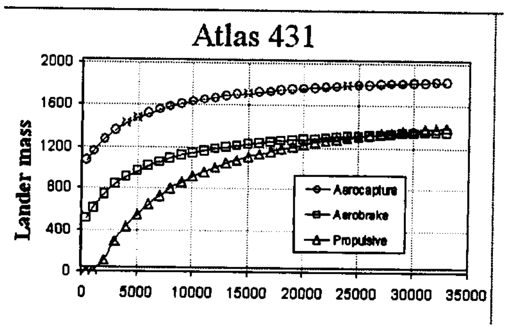
Mars In-space Propulsion: Summary of Analysis Approach

MSR Payload, Propellant & Inert Mass Allocations

Number	1	2	3	4	5	6	7	8	9
Inert Stg Mass	803	798	864	863	1052	2448		657	
Propellant Mass	2,593	2,541	2,589	2,260	2,751	2,467		612	
Payload Mass Inbound	150	150	150	150	150	150		75	
Payload Mass Outbound	503	561	447	777	97	0		1609	
Total Launch Vehicle Capability	4050	4050	4050	4050	4050	4050		4050	



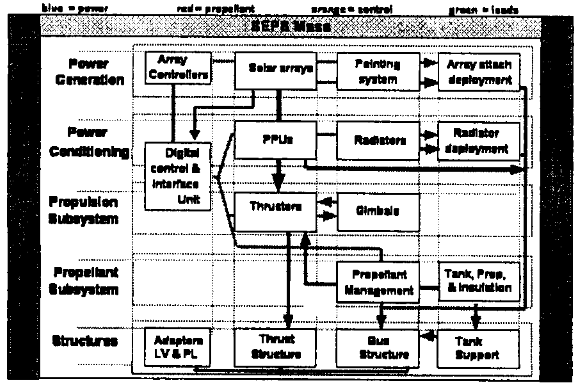
MSR Lander Mass vs. Mars Orbit Apoapsis



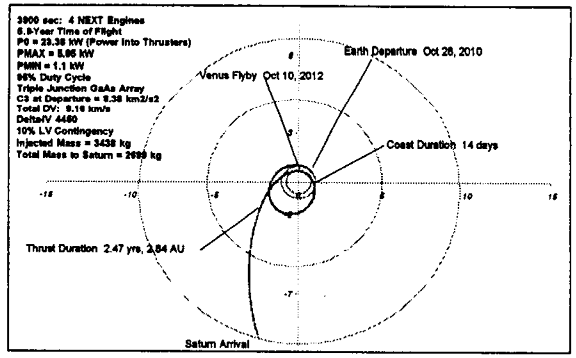
- Reference missions selected
  - Figures of merit defined for comparison
  - Culling process completed, yielding mission and system suite
- Overall analysis approach defined
  - Technology specific system models
  - Technology specific trajectory models
- Analyses independently performed for different technologies
- Overall analysis approach, reference missions and specific technology analyses will be outlined in the following pages

Overall Analyses Approach

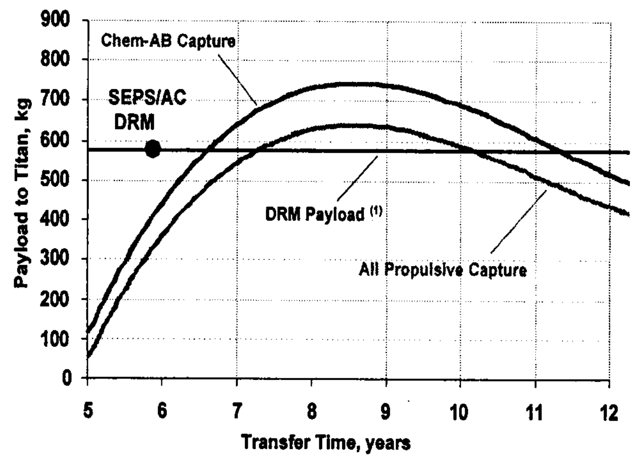
- **Systems Analyses**
  - System models developed for each technology investigated
    - Technology specific
    - Flexible – rapidly modified & EXCEL format
    - Experience – based models
    - Physics –based models



- **Mission Analyses**
  - Trajectory generation and optimization for Mars mission profiles of interest
    - SEPTOP for Solar Electric
    - Mission contours for high thrust cases



- **Assessment based on figures of merit**
  - Reference missions created to facilitate technology comparisons
  - Figures of merit for comparison include:
    - Trip Time for reference payload delivery
    - Cost for system (all technologies assumed to be at TRL 6)
  - Risk not currently investigated however it is reflected to some level in the cost analysis



Global Technology Assumptions

- **In-Space Technology suite includes**
  - Chemical propulsion
    - With Aerobraking or Aerocapture
  - Electric propulsion
- **Launch vehicles assumed included Delta & Atlas**

Analyses Outline

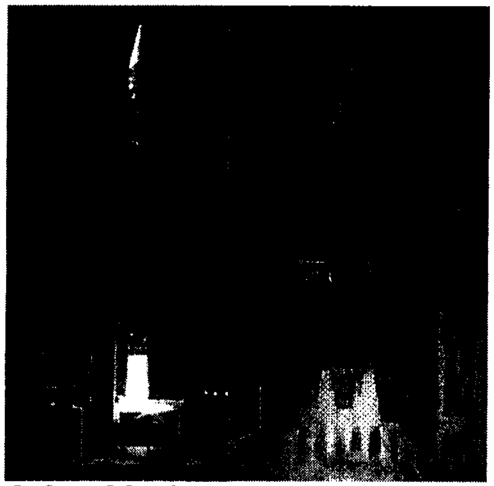
- Propulsion Technologies Definition and Assumptions
- Chemical Propulsion Performance
- SEPS Performance
- Propulsion Comparisons
- Conclusions

Systems

Launch Vehicles Assumed

1st Launch Aug 21, 2002

1st Launch Nov 20, 2002



Atlas-V 400 Delta-IV 4240

Launch Vehicle	Launch Mass to C3 = 0 (kg) (LV Margin 0%)	Launch Mass to C3 = 10 (kg) (LV Margin 2%)	Estimated cost[2] (millions)
Atlas-V 431	5536	4527	~ 75 - 90
Atlas-V 421	4880	3993	
Delta-IV 4450[1]	4583	3612	~ 70 - 95
Delta-IV 4240	4075	3212	
Delta-II 2925	1250	980	~ 50 - 55
Zenit	2900	TBD	~ 75

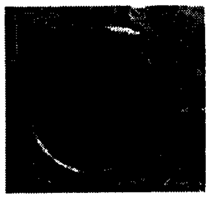
[redacted]

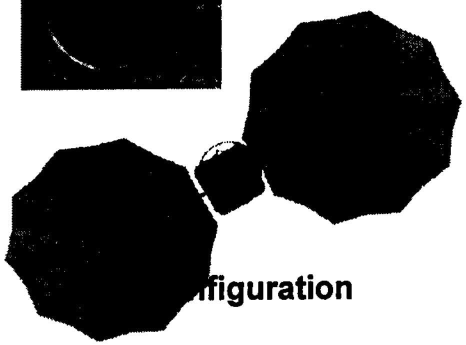
(1) Launch vehicle assumed in NASA aerocapture DRM case
(2) AIAA / Isakowitz, 3rd Edition, 1999

General In-Space Technologies

Solar Electric Propulsion

NEXT Thruster

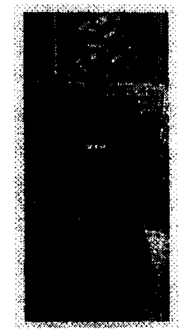




figuration

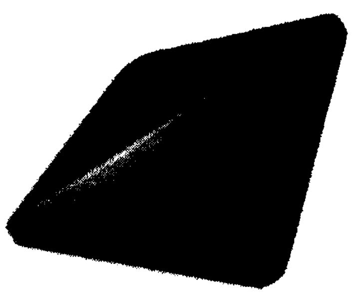
Chemical Propulsion

TRW ADMLAE
Pressure Fed NTO/N_2H_4



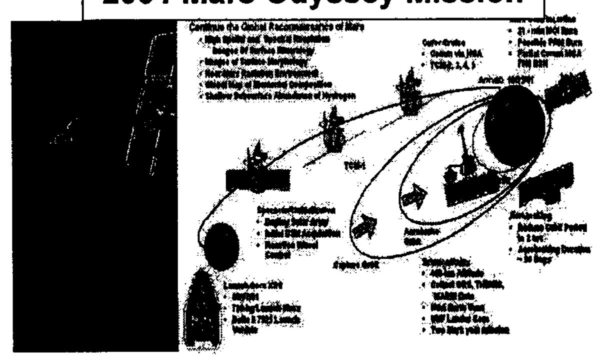
Aerojet R-4D-15DM
Pressure Fed NTO/N_2H_4

Aerocapture Propulsion



Aerobraking Propulsion

2001 Mars Odyssey Mission

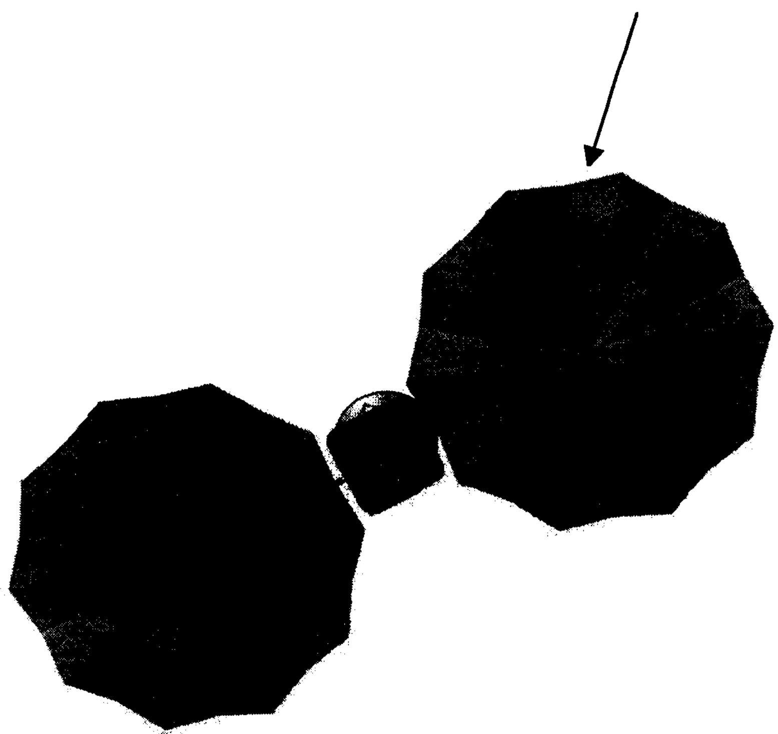


SEP System Assumptions

SEPS Power

Array power (end-of-life): 22 - 44 kWe @ 1AU

Technology and configuration: Two Ultraflex Arrays



SEPS Propulsion

Thruster: NEXT, ~ 4000 sec Isp
- High Isp throttling
- High Thrust throttling
- 6 & 7 kWe
- 40 cm grids
- 2, 3, & 4 active thrusters

Power Processing Unit: NGI, 6.25 kWe

Thruster: GRC Hall – 3350 sec Isp
- High Isp throttling
- High Thrust throttling
- 10 kWe
- 2 active thrusters

Power Processing Unit: Constant 94% efficiency

Propellant management system: NGI

Propellant: Xenon

SEPS Propulsion Contingencies, Redundancy, & Other Assumptions

Baseline Contingencies:

- LV: 2% of LV nominal capacity baseline (10% also investigated)
- Propellant: 10% of total deterministic Xe propellant
- Dry mass: 30% of dry mass
- Power: 10% of baseline array added

Redundancy:

- One extra ion system (thruster, PPU, Propellant Distribution String, & DCIU)

Others:

- Propulsion system duty cycle = 95% baseline
- ACS is provided by Ion Propulsion System during low thrust burn
- ACS is provided by RCS for periods when Ion Propulsion System is not active
- 2% of array area added per year of propulsion power-on time for end-of-life requirements

[redacted]

Global Chemical Propulsion Systems Assumptions

Propellant Combinations Investigated

- NTO/N_2H_4 (I_{sp} = 330s)
- LOX/N_2H_4 (I_{sp} = 343s)
- LOX/CH_4 (I_{sp} = 344s)
- F_2/N_2H_4 (I_{sp} = 380s)
- LOX/H_2 (I_{sp} = 420s)

TRW ADMLAE
Pressure Fed NTO/N_2H_4

General Engine Assumptions

- 3 main engines
- Thrust sized for vehicle initial capture T/W = 0.5
- Thrust vector control system
- Tankage: pressure feed ~250 psia, ullage = 3%
- Chamber pressure: 100 psi
- Pressurization: high pressure GHe bottle, regulated
- 16 RCS thrusters, Hydrazine monopropellant 220 sec Isp

Chemical Stage Contingencies & Other Assumptions

Contingencies:

- Propellant: 3.0% of total deterministic propellant
- Dry Mass: 30% of total mass (non payload) delivered
- Power: Provided batteries
- Structure: Size based on historical data for actual spacecraft

Others:

- Propellant tank pressures are ~ 250 psia
- 20 m/s RCS delta-V at Mars includes maintaining final parking orbit
- 10 m/s RCS delta-V for 3 other events (E & M departure, E arrival)
- 30 m/s delta-V for course correction and aimpoint maneuvers (each leg)
- 40 m/s delta-V for Earth divert
- 2.0% gravity loss penalty for propulsive burns

[redacted]

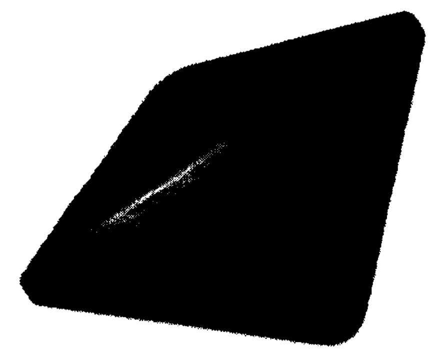
Mars Aerocapture Assumptions

- Initial aerocapture brake mass set to 20% of total captured mass including aeroshell (10, 15, 25, and 30% also evaluated)

- Propulsive ΔV applied post aerocapture: 30 m/s

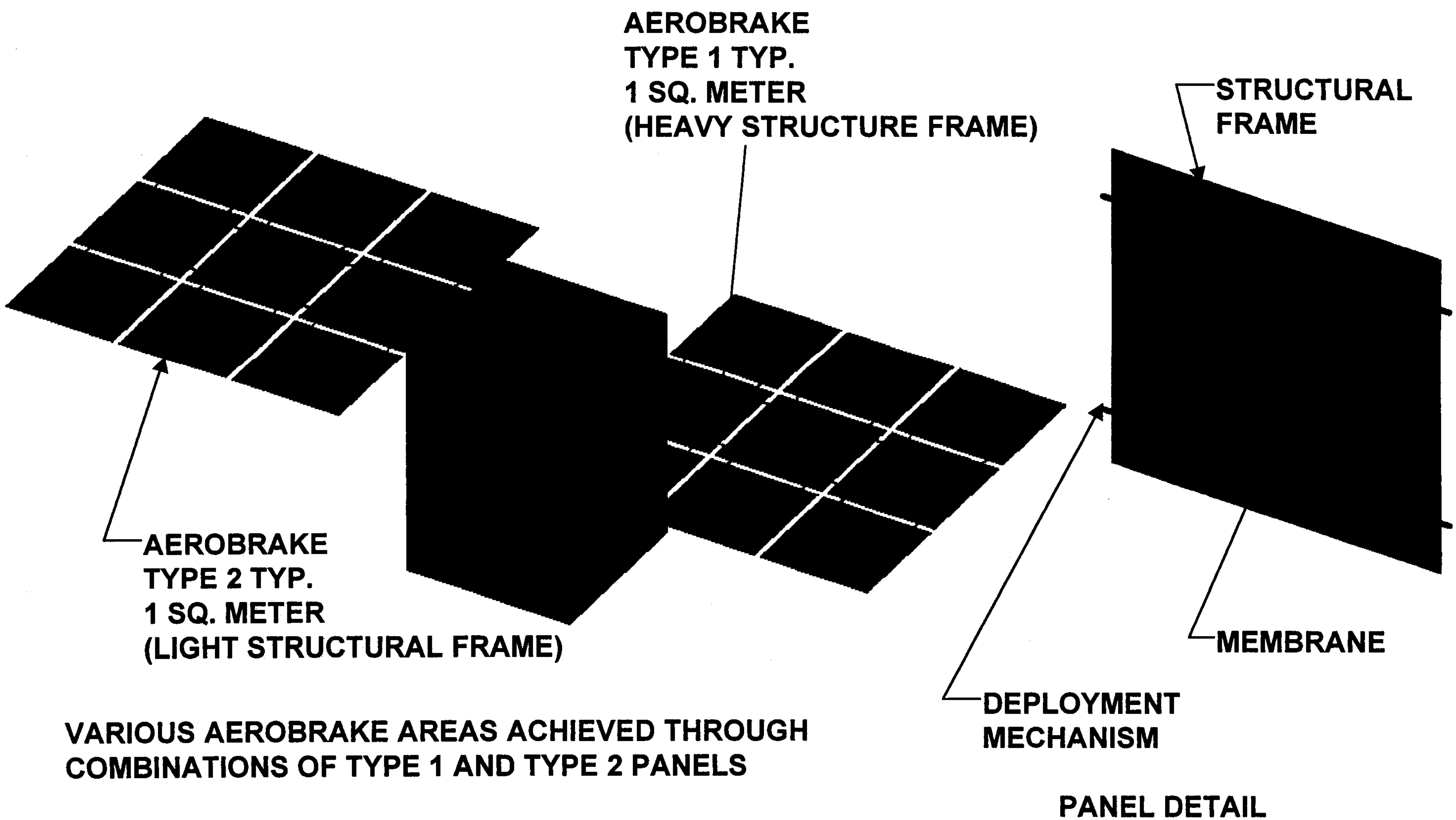
- Aeroshell jettisoned from orbiter prior to Mars departure

