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Enceladus Clipper

Professor Dan Goebel- MAE 161C
Team 4: Cole Bramante, Isabel Catalano, Mohamed Elshal, Haniah Hamza, Anli Liu, Serena Nathan, Aidan Scott, Alexander Wu

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Spacecraft + Mission Overview

Team 4

Systems Engineer- Haniah Hamza

Mission Planning/ Trajectory- Aidan Scott

Payload- Serena Nathan

Power- Alexander Wu

Propulsion- Mohamed Elshal

Thermal- Isabel Catalano

ACS + Communication- Anli Liu

Structures- Cole Bramante

Mission Objectives

Level 1	● Return sample from water jets by Enceladus ● Perform high-res imaging of Enceladus surface to support site selection for future lander
Level 2	● Launch in 2032 ● Mission Duration 12-15 years ● Orbit Saturn with Enceladus flybys ● Survive radiation and extreme temperatures of Saturn system ● Entry velocity <12 km/s ● Communicate with DSN Network on 34 m antennas ● Return >=1 gram water sample ● Mass spectrometry of plume particles/gases ● Photograph Enceladus surface ● Minimize needed propellant mass ● Minimize needed gravity assists

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Mission Objectives

Level 3	● Infrared spectrometry of Enceladus ice surface, map thermal emissions, and surface mineralogy ● Utilize TAGSAM for sample collection ● Utilize Stardust ERV with ablative heat shield and parachute recovery system ● Safely land ERV at UTTR West Desert (South range) during Fall ● Utilize guided control with assisted optical navigation ● QPSK modulation scheme with bit error < 10^-5 ● Redirect RTG thermal radiation to keep instrumentation at operable temperatures at Saturn ● Perform 3-5 flybys of Enceladus for sample collection

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Preliminary Trajectory

Dr. David Oh's Low-thrust Transfer Model: Earth to Saturn SOI

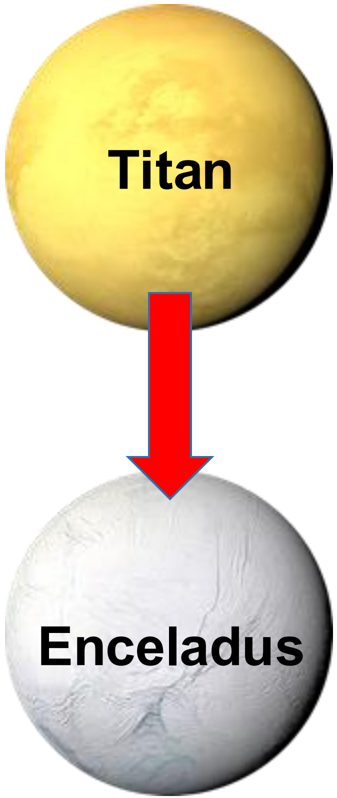
Inputs	
Time of Flight [yr]	5.8
Launch C3 [km^2/s^2]	125
Input Power [kW]	1.5
Thruster Efficiency	0.7
S/C Wet Mass [kg]	3200

Outputs	
Optimal I_{sp} [s]	2718
Mean acceleration [$km/s^2/yr$]	2.934
Burn time [yr]	5.51
Adjusted mean acceleration [$km/s^2/yr$]	0.397
Δv [km/s]	2.189
Optimal effective exit velocity [km/s]	1.095
Propellant mass [kg]	252.4

Preliminary Trajectory

Trajectory within Saturn SOI (Enceladus Flybys)

- DSM performed to change parabolic arrival from Saturn SOI to Titan
- Two Titan gravity assists are performed to lower orbital specific energy
    - First gravity assist off Titan: Δv=1.759 km/s
    - Second gravity assist off Titan: Δv=1.184 km/s
- Burn at apoapsis targeting Enceladus at periapsis: Δv=0.536 km/s
- Burn at Enceladus lowering apoapsis for timely flybys: Δv=0.692 km/s
- 5 flybys of Enceladus follow
- Assuming identical trajectory to escape Saturn:
    - Total time in Saturn SOI: 1.36 years
    - Total propellant Δv needed: 2.6 km/s