- Two capture modes evaluated: Lander Direct Entry and Lander captured with Orbiter



Preliminary Data

Aerobrake System Concept



VARIOUS AEROBRAKE AREAS ACHIEVED THROUGH COMBINATIONS OF TYPE 1 AND TYPE 2 PANELS

- STOWED AEROBRAKE PANELS PACKAGE INTO A 1 METER X 1 METER X .13 METER VOLUME

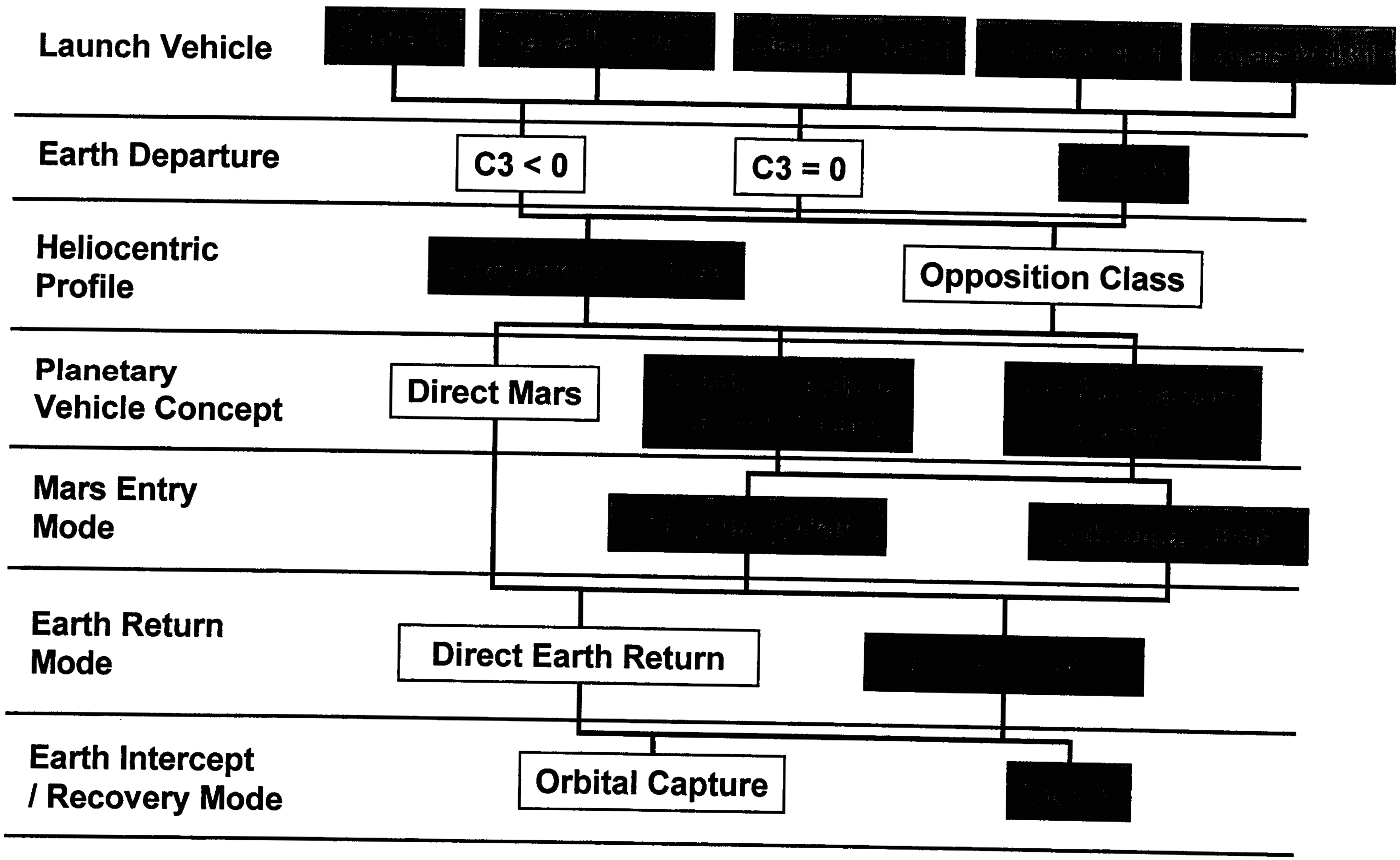
Chemical Propulsion Performance

- All propulsive

- Aerocapture

- Aerobraking

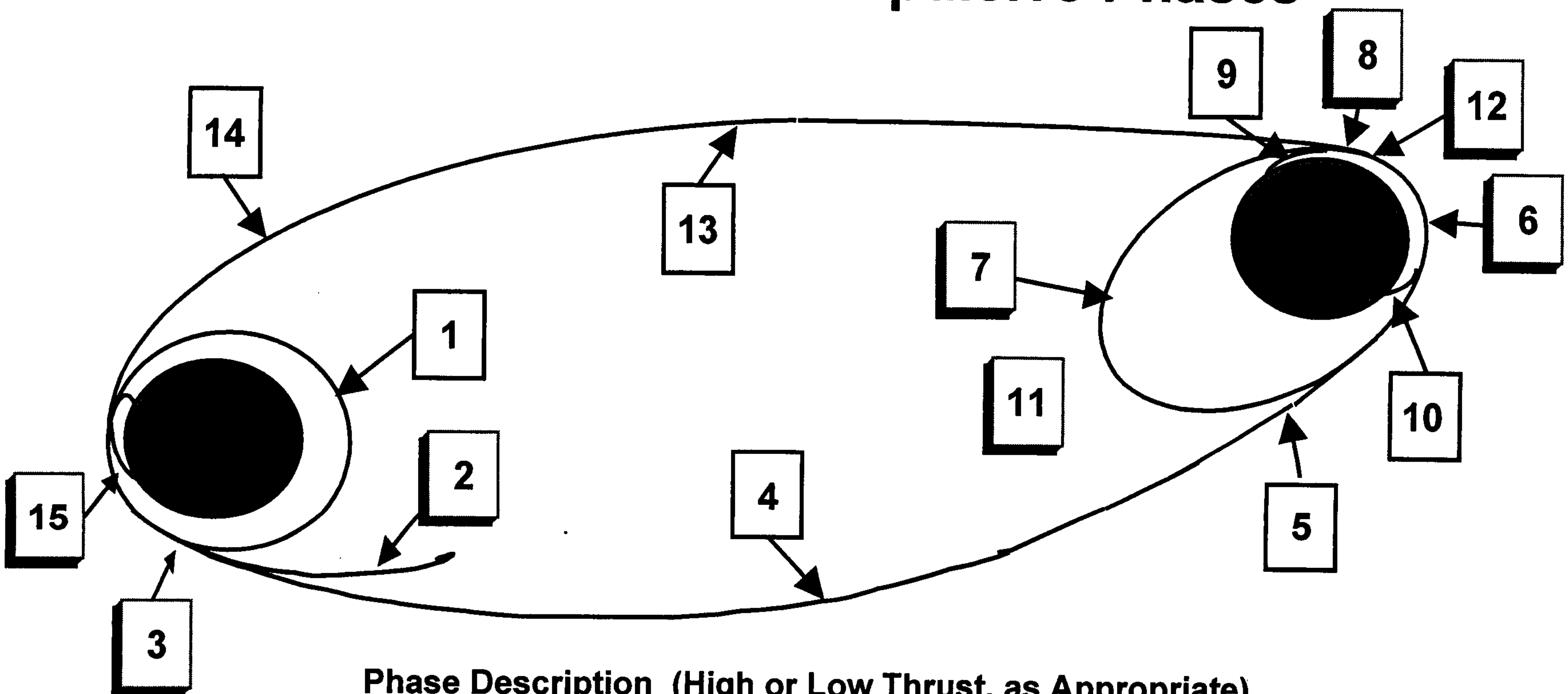
Mars Mission Trajectory Options



Preliminary Data

Selected Traded

Possible Mission Propulsive Phases

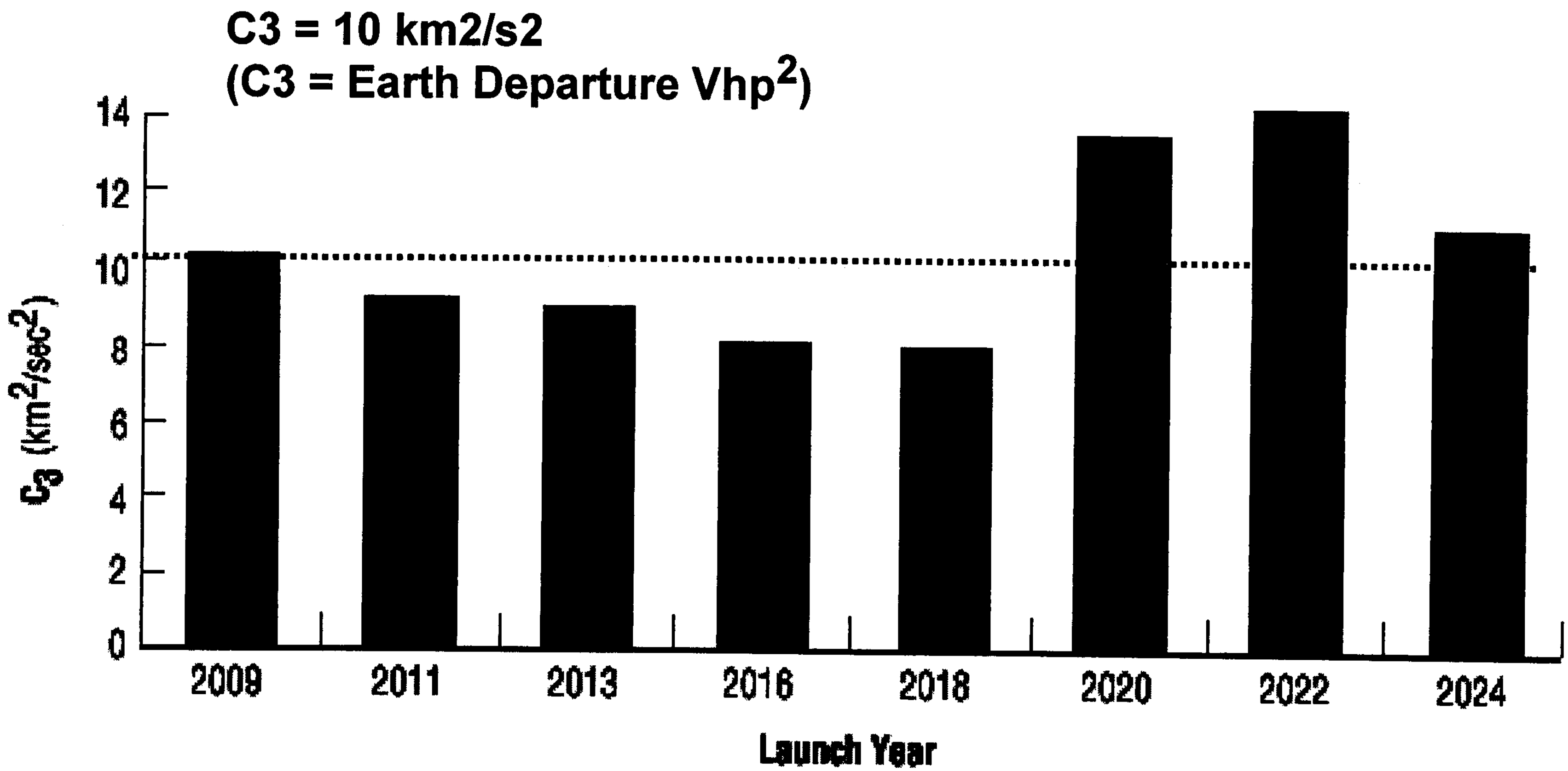


Phase Description (High or Low Thrust, as Appropriate)

1	Earth Parking Orbit	9	Mars Descent
2	Earth Escape Departure (C3=0, or sub escape)	10	Mars Ascent and Rendezvous
3	Trans Mars Injection	11	Mars Spiral Out
4	Outbound Midcourse Maneuver	12	Trans Earth Injection
5	Mars Aim point Maneuver	13	Inbound Midcourse Maneuver
6	Mars Aerocapture	14	Earth Aim point Maneuver
7	Mars Spiral Down	15	Direct Entry and Descent
8	Mars Parking Orbit (Insertion and Maintenance)		

Preliminary Data

Typical Earth Departure C3 vs Departure Year
Chemical Missions



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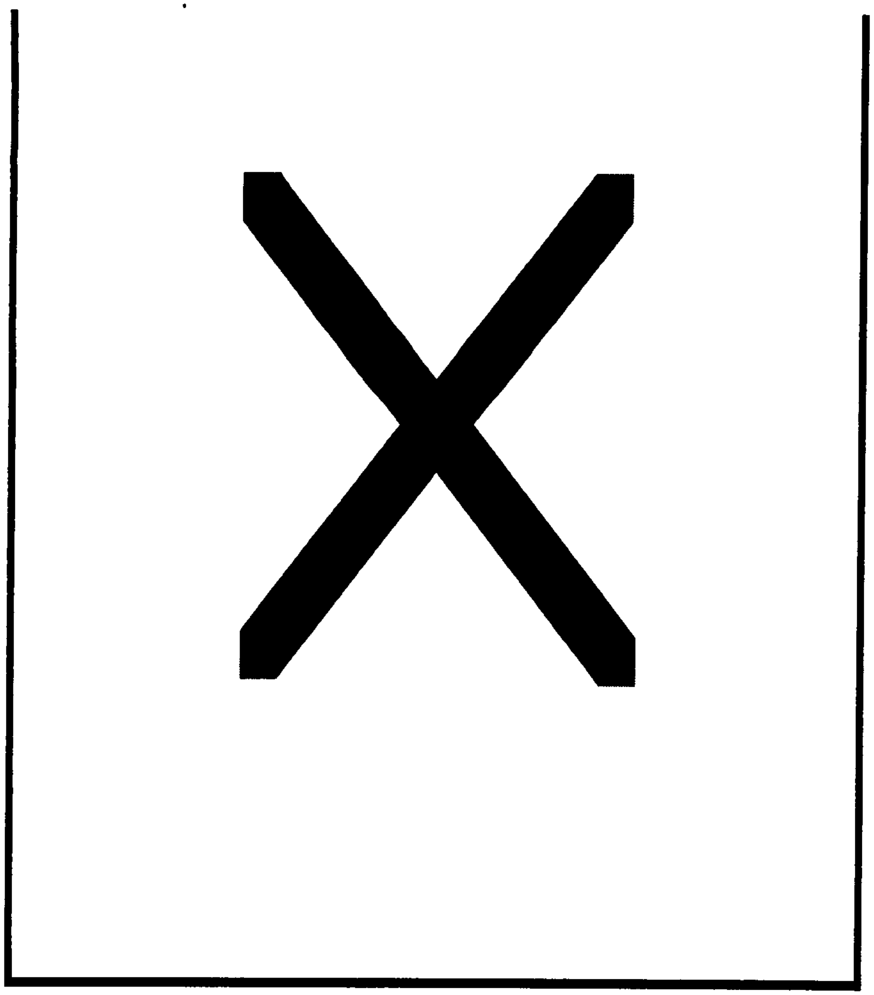
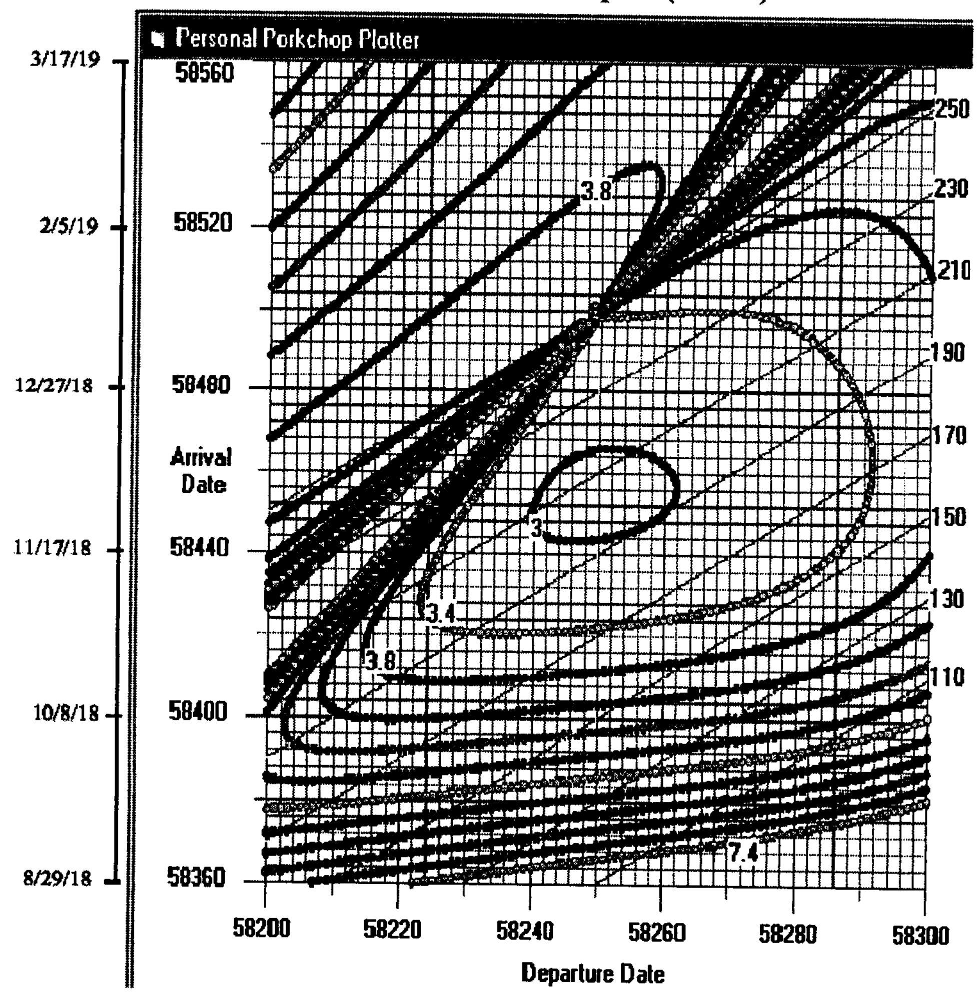
Example 2011 & 2018 Earth-Mars High Thrust Transfers

V_{hp} Arrival Mars = 3.0 km/s (2011); 3.0 km/s (2018)



Earth-Mars Trajectories
2018 Conjunction Class
Arrival Excess Speed (km/sec)



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Chemical Propulsion Results

Mars Sample Return Mission

Chemical MSR Round Trip Mission ΔV Sets (m/s)

Baseline: Hyperbolic Entry (Vhp=3.0 km2/s2) to 400 km circular Parking Orbit.

	All Propulsive	Propulsive/ Aerobraking	Aerocapture
Outbound Leg:			
- Trans-Mars Injection	= 0	= 0	= 0
- Outbound midcourse correction	= 30	= 30	= 30
Mars Arrival: (V_{hp} = 3.0)			
- MOI propulsive capture	= 2,261	= 1,097	
-Corrective maneuvers	= 0	= 101	= 135
Rendezvous: (with Ascent stage)	= 100	= 100	= 100
Mars Departure: (V_{hp} = 3.1)			
- Trans Earth Injection	= 2,315	= 2,315	= 2,315
Inbound Leg:			
- Inbound midcourse correction	= 30	= 30	= 30
- Earth Divert	= 40	= 40	= 40
G-Losses: - 2% of total	= 96	= 74	= 53
Total:	= 4,872	= 3,787	= 2,703
Percentage	= 100 %	= 78 %	= 55 %

Preliminary Data [redacted]

Lander Direct Entry

MSR Transfer Stage

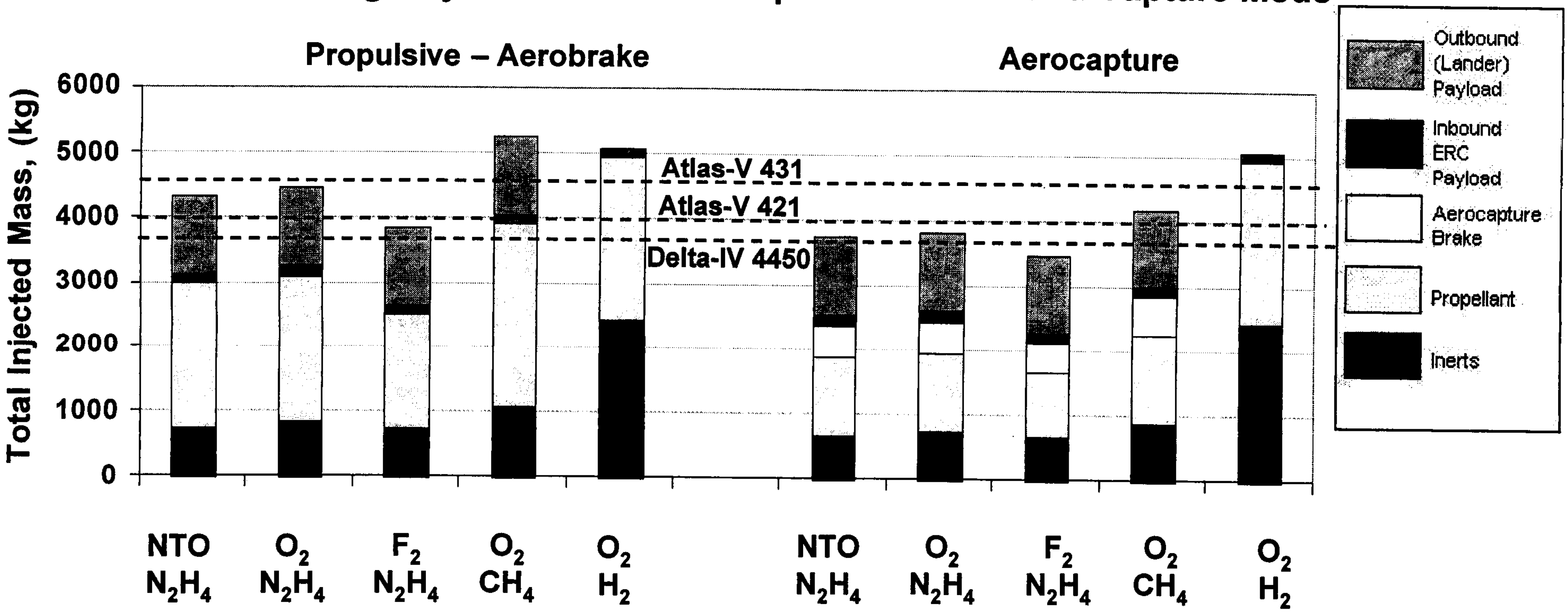
- Lander separates pre-MOC and conducts direct entry to landing
- Orbiter captures without lander into prescribed orbit
- MOC orbiter propellant reduced

Chemical MSR Transfer Stage Trade:

LANDER DIRECT ENTRY (LDE)

Given 1200 kg Outbound P/L, 150 kg Inbound P/L, Solve for Injected Mass

MSR Stage Injected Mass vs. Propellant Choice and Capture Mode

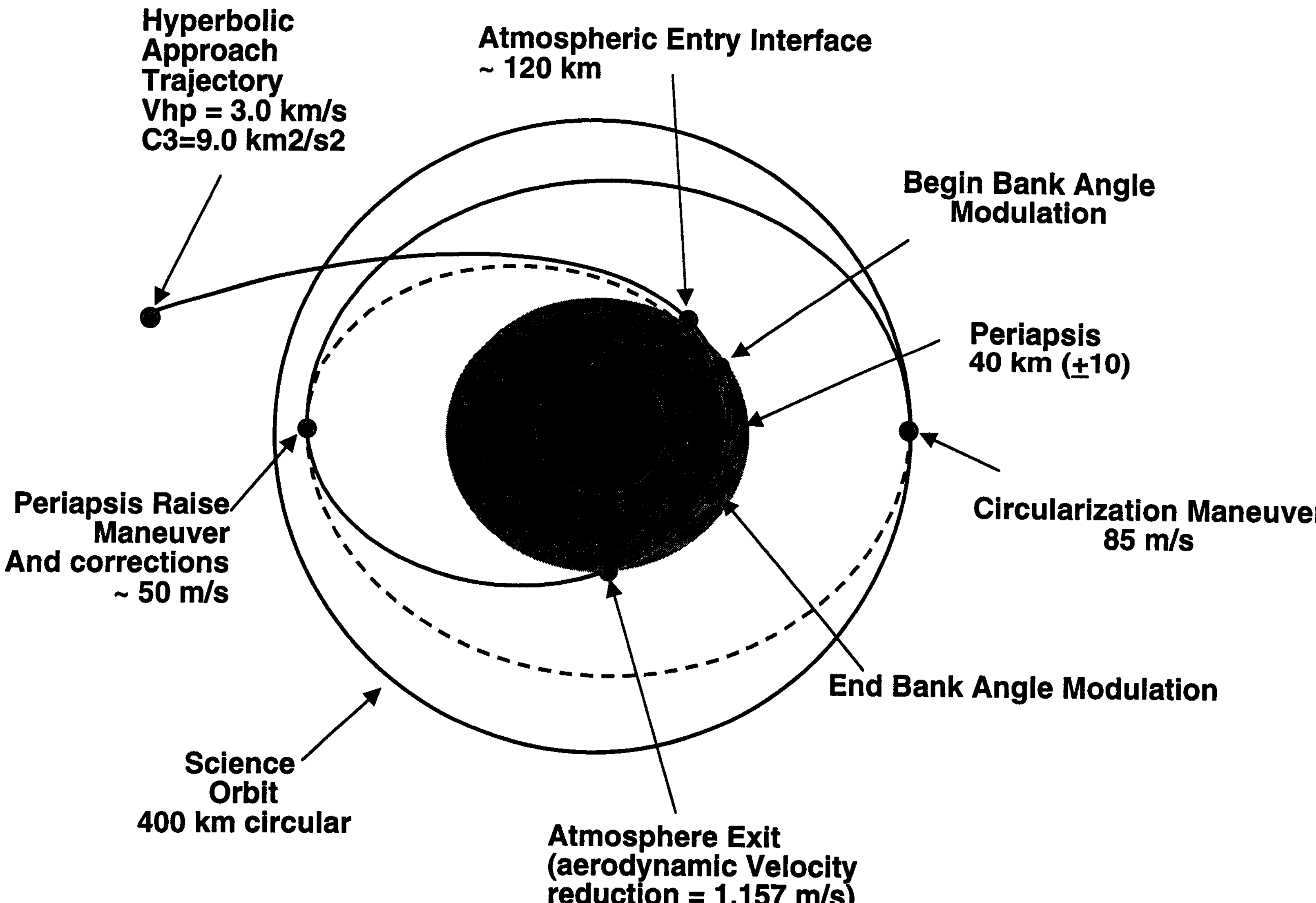


LV to C3=10km²/s², V_{hp} Mars Arrive = 3.0 km/s, V_{hp} Depart Mars=3.1 km/s, Rendezvous ΔV = 100m/s, E Divert ΔV=40m/s, Mid-Course Corrections ΔV = 30m/s, Post Aerocapture ΔV=50m/s

Preliminary Data

[redacted]

Mars Aerocapture Diagram

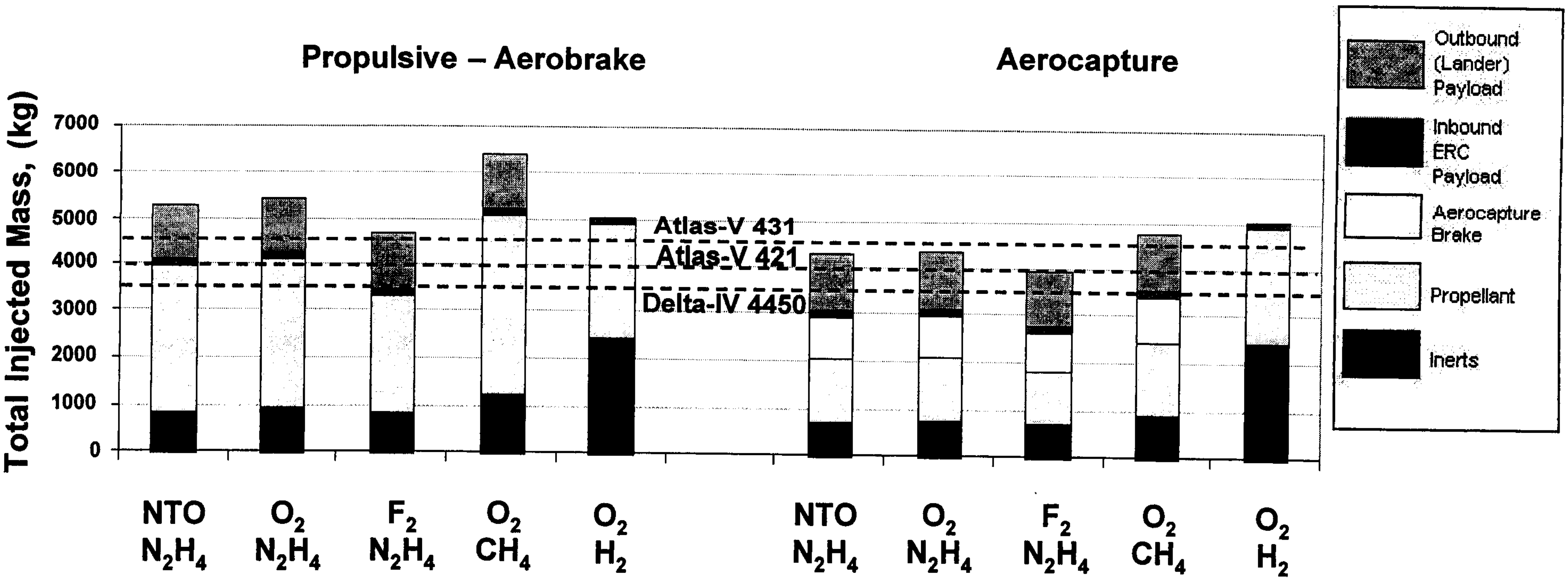


Chemical MSR Transfer Stage

LANDER CAPTURE WITH ORBITER (LCO)

Given 1200 kg Outbound P/L, 150 kg Inbound P/L, Solve for Injected Mass

MSR Stage Injected Mass vs. Propellant Choice and Capture Mode



LV to C3=10km^2/s^2, V_{hp} Mars Arrive = 3.0 km/s, V_{hp} Depart Mars=3.1 km/s,
Rendezvous ΔV = 100m/s, E Divert ΔV=40m/s, Mid-Course Corrections ΔV = 30m/s, Post Aerocapture ΔV=50m/s