Preliminary Trajectory

Dr. David Oh's Low-thrust Transfer Model: Saturn to Earth

Inputs	
Time of Flight [yr]	7.80
Launch C3 [km^2/s^2]	0
Input Power [kW]	1.5
Thruster Efficiency	0.7
S/C Wet Mass [kg]	2947

Outputs	
Optimal I_{sp} [s]	809.9
Mean acceleration [$km/s^2/yr$]	1.473
Burn time [yr]	7.41
Δv [km/s] (Assumes planetary gravity assists give 5 km/s)	5.913
Optimal effective exit velocity [km/s]	0.457
Propellant mass [kg]	320.3

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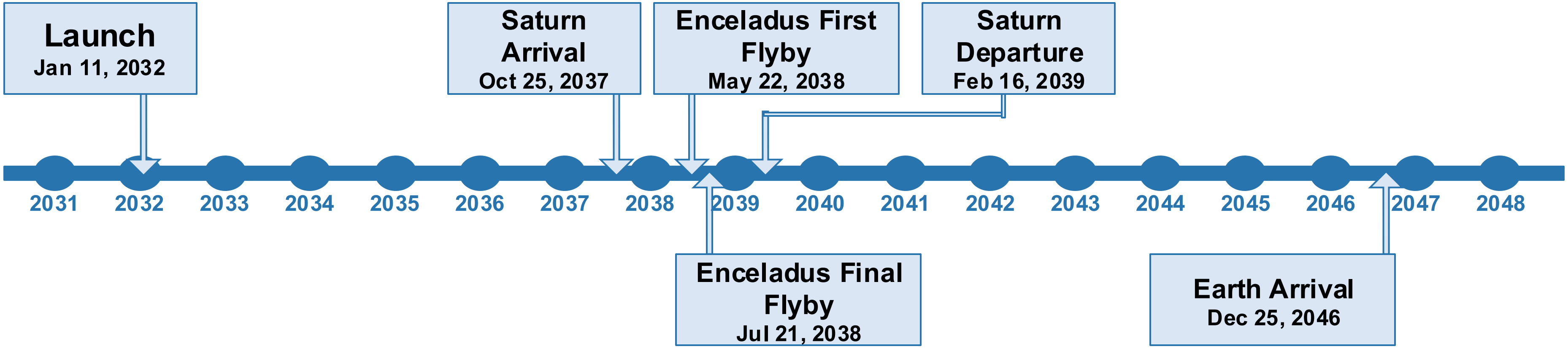
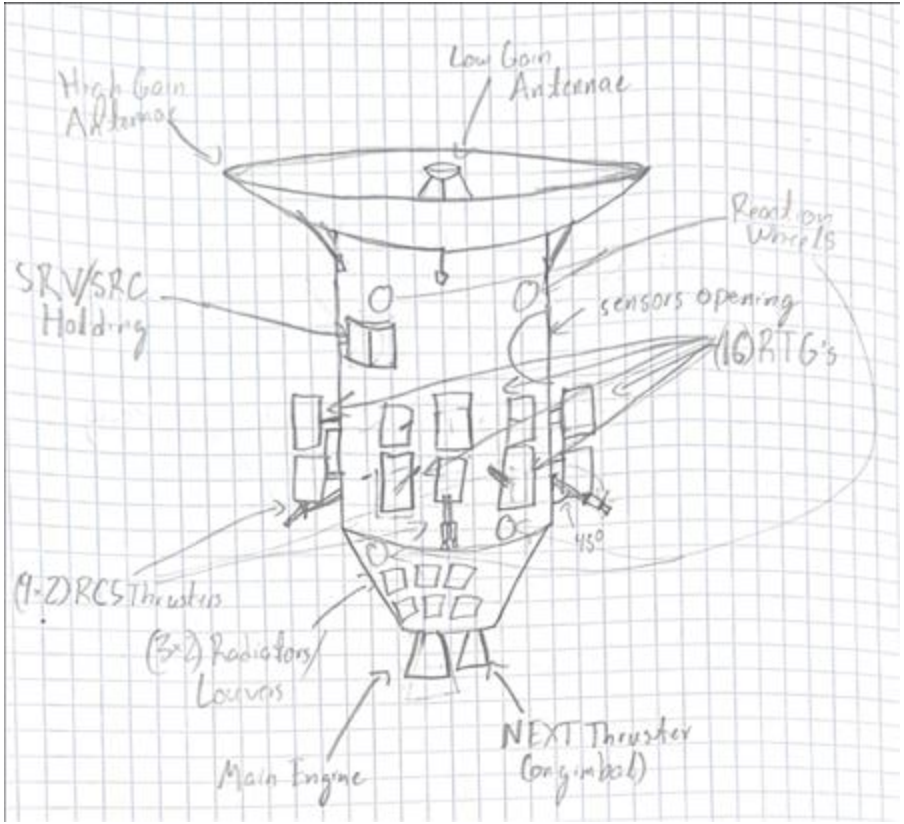
Trajectory Timeline