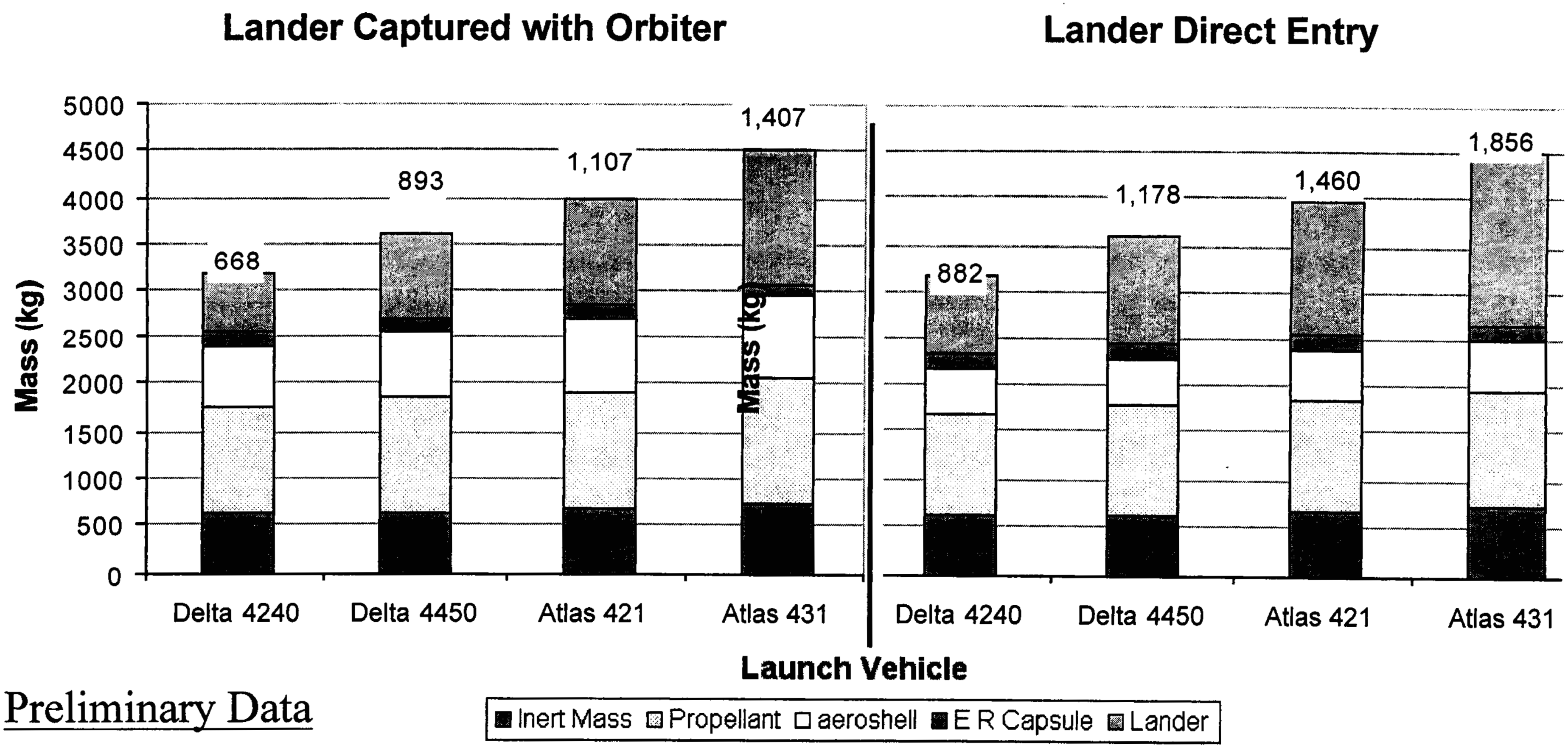
[redacted]

Chemical MSR Transfer Stage

Aerocapture at Mars, Storable NTO/N2H4 Propellant

Launch Vehicle C3=10 km2/s2, Mars Vhp=3.0 km/s, Aerocapture brake 20%

Lander Mass vs. Launch Vehicle



Preliminary Data

[redacted]

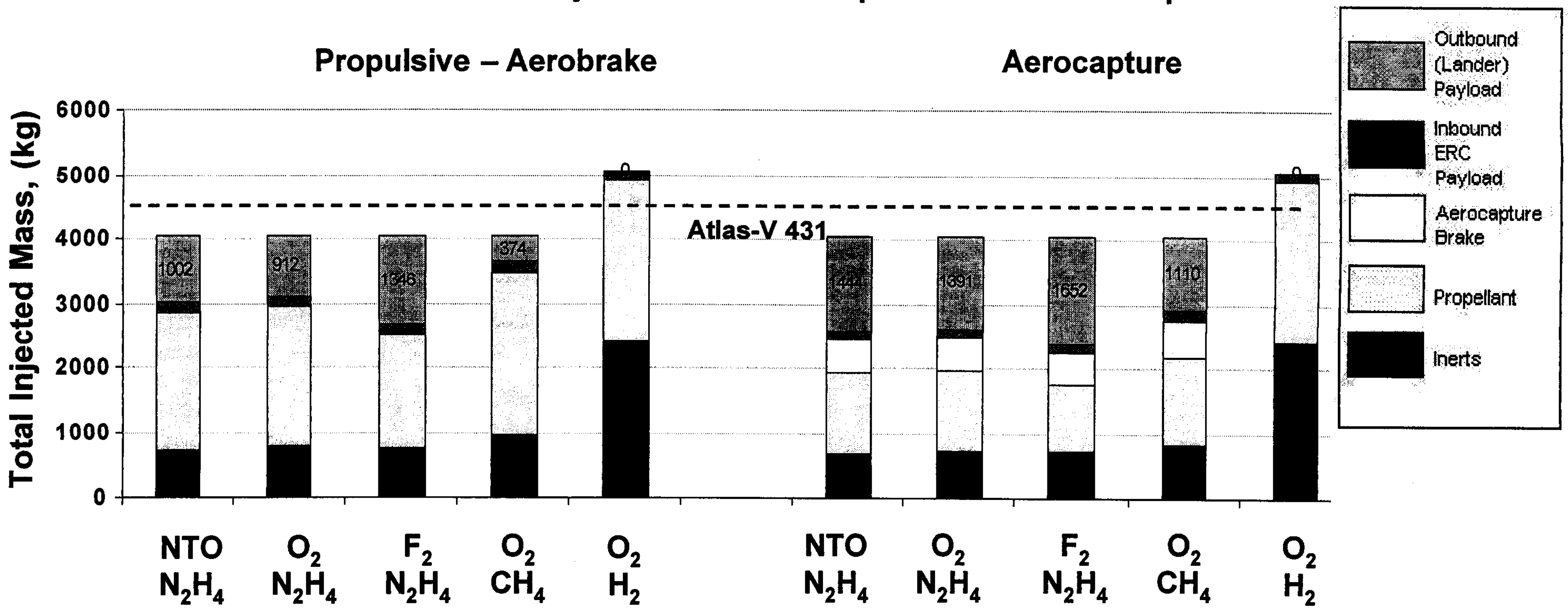
27-Oct-2003

Chemical MSR Transfer Stage Trade:

LANDER DIRECT ENTRY

Atlas-V 431 Injected Mass, 150 kg Inbound P/L, Solve for Outbound P/L

MSR Mission Vehicle Injected Mass vs. Propellant Choice vs. Capture Mode



Preliminary Data

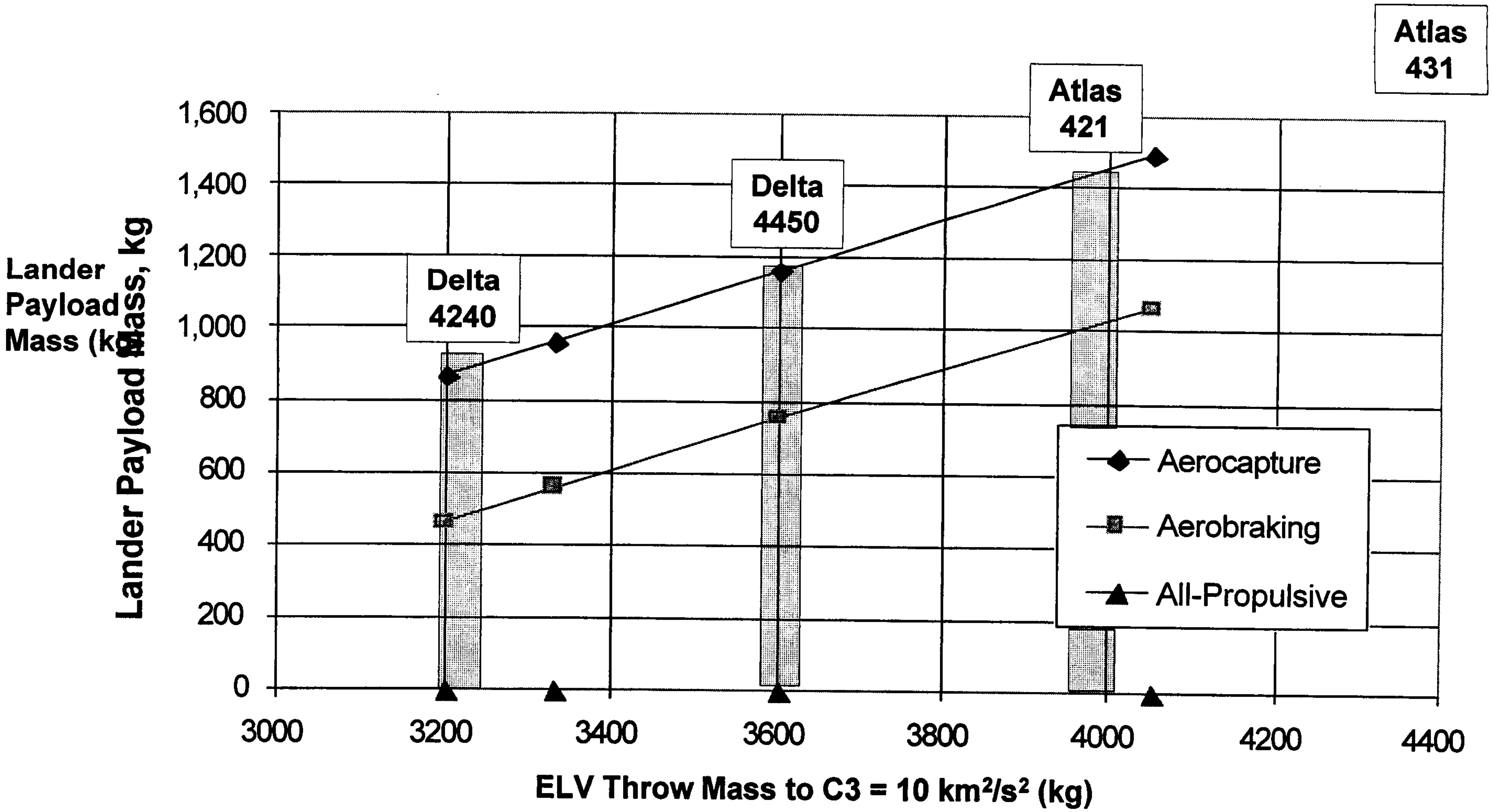
[redacted]

MSR Mission Transfer Stage:

Lander Mass vs. LV Throw Mass and Capture Method

Lander Direct Entry

Baseline Storable NTO/N_2H_4 Propellant



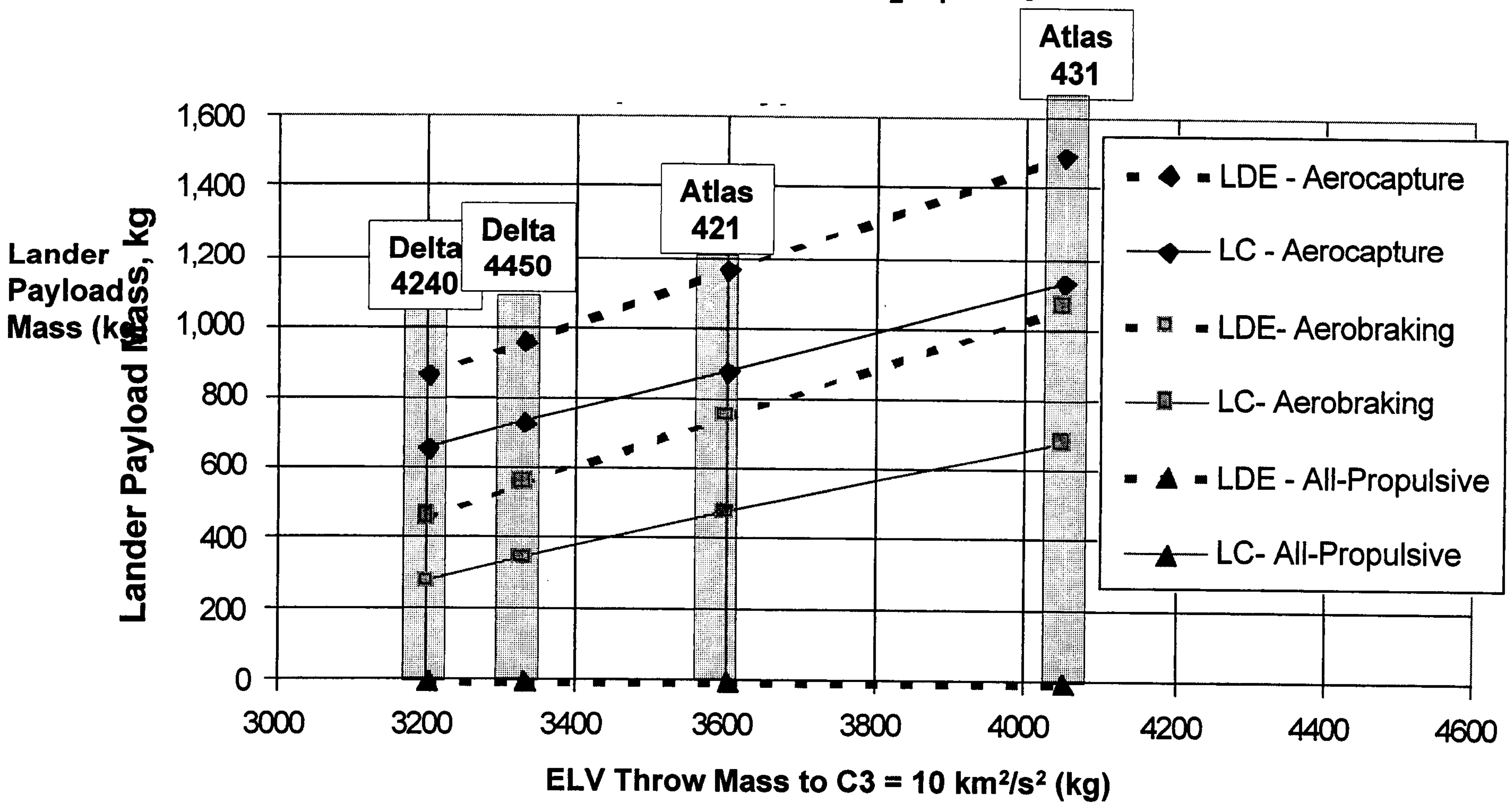
Preliminary Data

MSR Mission Transfer Stage:
Lander Mass vs. LV Throw Mass and Capture Method

LDE = Lander Direct Entry - - - - - -

LC = Lander Captured with Orbiter ———

Baseline Storable NTO/N_2H_4 Propellant

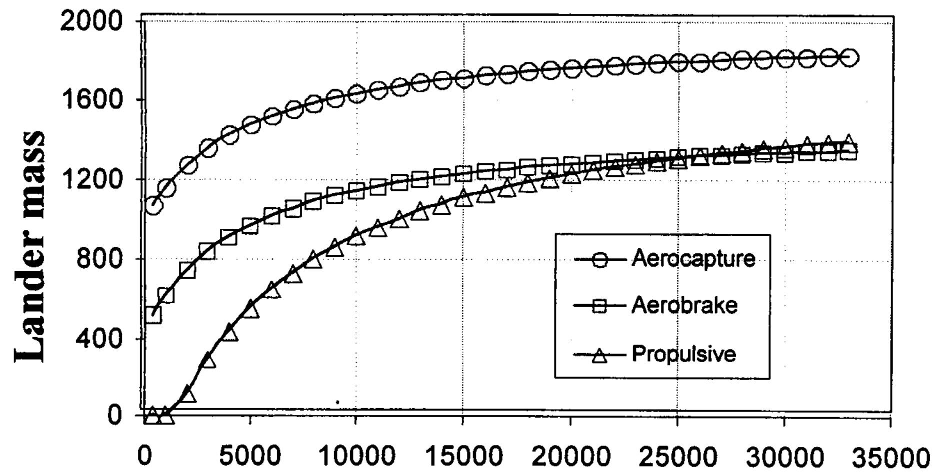


<u>Preliminary Data</u>

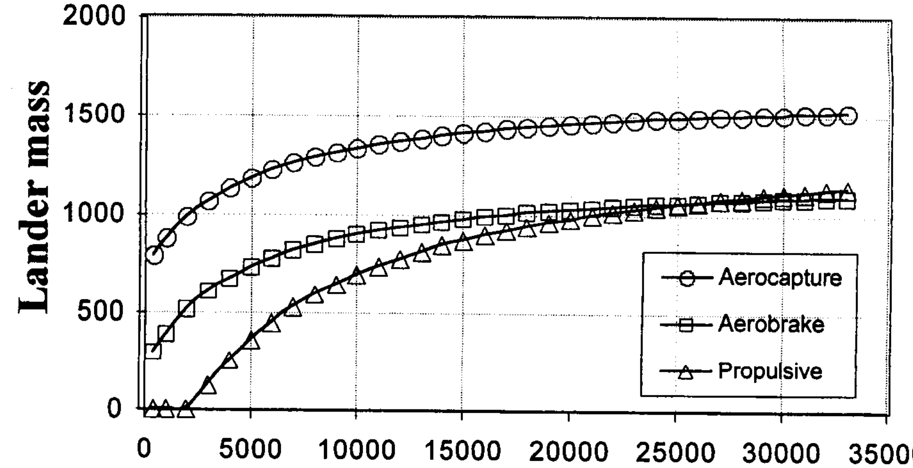
MSR Transfer Stage: Mars Final Orbit Sensitivities