Total Mission Duration	14.96 years
Estimated Propellant Δv Required	5.70 km/s



General Design



Propulsion Trade Study

Candidate Architecture

Metric	All-Chemical	Electric Propulsion (EP)	Nuclear-Electric Propulsion (NEP)	Solar Sail
Thruster	Storable biprop (Hydrazine/NTO, Isp = 320 s) or cryogenic LOX/LH2 (Isp = 450 s)	Hall/ion engine (Isp=3000 - 4000 s); PPU =1.5 - 5 kW	Ion engine (Isp=6000 s); power from small fission reactor (Kilopower)	Sail area will be huge to generate 1mN of thrust at Saturn
Pros	High-thrust for all maneuvers; mature TRL = 9	Low propellant mass (<20%); high Isp; mature (NEXT Isp = 4100 s has flown in test)	Very low propellant mass (<10%); moderate thrust	Zero propellant; continuous thrust
Cons	Very high propellant fraction (75 - 85%) >> little margin for structure & payload	Low thrust (200 mN), requires years of continuous thrust; power system mass; solar arrays at 10 AU are huge or must use RTG.	Reactor mass (1 500 kg), low TRL (3 – 4), cost and safety risk	Ultra-low acceleration, very long cruise times; complex attitude control; deployment risk.

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Propulsion Trade Study

Recommended configuration: Hybrid (NEP + Chemical)
Cruise burns (Earth ⟺ Saturn): NEP (Isp around 4100 s, PPU = 1.5 kW).
Propellant: Xenon
RTGs to supply continuous power

Periapsis burns (Titan, Enceladus insertion/escape): Small biprop system (Isp around 320 s) sized for Dv_total = 2.6 km/s

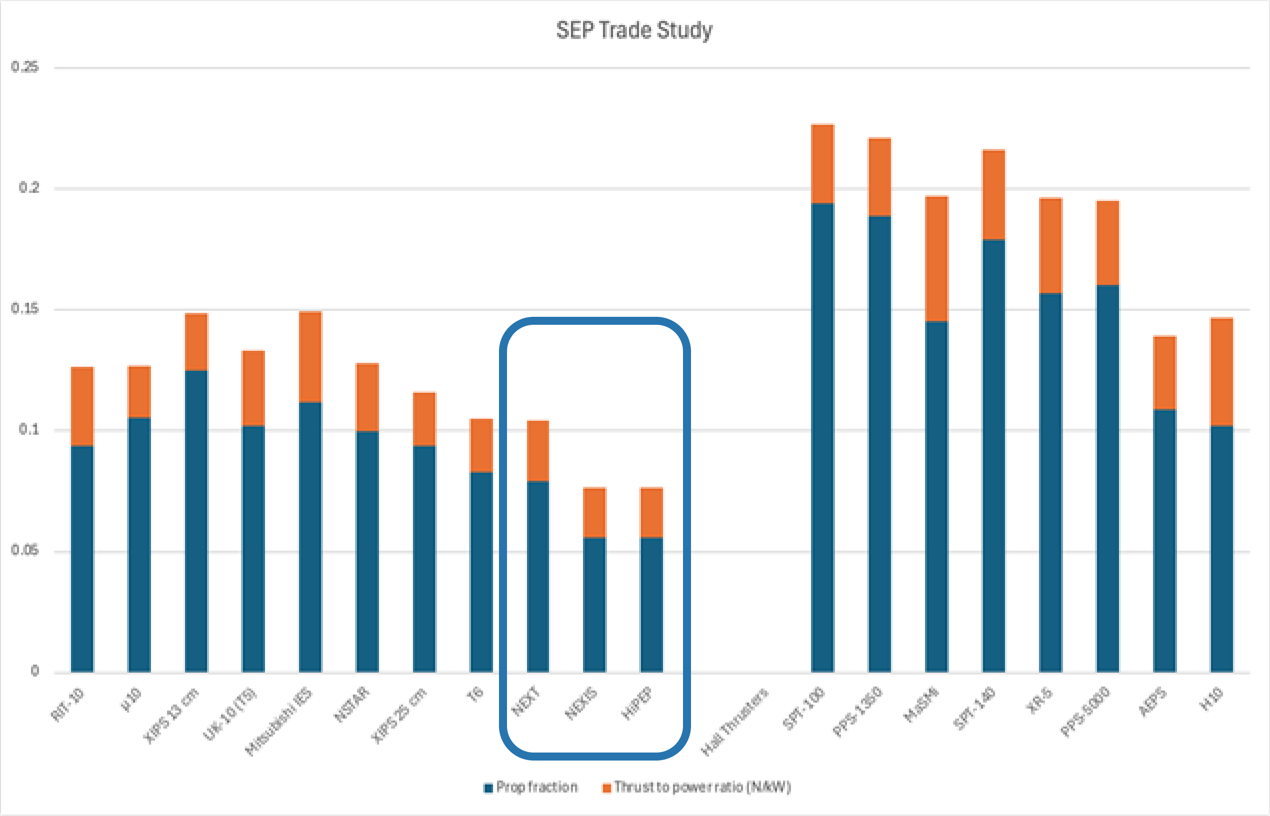
Estimated structural dry mass + instruments: = 1676 kg

Total wet mass: 2049 at launch → compatible with a medium-class launcher (e.g., Falcon Heavy).

NEP Trade Study

Next Thruster stands out by having low prop mass fraction (about 8%) and still delivering respectable thrust-to-power ratio (0.025 N/kW), and both thruster and PPU masses are moderate.

(12.4, 24 kg respectively)



Chemical Trade Study

Similar to SEP, Trade study has been done on various types of chemical prop systems
Among Liquid Bi-prop, Hypergolic, Solid rocket motor engines >> best option was Hypergolic bi-prob R-4D engine due it’s low propellant mass, high Isp and very low power consumption.

Hypergolic Thrusters	Propellants	Isp (s)	Thrust (N)	Mass (kg)	Power (kW)
R-4D	MMH/NTO	312	490	4.5	0.1
AJ10-190	MMH/NTO	319	26700	120	1
MR-104	MMH/NTO	220	4.4	1.2	0.1