Initial: 400 km by 33,000 km Elliptical Mars Orbit - Lower apoapsis
Lander Captured with Orbiter. Revision 0 data (to be updated)

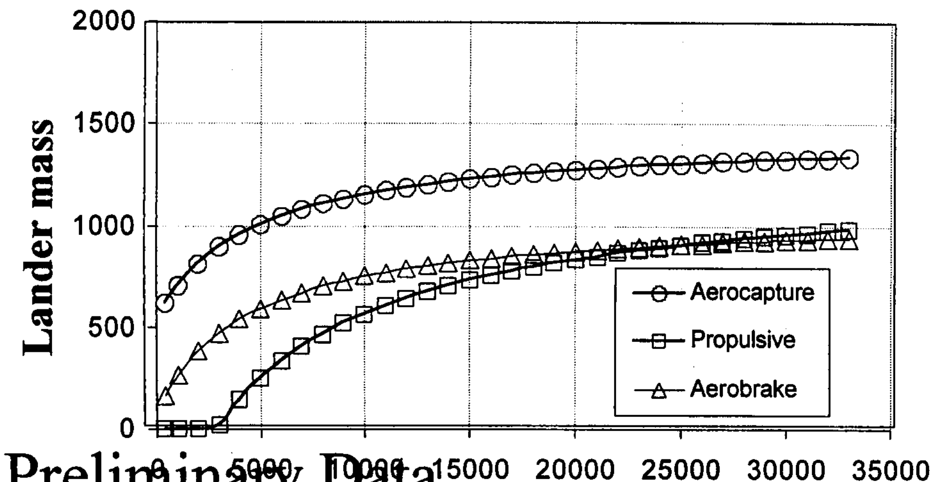
Atlas 431



Atlas 421

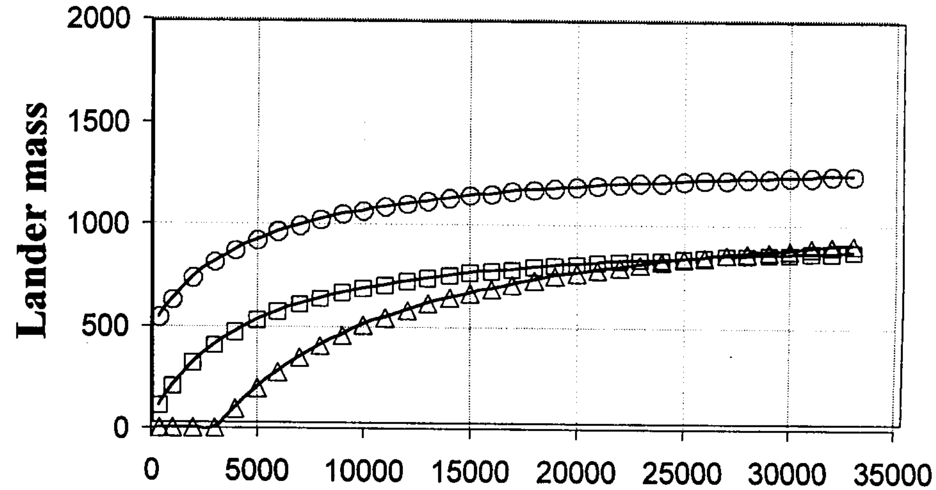


Delta IV 4450



Preliminary Data

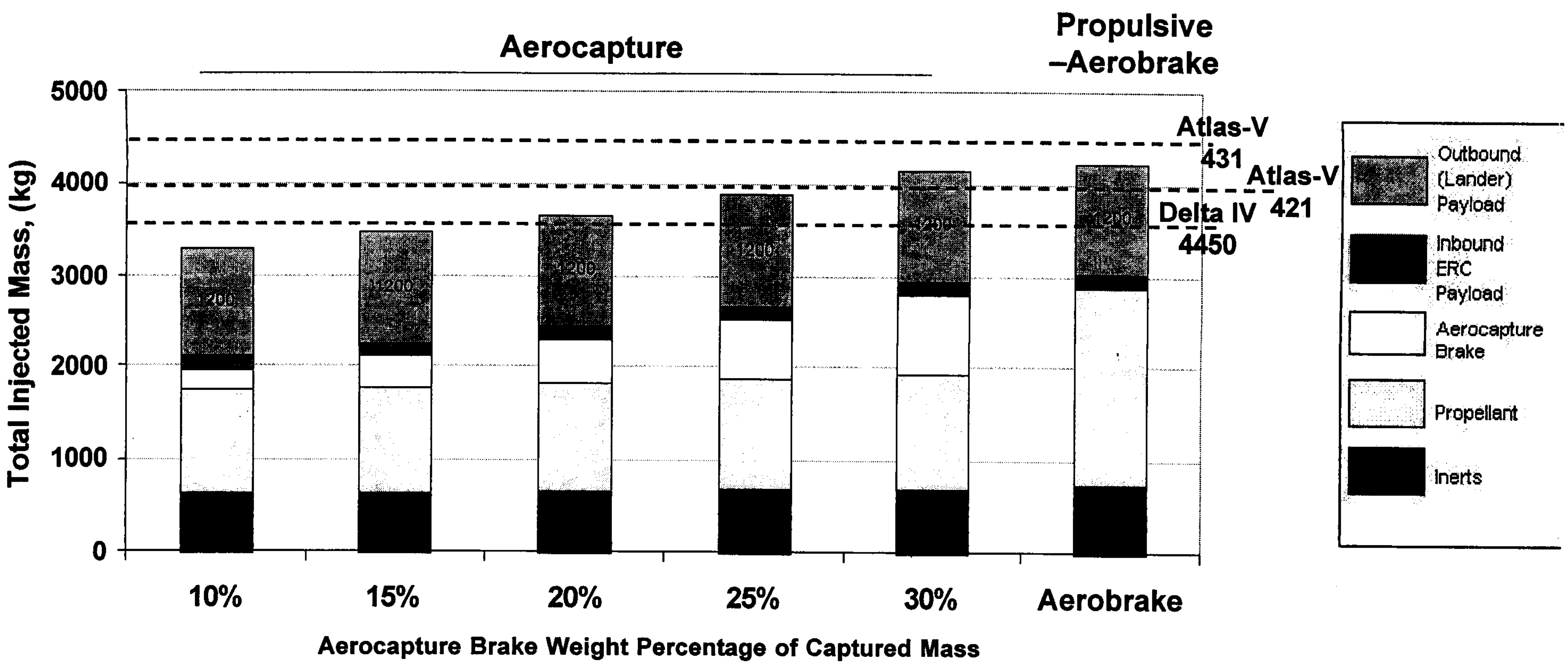
Delta IV 4240



Chemical MSR: Injected Mass vs Aerocapture Brake Percentage

LANDER DIRECT ENTRY

Given 1200 kg Outbound P/L, 150 kg Inbound P/L, Solve for Injected Mass*



LV to C3=10km^2/s^2, V_{hp} Mars Arrive = 3.0 km/s, V_{hp} Depart Mars=3.1 km/s,
Rendezvous ΔV = 100m/s, E Divert ΔV=40m/s, Mid-Course Correction ΔV = 30m/s, Post Aerocapture ΔV=50m/s

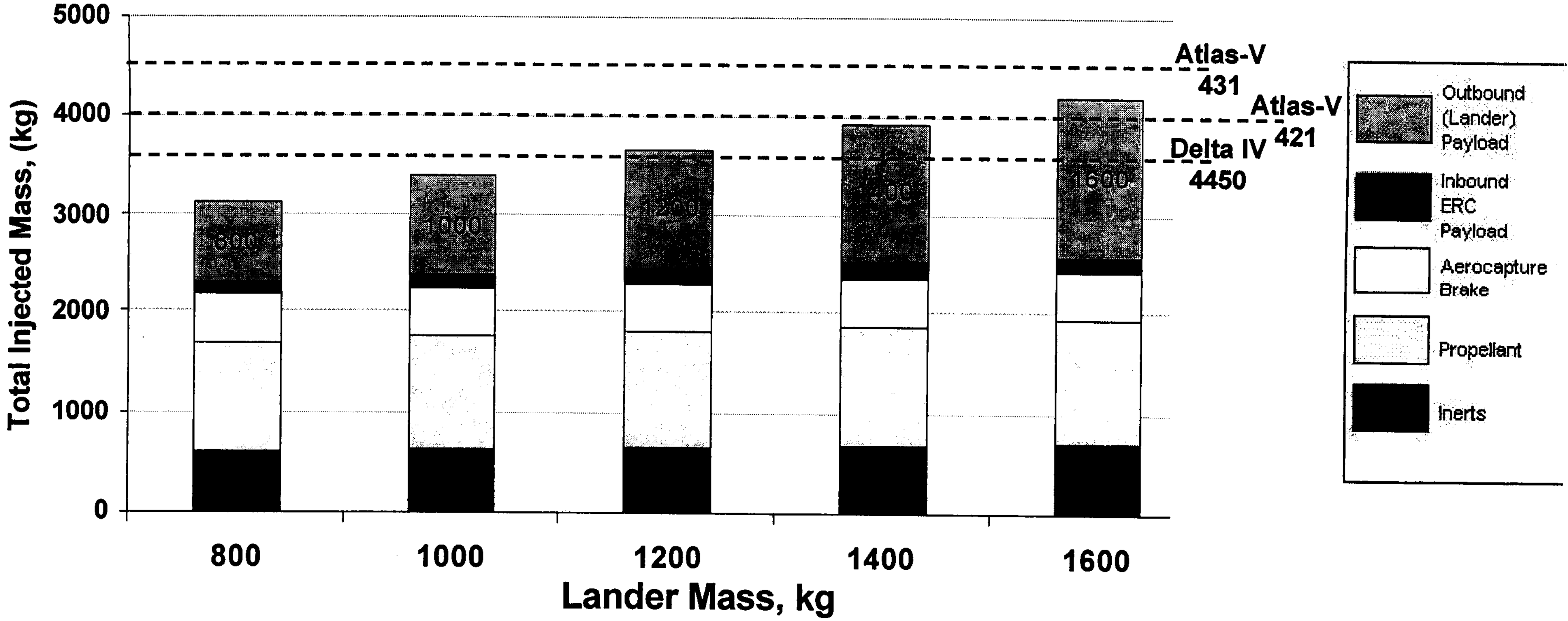
Preliminary Data

[redacted]

Chemical MSR: Injected Mass vs Mars Lander Payload Mass

LANDER DIRECT ENTRY

Given 800 to 1600 kg Outbound P/L, 150 kg Inbound, Solve for Injected Mass, Aerocapture Mode



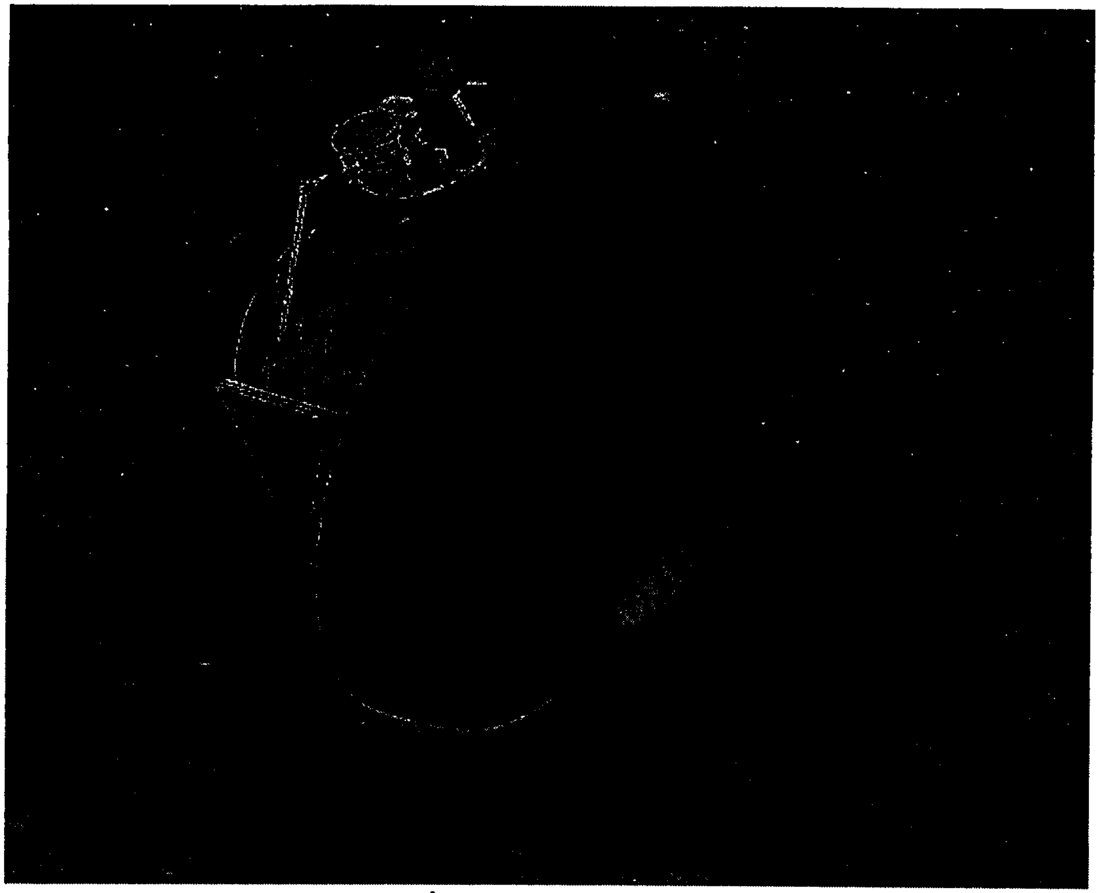
LV to C3=10km^2/s^2, V_{hp} Mars Arrive = 3.0 km/s, V_{hp} Depart Mars=3.1 km/s, Rendezvous ΔV = 100m/s, E Divert ΔV=40m/s, Mid-Course Correction ΔV = 30m/s, Post Aerocapture ΔV=50m/s

Preliminary Data

[redacted]

Mars Aerocapture Benefits and Drawbacks for MSR

Aerodynamic deceleration from Hyperbolic entry to Low Mars Orbit Velocity



Benefits

For baseline mission
Reduction in Mars capture ΔV*
2,120 m/s vs. all propulsive
1,040 m/s vs. propulsive-aerobrake

Reduction in propellant*
2,890 kg vs. all propulsive
994 kg vs. propulsive-aerobrake

Disadvantages

- 495 kg** Aeroshell mass
- Aero-thermal technology development
- GN&C development (steering via rolling lift vector about vehicle Cg)
- Mars atmospheric variations
- Jettison for Earth Return Leg
- Spacecraft heating
- Cryo-cooler peak load

*MSR mission baseline: 1200 kg Lander (Direct Entry), Orbiter 400 km circ LMO, 150 kg ERC.
** Brake mass 20% of total capture mass including aeroshell mass.