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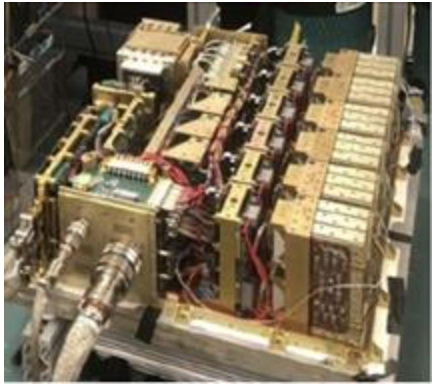
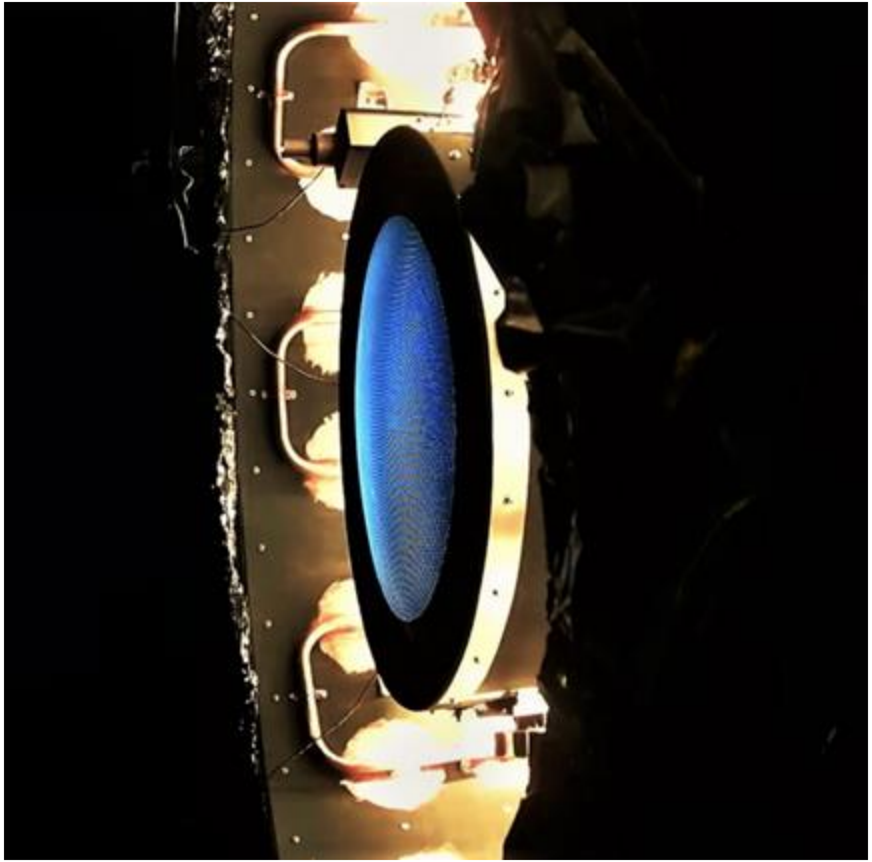
Chosen NEP Engine

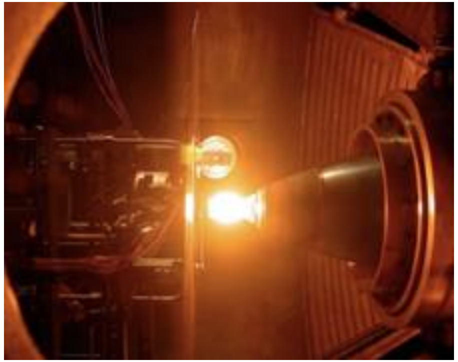
Thruster: Next-C
Propellant: Xenon, mp = 161 kg
mass fraction = 0.08
power: 6.9 kW
Thrust: 0.235 N
Thruster mass: 12.4 kg
Thruster eff: 0.70
PPU mass: 24 kg
PPU eff: 0.94
Isp: 4190 s, Dv = 3.5 km/s

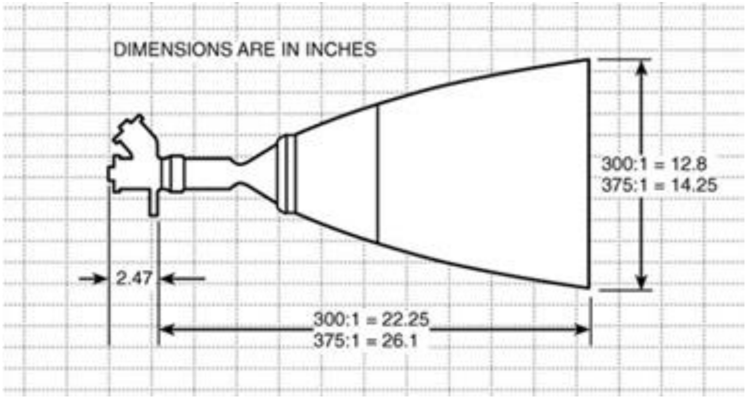




Chosen Chem Engine

Thruster: R-4D 15 HiPAT
Propellant: MMH/NTO, mp = 1172 kg
mass fraction = 0.57
power: 0.1 kW
Thrust: 490 N
Thruster mass: 4.5 kg
Isp: 312 s
Dv = 2.6 km/s





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ACS AUX thrusters

Performed trade study on different ACS thrusters, prioritized Thrust, Isp for faster slew or larger spacecraft. MR-111G engine fit these categories.

MR-111G 4N (8X)
Propellant: hydrazine monopropellant.
Mass: 0.37 kg (includes engine, valves, and heaters)
Isp: 219 to 229 s
thrust: 1.8 to 4.9 N (steady state).

Subsystem Overviews

Payload Instruments

Dust Analyzer

Why Chosen: Essential for assessing environmental hazards during proximity operations and identifying compositional variations.
Trade-offs: Moderate mass/power load; sensitive to high-velocity particle impacts.
Alternatives: Optical dust counters (lower mass, no compositional data); passive collectors (no in-situ readings).

Mass Spectrometer

Why Chosen: High-precision, direct compositional analysis; space-proven (e.g. Rosetta).
Trade-offs: High power consumption; requires vent proximity for best results.
Alternatives: Tunable laser spectrometers (lighter, narrower range).

Infrared Spectrometer (IR)

Why Chosen: Detects water/CO_2 ice, organics, and thermal anomalies.
Trade-offs: Needs calibration/cooling; sensitive to thermal drift.
Alternatives: Multispectral imagers (broader bands, lower spectral detail).

Payload Instruments

Visible/Near-IR Camera

Why Chosen: Proven, low-power, high-resolution imaging with filter flexibility.
Trade-offs: No compositional data; dependent on lighting.
Alternatives: Hyperspectral imagers (adds mass, higher data rates).

Optical Sensor / NavCam combination

Why Chosen: Multipurpose, flight-proven, consolidates navigation and imaging.
Trade-offs: Higher data rate and integration complexity.
Alternatives: Separate dedicated systems (increased redundancy, higher mass).

Ice-Penetrating Radar Sounder

Why Chosen: 3D subsurface ice mapping, vital for site selection.
Trade-offs: High power/data demands; clutter near surface features.
Alternatives: Surface-penetrating LIDAR (shallower, lower resolution).

Payload Sample Collection + ERV

Sample Collection & Return Payload

- **TAGSAM (Touch-and-Go Sample Acquisition Mechanism)**
  - Quick regolith/dust collection using a burst of nitrogen gas
  - Proven on **OSIRIS-REx**
  - Simple, low-risk, minimal contact time
- **SRC based on Stardust Sample Return Capsule (SRC) / OSIRIS-REx Sample Canister**
  - Secure containment of collected material
  - Proven safe reentry and recovery design
- **Stardust Sample Return Vehicle (SRV)**
  - Heatshield-equipped return capsule with parachutes
  - Adapted from Stardust, OSIRIS-REx heritage
- **406 MHz UHF Locator Beacon (ELT)**
  - Activates on landing for capsule recovery
  - Standard, low-power, reliable heritage system

Payload Sample Collection + ERV

Trade-offs

- **TAGSAM**
  - ✅ Proven and simple
  - ❌ Limited to surface dust and regolith
- **Alternatives**
  - *Coring drill*: deeper sampling but complex and heavy
  - *Sticky pads/Aerogels*: great for micro-particles, not bulk material
  - *Scoop*: simple but contamination risk and inefficient for fine dust

Vapor Collection

- **Not optimal with TAGSAM** — designed for particulates
- **Alternatives (not selected)**:
  - Cryotrap canisters
  - Aerogel vapor absorbers
  - Sealed quick-close samplers
- **Reason not chosen**: added mass, risk, and complexity

Payload Sample Collection + ERV

Heritage Data

- **Stardust (2006)**: Successful comet dust return
- **Genesis (2004)**: Solar wind collection, parachute failure
- **OSIRIS-REx (2023)**: Asteroid regolith return using TAGSAM & SRC

Downsides

- Sample quantity limit (hundreds of grams)
- No vapor containment — volatiles lost post-collection
- Risk during Earth reentry (parachute or landing site issues)
- Telemetry blackout during reentry — reliant on ELT beacon for recovery

Payload Sample Collection + ERV - Water Vapor Capture in TAGSAM — Integration Concept

How?