Chemical Propulsion Results

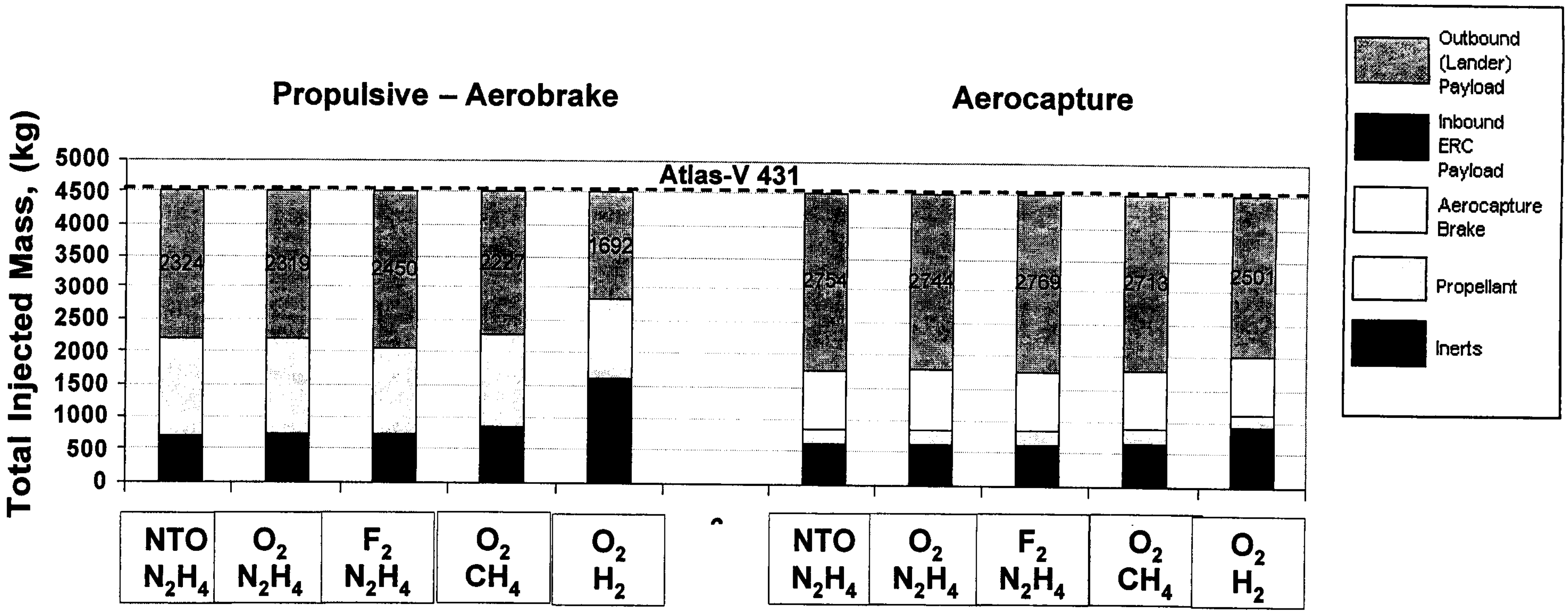
Mars One Way Payload Delivery Mission

Chemical Mars One-Way Delivery Mission:

Payload Mass vs. Propellant Type vs. Capture Mode

LANDER CAPTURED WITH ORBITER

Atlas V - 431 to C3=10 km^2/s^2, Mars arrival V_{hp} = 3.0 km/s, LMO = 400 km circular



Preliminary Data

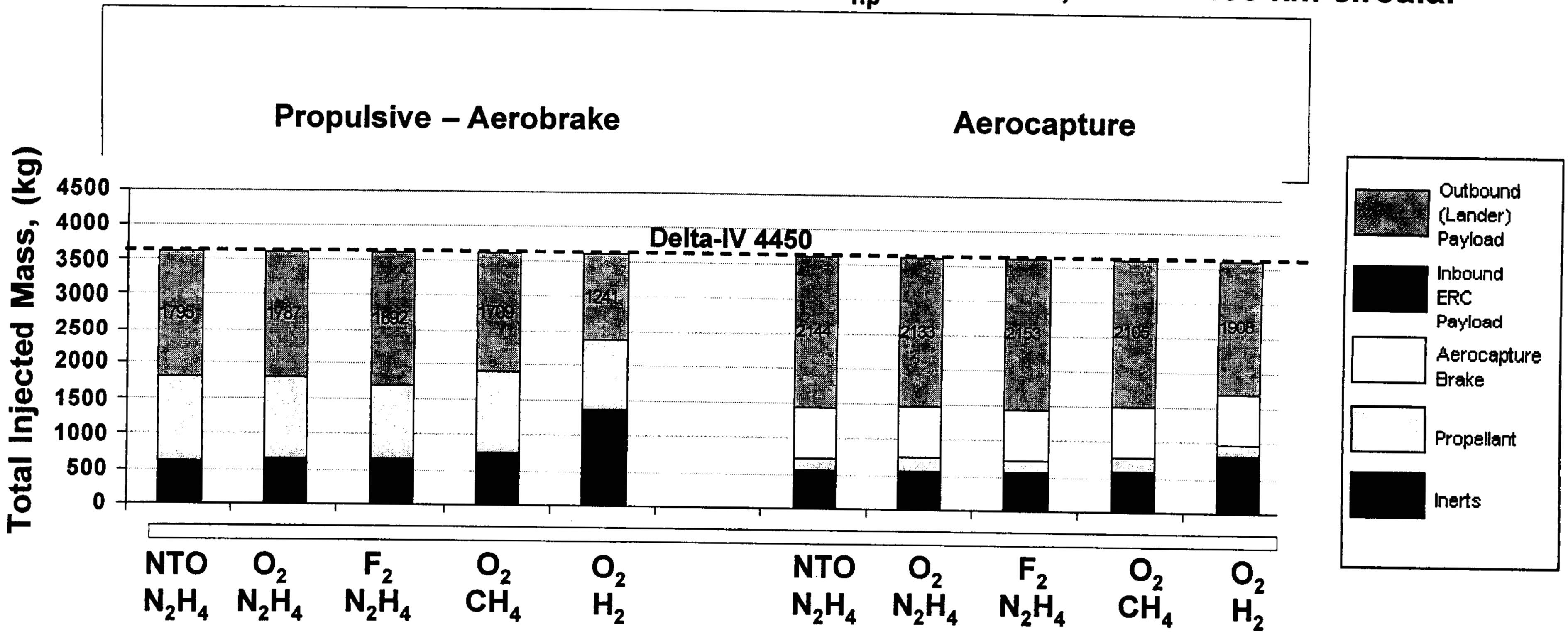
[redacted]

Chemical Mars One-Way Delivery Mission:

Payload Mass vs. Propellant Type vs. Capture Mode

LANDER CAPTURED WITH ORBITER

Delta-IV 4450 to C3=10 km^2/s^2, Mars Arrival V_{hp} = 3.0 km/s, LMO = 400 km circular

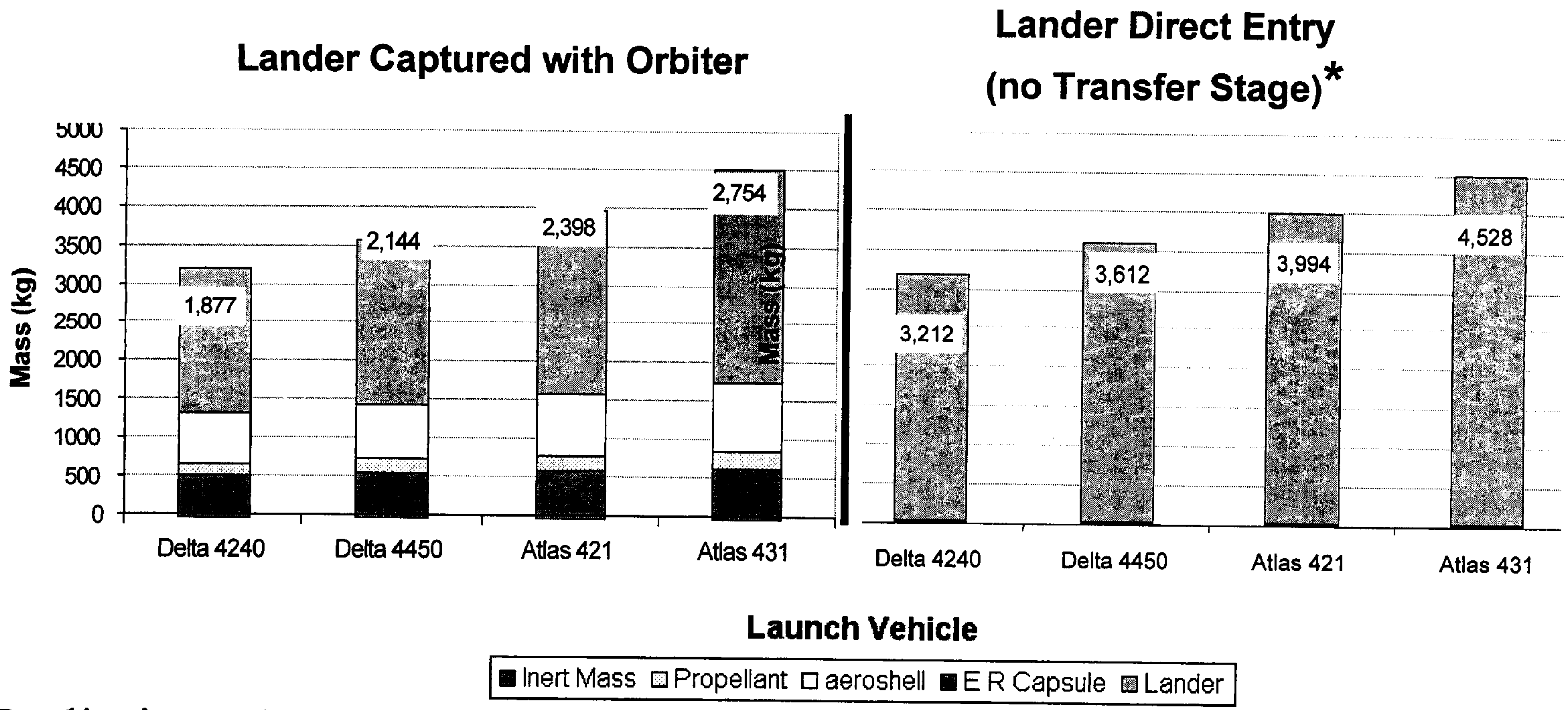


Preliminary Data

[redacted]

Chemical Mars One-Way Transfer Stage

Aerocapture at Mars, Storable NTO/N2H4 Propellant
Lander Mass vs. Launch Vehicle (All LV's to C3=10 km^2/s^2)



Preliminary Data

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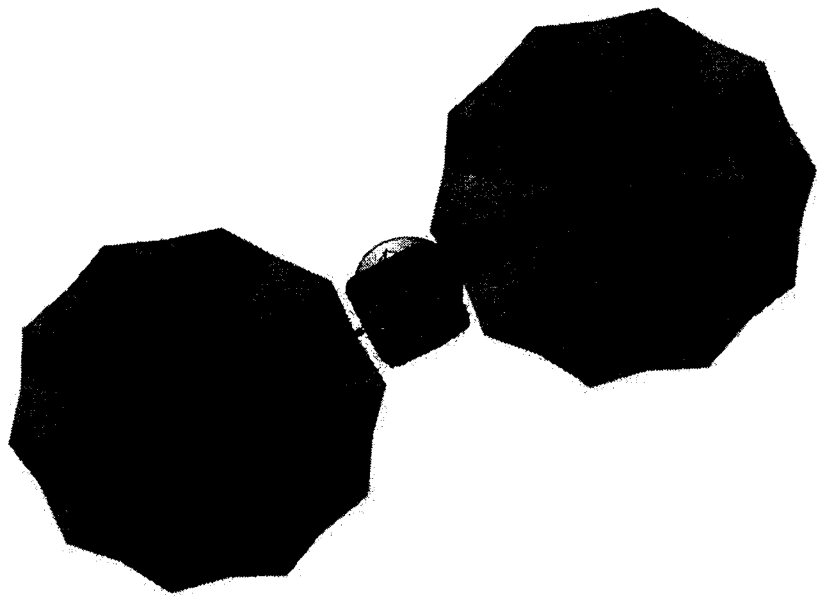
Solar Electric Propulsion Performance

-Lander to low Mars orbit

- Lander Mars direct entry



NEXT Ion Thruster Technology

NEXT Ion Thruster

Electrostatic acceleration of xenon ions to produce thrust

- NSTAR accelerated Deep Space 1 to first EP powered beyond Earth mission, (3 year mission)
- 6.06 kWe (6 kW) Standard version
- 6.85 kWe (7 kW) High Power version
- 4086 sec Isp at Max Power
- 70.1 % efficiency at Max Power
- 13.46 kg mass
- Current ion thrusters in development up to TBD kW power levels.

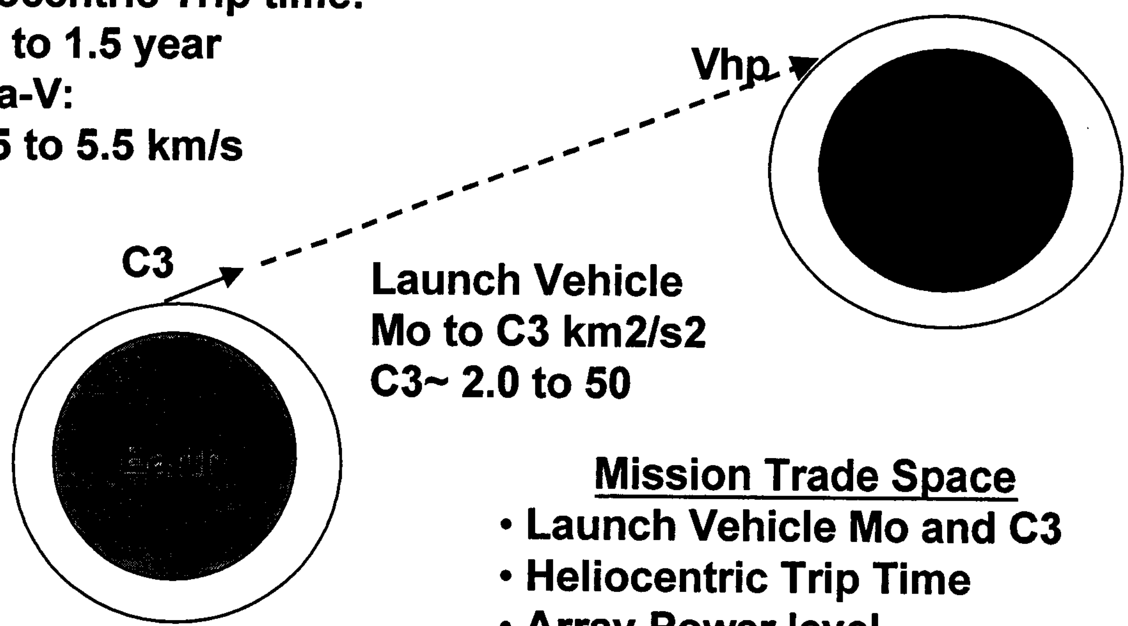
Mars Outbound Earth-Mars transfer

For MSR Mission or One-Way Payload Delivery

SEP Stage
Po = Input (array size)
Thrust = f (Thruster, #, Po)
Isp = f (Thruster, Po)
Heliocentric Trip time:
~0.8 to 1.5 year
Delta-V:
~ 2.5 to 5.5 km/s

Mars SOI
Lander Direct Entry
(Mars Vhp=0 MSR)
(Mars Vhp=3 One-way)
Or Lander Capture

SEP Spiral Down
Po = f (1.5 AU, array)
Spiral down time
~ 0.5 to 1.4 year
Delta-V ~ 2.7 km/s
400 km circular orbit
(with or w/o lander)



Launch Vehicle
Mo to C3 km2/s2
C3~ 2.0 to 50

Mission Trade Space
- Launch Vehicle Mo and C3
- Heliocentric Trip Time
- Array Power level
- Earth Departure date
- Mars Arrival Vhp
- Lander drop off or capture
- Final orbit altitude

Technology Trade
- Thruster type
- Thruster power level
- Thruster number

Solar Electric Propulsion Results

Mars Sample Return Mission

SEP Data Set 1:

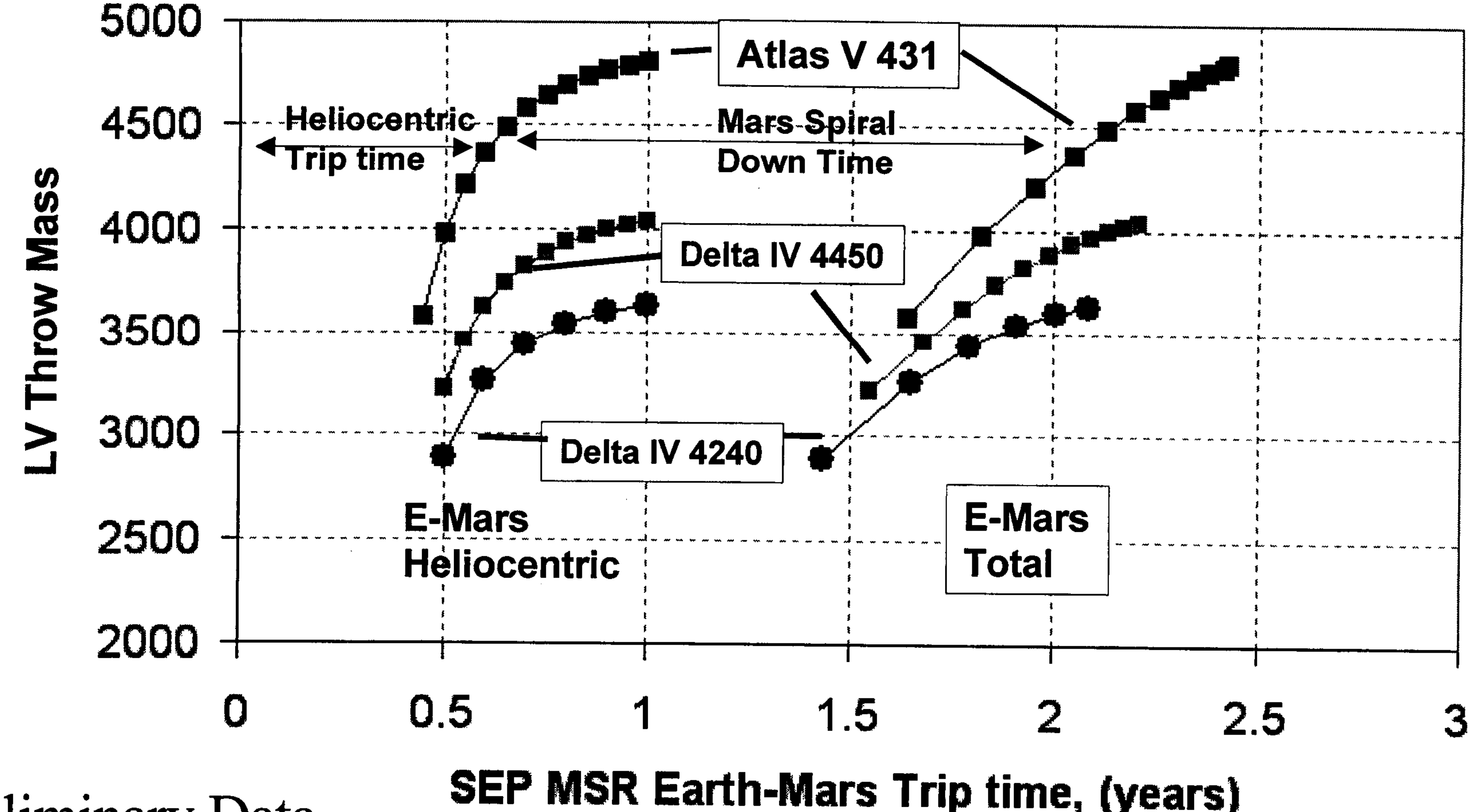
1. Capture Lander with Orbiter
2. Po = 25 kW at 1 AU
3. 4 x 6 kWe NEXT thrusters
4. 3 launch vehicles: Atlas-V 431, Delta-IV 4450 & 4240
5. Total E-M trip times from 1.3 to 2.3 years

SEPS Mars Spiral Down Time

SEP Data Set 1: Po = 25 kWe Array, 4 x 6kW NEXT

Lander Captured with Orbiter

Edelbaum Approximation in SEPTOP



Preliminary Data

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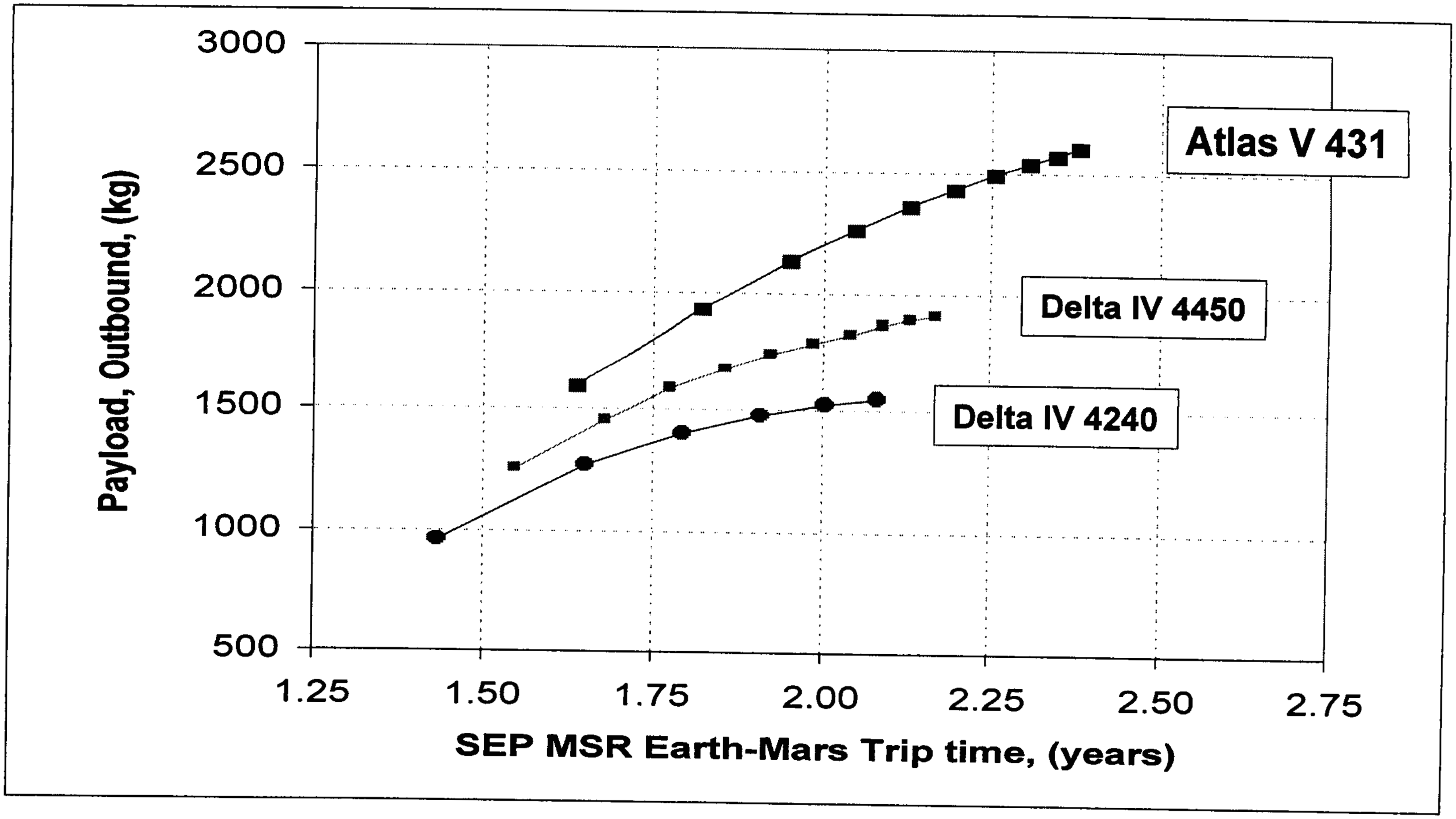
SEP MSR: Outbound Payload vs Total E-Mars Trip Time

SEP Data Set 1: Po = 25 kWe, 4 x 6kW NEXT
Lander Captured with Orbiter



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SEP MSR: Power Parameters

SEP Data Set 1: Po = 25 kWe, 4 x 6kW NEXT Atlas-V 431

Lander Capture with Orbiter

Power budget:		**Earth**	**Venus**		**Mars**	
AU - **array** -		1.00	0.73		**1.50**	-
Sunlight Intensity	**margin**	**1,358**	2,584		604	W / m2
Array Area with Margin	**10%**	**88.0**	88.0		**88.0**	m2
Array Area Required		**80.0**	80.0		**80.0**	m2
Array Power for Costing	**cell eff**	27.5				kWe
Array Power	**23.0%**	**25.0**	47.6	**23.0%**	**11.11**	kWe
- Po into IPS -						
Housekeeping Power		**0.25**	0.25		**0.25**	kWe
Power Feathered	max allowed	**0.00**	22.6		**0.0**	kWe
Act max power IPS	**24.75**	**24.75**	**24.75**		**10.86**	kWe
into cable to ppu	**99.5%**	**24.75**		**99.5%**	**10.81**	
- into PPU and Thrusters-			94.0%			
Act max into PPU's	**94.0%**	**24.63**	**24.63**	**94.9%**	**10.81**	kWe
into cable to thruster	**100.0%**	**23.15**		**100.0%**	**10.81**	
Act max Po Thrusters	**69.2%**	**23.15**	23.15	**68.6%**	**10.26**	kWe
Thrust total		0.80	0.80		0.35	N
Jet Power Total		16.0	16.0		7.0	kWt
PPU Waste Heat		1.48	0.37		0.55	kWt
Individual budget:						
PPU Power	**94.0%**	**6.16**	6.16	**94.9%**	**5.40**	kWe
Oper Po per Thruster	**69.2%**	**5.79**	5.79	**68.6%**	**5.13**	kWe
Isp		**4097**	4097		**4075**	sec
thrusters on at Mars					2.0	-

Preliminary

Data

[redacted]

SEP MSR Preliminary Weight Statement

SEP Data Set 1: 25 kWe, 4 x 6 kW NEXT, Atlas-V 431

Lander Capture to LMO

6 kW NEXT THRUSTER SEP WBS **Revison 3**

Mars Sample Return **5-Nov**

		Unit	Margin	Total	Atlas-V 431	Launch Vehicle
		kg		kg	3.95	Earth Depart C3
1	**Power Gen**	**119**	30%	**154**	2.25	E-Mars Trip Time (y)
2	**Power Distribution**	**35**	30%	**45**	0.00	Mars-E Trip Time (y)
3	**Propulsion**	**237**	5%	**249**	25.0	Array Power (kW)
4	**Tankage & Feed Sys**	**75**	30%	**97**	6.16	PPU Max (kW)
5	**Thermal Control**	**31**	30%	**40**	0.94	PPU Eff (%)
6	**Structure**	**138**	30%	**180**	6.06	Thruster Max (kW)
7	**Mechanisms**	**17**	30%	**23**	0.69	Thruster Eff (%)
8	**Adapters**	**54**	30%	**70**	4	Thrusters
9	**ACS**	**45**	30%	**58**	4097	Isp (sec)
10	**Other**	**9**	30%	**12**		
					928	**STG MASS**
11	**Telecom, C&DH**	**32**	30%	**42**		
12	**GN&C**	**20**	30%	**26**		
13	**Other**	**18**	30%	**23**		
14	**Rendezvous Instr Suite**	**40**	30%	**52**	**143**	**ORBITER RELATED**
15	**Reserves**			**82**	**1,153**	**INB BURNOUT**
16	**Propellant Inbound**			**174**		
17	**Rendezvous**			**7**	**1,334**	**OUTB BURNOUT**
18	**Outbound**			**641**	**1,975**	**WET MASS**
19	**Payload Outbound**			**2,547**		
20	**Inbound**			**130**	**2,677**	**PAYLOADS**
21	**Launch Mass**			**4,652**	**4,652**	**LAUNCH**

Preliminary Data

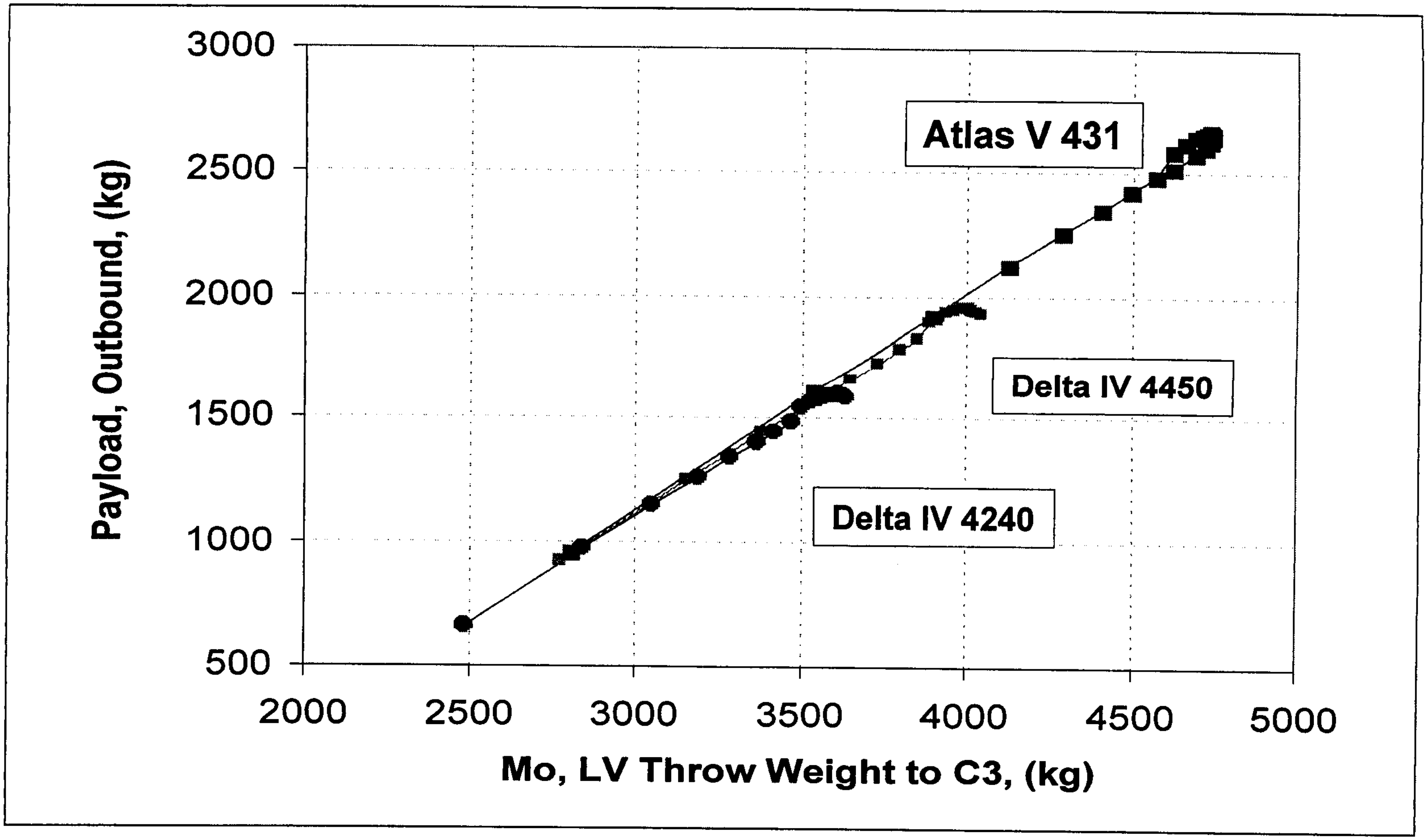
Solar Electric Propulsion Results

Mars Sample Return Mission

SEP Data Set 2:

1. Capture Lander with Orbiter down to 400 km Circular Orbit
2. Po = 22 kW at 1 AU
3. 3 x 6 kWe NEXT thrusters
4. 3 launch vehicles: Atlas-V 431, Delta-IV 4450 & 4240
5. Total E-M trip times from 1.3 to 2.3 years

SEP MSR: Outbound Payload vs LV Throw Weight
SEP Data Set 2: Po = 22 kWe, 3 x 6kW NEXT
Lander Captured with Orbiter (to LMO 400 km)



Preliminary Data

SEP MSR: SEPTOP Trajectory Parameters

SEP Data Set 2: Po = 22 kWe, 3 x 6kW NEXT, Atlas-V 431

Lander Captured with Orbiter

Outbound: 0.8 y, Mars Spiral Down Time = 1.75 y, Inbound: 1.1 y

-- SEPTOP --	Outbound	Inbound	
Departure Date jdate	-104.27	-84.98	date
Julian Date adate	187.93	316.79	days
P o (Array Power)	22	22	kWe
C3	4.3012		km2/s2
Transfer Time (tend)	0.8	1.1	years
Power On Time tp	806.4	280.1	days
Delta Velocity vac	4.810	5.270	km/s
Vhp at destination			km/s
M o	4,622	1,200	kg
M propellant M p	529	149	kg
M delivered M d	4,093	1,052	kg

[redacted]

Preliminary Data

SEP MSR: Power Parameters

SEP Data Set 2: Po = 22 kWe, 3 x 6kW NEXT Atlas-V 431

Lander Captured with Orbiter

Power budget:		**Earth**	Venus		**Mars**	
AU - array -		1.00	0.73		**1.50**	-
Sunlight Intensity	**margin**	**1,358**	2,584		604	W / m2
Array Area with Margin	**10%**	**77.5**	77.5		**77.5**	m2
Array Area Required		**70.4**	70.4		**70.4**	m2
Array Power for Costing	**cell eff**	24.2				kWe
Array Power	**23.0%**	**22.0**	41.9	**23.0%**	**9.78**	kWe
- Po into IPS -						
Housekeeping Power		**0.25**	0.25		**0.25**	kWe
Power Feathered	max allowed	**2.65**	22.5		**0.0**	kWe
Act max power IPS	**19.10**	**19.10**	19.10		**9.53**	kWe
into cable to ppu	**99.5%**	**19.10**		**99.5%**	**9.48**	
- into PPU and Thrusters-			94.0%			
Act max into PPU's	**94.0%**	**19.00**	19.00	**94.6%**	**9.48**	kWe
into cable to thruster	**100.0%**	**17.86**		**100.0%**	**9.48**	
Act max Po Thrusters	**69.2%**	**17.86**	17.86	**67.8%**	**8.97**	kWe
Thrust total		0.62	0.62		0.31	N
Jet Power Total		12.4	12.4		6.1	kWt
PPU Waste Heat		1.14	0.38		0.51	kWt
Individual budget:						
PPU Power	**94.0%**	**6.33**	6.33	**94.6%**	**4.74**	kWe
Oper Po per Thruster	**69.2%**	**5.95**	5.95	**67.8%**	**4.48**	kWe
Isp		**4097**	4097		**4045**	sec
thrusters on		**3.0**			**2.0**	-

Preliminary

Data

Solar Electric Propulsion Results

Mars Sample Return Mission

SEP Data Set 3:

1. Lander Direct Entry
2. Po = 22 kW at 1 AU
3. 2 x 7 kWe High Power NEXT thrusters
4. 3 launch vehicles: Atlas-V 431, Delta-IV 4450

SEP MSR NEXT Thruster Preliminary Weight Statement

SEP Data Set 3: Po=22 kWe, 2 x 7kW NEXT Thrusters, Delta-IV 4450
Lander Direct Entry Mode, 1200 kg Lander dropped at Mars C3=0

7 kW NEXT THRUSTER SEP WBS **Revison 1**
Mars Sample Return **4-Nov**

		Unit kg	Margin	Total kg
1	Power Gen	103	30%	134
2	Power Distribution	23	30%	29
3	Propulsion	151	5%	159
4	Tankage & Feed Sys	47	30%	61
5	Thermal Control	23	30%	30
6	Structure	90	30%	117
7	Mechanisms	15	30%	20
8	Adapters	32	30%	42
9	ACS	37	30%	49
10	Other	9	30%	12
11	Telecom, C&DH	32	30%	42
12	GN&C	20	30%	26
13	Other	18	30%	23
14	Rendezvous Instr Suite	40	30%	52
15	Reserves			51
16	Propellant Inbound			152
17	Rendezvous			6
18	Outbound			354
19	Payload Outbound			1,165
20	Inbound			252
21	Launch Mass			2,775

4450	Launch Vehicle
17.51	Earth Depart C3
1.47	E-Mars Trip Time (y)
1.29	Mars-E Trip Time (y)
22.0	Array Power (kW)
7.29	PPU Max (kW)
0.94	PPU Eff (%)
6.85	Thruster Max (kW)
0.70	Thruster Eff (%)
2	Thrusters
4116	Isp (sec)
652	**STG MASS**
143	**ORBITER RELATED**
846	**INB BURNOUT**
1,004	**OUTB BURNOUT**
1,358	**WET MASS**
1,416	**PAYLOADS**
2,775	**LAUNCH**

SEP MSR with NEXT Thrusters: Power Budget Page

SEP Data Set 3: Po=22 kWe, 2 x 7kW NEXT Thrusters, Delta-IV 4450

Power budget:		**Earth**	**Venus**		**Mars**	
AU - array -		1.00	0.73		**1.50**	-
Sunlight Intensity	**margin**	**1,358**	2,584		604	W / m2
Array Area with Margin	**10%**	**77.5**	77.5		**77.5**	m2
Array Area Required		**70.4**	70.4		**70.4**	m2
Array Power for Costing	**cell eff**	24.2				kWe
Array Power	**23.0%**	**22.0**	41.9	**23.0%**	**9.78**	kWe
- Po into IPS -						
Housekeeping Power		**0.25**	0.25		**0.25**	kWe
Power Feathered	max allowed	**7.10**	27.0		**0.0**	kWe
Act max power IPS	**25.0**	**14.65**	**14.65**		**9.53**	kWe
cable to ppu	**99.5%**	**14.57**		**99.5%**	**9.48**	
- into PPU and Thrusters-			94.0%			
Act max into PPU's	**94.0%**	**14.57**	**14.57**	**94.6%**	**9.48**	kWe
cable to thruster	**100.0%**	**14.57**		**100.0%**	**9.48**	
Act max Po Thrusters	**69.8%**	**13.70**	13.70	**67.8%**	**8.97**	kWe
Thrust total		0.47	0.47		0.31	N
Jet Power Total		9.6	9.6		6.1	kWt
PPU Waste Heat		0.87	0.44		0.51	kWt
Individual budget:						
PPU Power	**94.0%**	**7.29**	7.29	**94.6%**	**4.74**	kWe
Oper Po per Thruster	**69.8%**	**6.85**	6.85	**67.8%**	**4.48**	kWe
Isp		**4116**	4116		**4045**	sec
thrusters on at Mars					**2.0**	-

Solar Electric Propulsion Results

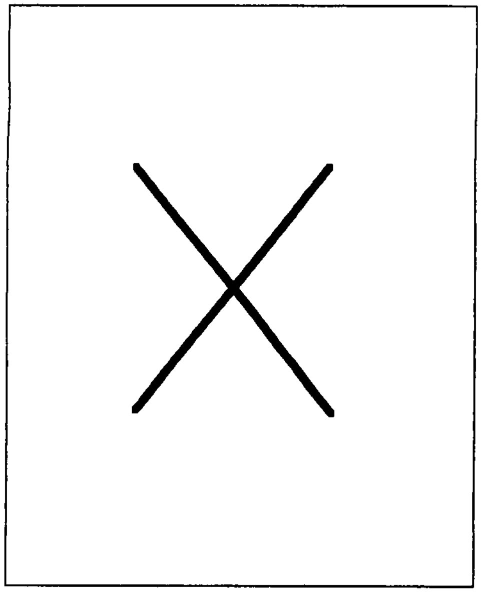
Mars Sample Return Mission

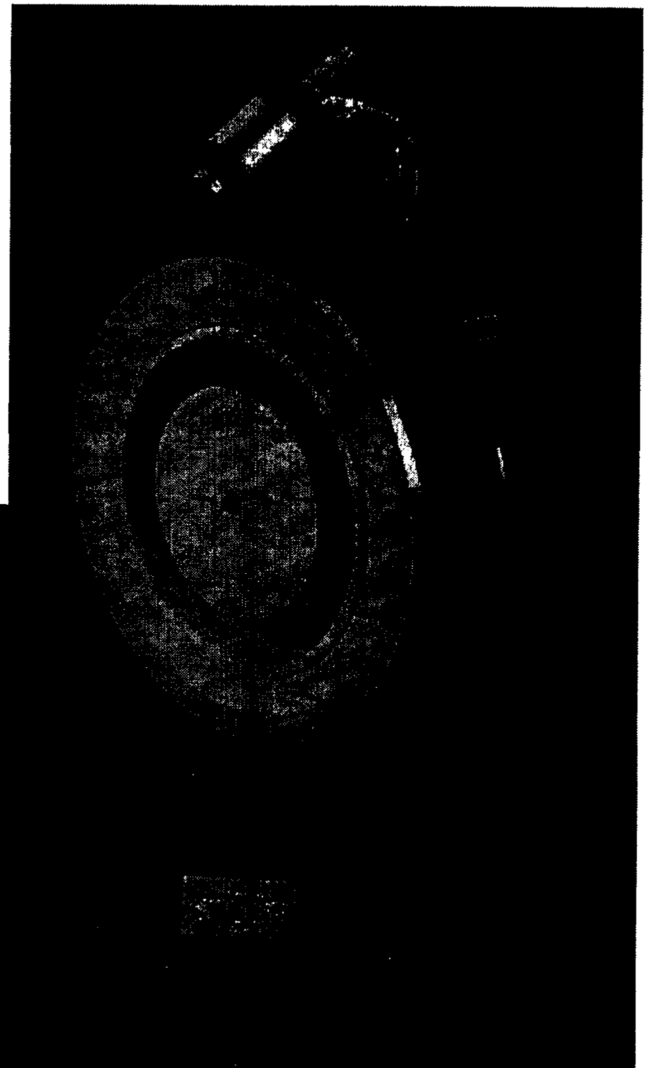
SEP Data Set 4:

1. Lander Direct Entry
2. Po = 22 kW at 1 AU
3. 2 x 10 kWe HALL thrusters
4. 3 launch vehicles: Atlas-V 431, Delta-IV 4450 & 4240

Hall Effect Thruster Technology

10 kW T-220 Pratt & Whitney





10 kW NASA-173 v2 GRC

- Electrostatic acceleration of xenon ions to produce thrust
- Version (T-220) achieved 1000-hrs life test at high power. (> 4.5 kWe) (GRC 2000 vacuum facility 12)
- Using “NASA-173 v2” GRC Hall thruster in analyses

9.95 kWe Max Power (“10 kW”)

- 3350 sec Isp at Max Power
- 0.609 % efficiency at Max Power
- 22.3 kg mass
- Current Hall thrusters of up to 100 kWe currently under development.

SEP MSR Hall Thruster Preliminary Weight Statement

SEP Data Set 4: Po=22 kWe, 2 x 10kW Hall Thrusters, Delta-IV 4450
Lander Direct Entry Mode, 1200 kg Lander dropped at Mars C3=0

10 kW HALL THRUSTER SEP WBS **Revison 1**
Mars Sample Return **4-Nov**

		Unit kg	Margin	Total kg
1	**Power Gen**	**103**	30%	**133**
2	**Power Distribution**	**29**	30%	**38**
3	**Propulsion**	**185**	30%	**241**
4	**Tankage & Feed Sys**	**81**	30%	**106**
5	**Thermal Control**	**31**	30%	**40**
6	**Structure**	**103**	30%	**134**
7	**Mechanisms**	**15**	30%	**20**
8	**Adapters**	**38**	30%	**49**
9	**ACS**	**33**	30%	**42**
10	**Other**	**9**	30%	**12**
11	**Telecom, C&DH**	**32**	30%	**42**
12	**GN&C**	**20**	30%	**26**
13	**Other**	**18**	30%	**23**
14	**Rendezvous Instr Suite**	**40**	30%	**52**
15	**Reserves**			**100**
16	**Propellant Inbound**			**276**
17	**Rendezvous**			**9**
18	**Outbound**			**725**
19	**Payload Outbound**			**1,128**
20	**Inbound**			**77**
21	**Launch Mass**			**3,272**

4450	Launch Vehicle
10.57	Earth Depart C3
1.29	E-Mars Trip Time (y)
1.13	Mars-E Trip Time (y)
22.0	Array Power (kW)
10.59	PPU Max (kW)
0.94	PPU Eff (%)
9.95	Thruster Max (kW)
0.61	Thruster Eff (%)
2	Thrusters
3380	Isp (sec)
815	**STG MASS**
143	**ORBITER RELATED**
1,058	**INB BURNOUT**
1,343	**OUTB BURNOUT**
2,067	**WET MASS**
1,204	**PAYLOADS**
3,272	**LAUNCH**

Preliminary Data

SEP MSR with Hall Thrusters: Power Budget Page

SEP Data Set 4: Po=22 kWe, 2 x 10kW Hall Thrusters, Delta-IV 4450

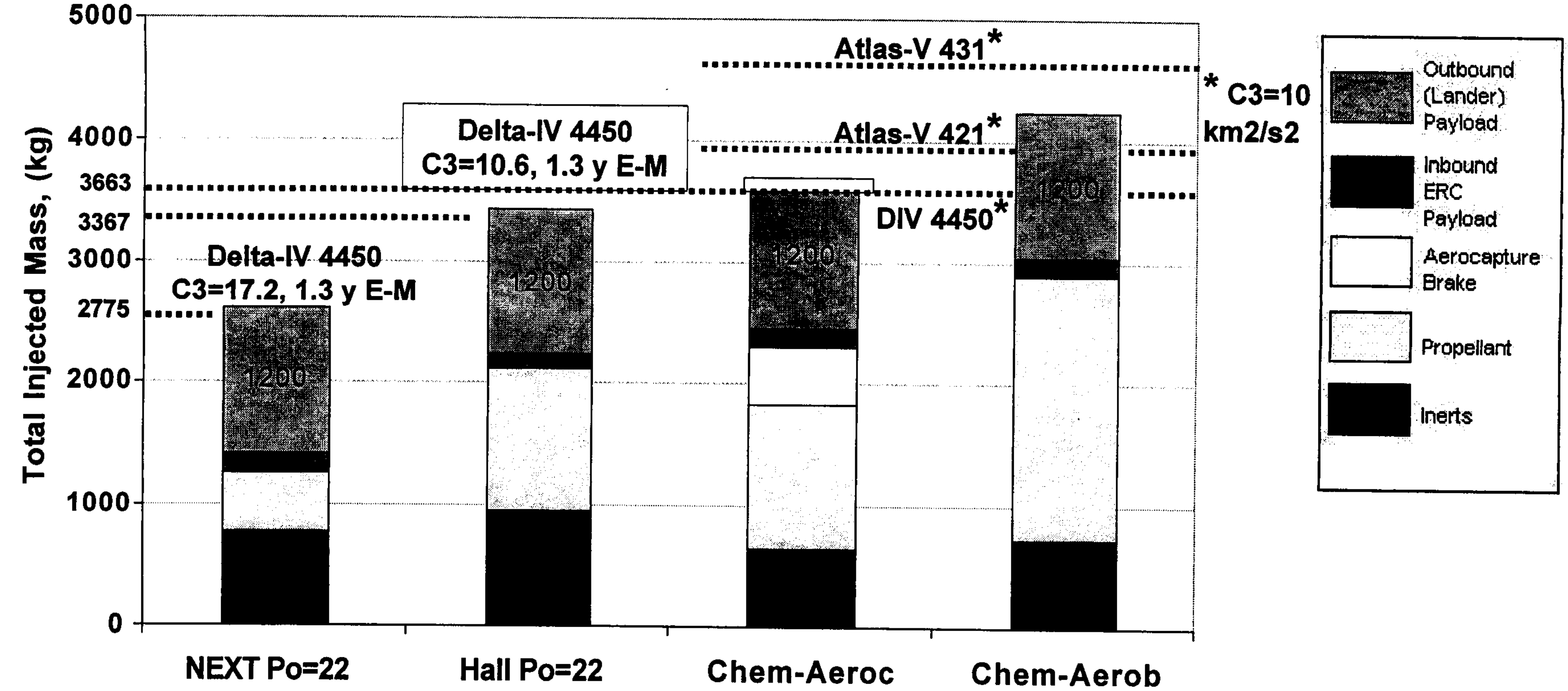
Power budget:		**Earth**	Venus		**Mars**	
AU **- array -**		1.00	0.73		**1.50**	-
Sunlight Intensity	**margin**	**1,358**	2,584		604	W / m2
Array Area with Margin	**10%**	**77.5**	77.5		**77.5**	m2
Array Area Required		**70.4**	70.4		**70.4**	m2
Array Power for Costing	**cell eff**	24.2				kWe
Array Power	**23.0%**	**22.0**	41.9	**23.0%**	**9.78**	kWe
- Po into IPS -						
Housekeeping Power		**0.25**	0.25		**0.25**	kWe
Power Feathered	max allowed	**0.47**	20.3		**0.0**	kWe
Act max power IPS	**25.0**	**21.28**	**21.28**		**9.53**	kWe
cable to ppu	**99.5%**	**21.17**		**99.5%**	**9.48**	
- into PPU and Thrusters-			94.0%			
Act max into PPU's	**94.0%**	**21.17**	**21.17**	**94.0%**	**9.48**	kWe
cable to thruster	**100.0%**	**21.17**		**100.0%**	**9.48**	
Act max Po Thrusters	**60.6%**	**19.90**	19.90	**59.5%**	**8.91**	kWe
Thrust total		0.73	0.73		0.36	N
Jet Power Total		12.1	12.1		5.3	kWt
PPU Waste Heat		1.27	0.64		0.57	kWt
Individual budget:						
PPU Power	**94.0%**	**10.59**	10.59	**94.0%**	**9.48**	kWe
Oper Po per Thruster	**60.6%**	**9.95**	9.95	**59.5%**	**8.91**	kWe
Isp		**3380**	3380		**3001**	sec
thrusters on at Mars					**1.0**	-

MSR: SEP NEXT & HALL vs Chem Aerocapture vs Aerobrake

Total Injected Mass vs Propulsion Technology

LANDER DIRECT ENTRY

Given 1200 kg Outbound P/L, 150 kg Inbound P/L, Solve for Injected Mass*



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Conclusions

The Mars Sample Return Mission is a key component of NASA Mars missions Plans. MSR follows rover missions, and is a precursor to Human Mars missions.

Variety of in-space propulsion systems and missions modes were evaluated

Aerocapture and Solar Electric Propulsion options can provide key missions benefits at the cost of new technology development.

On going and future studies will provide more definition into the overall picture for Mars Sample Return missions in particular and other, more ambitious Mars missions on the planning horizon.