- Integrate passive Zeolite 13X pouches or porous panels inside the TAGSAM collection head.
- Position along interior walls, away from regolith collection path and nitrogen jets.
- Adsorbs water vapor during sampling event, prior to sealing and return.

Post-Return

- Retrieve sorbent pouches in curation facility.
- Heat to release trapped vapor for isotopic and compositional analysis.

Advantages

- Proven material (ISS, Shuttle)
- No power, minimal mass
- First-of-its-kind volatile capture for asteroid sample return

Power

Trade study, assuming ~2kW power generation at BOM

	ROSA	ASRG	Kilopower
Power Degradation (Pct./Yr)	2.70	1.40	**Negligible**
W_e/Kg - Launch	**250.00**	4.00	2.50
W_e/Kg - Enceladus	2.36	**3.69**	~2.50
Stowed Volume (m^3)	3.10	**2.20**	4.52
Heat Generation (W_t)	**Variable**	8192	8000

Selection Criteria:

- Specific Power (W_e/kg)
- Degradation constant
- Thermal output

ASRG provides superior specific power at Enceladus, where power needs are greatest.

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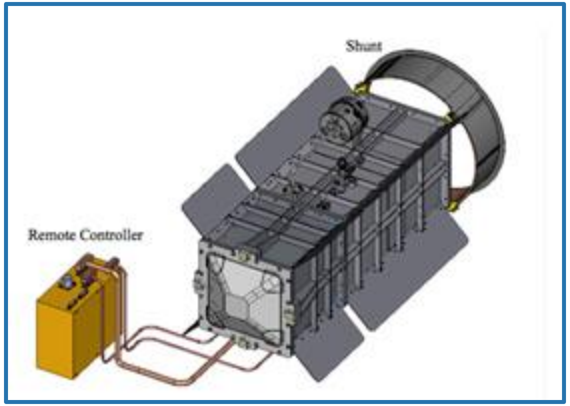
Power

Power system: Advanced Stirling Radioisotope Generator (ASRG)

Specifications	
Quantity	**16**
BOM Output (W_e)	**2048.0**
EOM Output (W_e)	**1658.4**
Mass (kg)	**512.0**
Volume (m^3)	**2.2**
BOM Heat generation (W_t)	**4096.0**
EOM Heat generation (W_t)	**3316.7**



Length: **76.2 cm** Width: **39.4 cm** Height: **45.7 cm**

Concerns:

- Heat Dissipation
- Radiation Shielding
- Novelty

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Power

Secondary Battery: ABSL 8s16p Li-ion Battery

Specifications	
Capacity	**56 A-h**
Energy	**1628 Wh**
Max. Current	**25 A**
Mass	**7.8 kg**
Nominal Voltage	**29V**

Length: **36.4 cm** Width: **20.3 cm** Height: **9.8 cm**

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Thermal

Multi-Layer Insulation (MLI):

- Application: covers surface area of spacecraft (excluding the antenna) to protect from extreme temperatures of the space environment
- Requirements: spacecraft temperature must stay between 273.15 K (0 ℃) and 313.15 K (50 ℃)
- Material:
  - Outer Layer: Black Kapton (BK), carbon filled
    - Thickness: 1 mil
  - Middle Layers: 24 layers of Embossed Kapton (EK), aluminized on both sides
    - Thickness: ⅓ mil each
  - Inner Layer: Aluminized Kapton (AK), aluminized on both sides
    - Thickness: 1 mil

Thermal

Multi-Layer Insulation (MLI):

Layup	Allowable Temperature Range (°C) Continuous	Intermittent
1. SSAK+EK	-184 to +149	-184 to +260
2. BKn+EK	-184 to +149	-184 to +260
3. SSAK+MN	-251 to +121	max 220
4. BKn+MN	-251 to +121	max 220
5. BK+EK	-251 to +288	-251 to +399

Data Sources: DuPont Technical Information Bulletins; Sheldahl Red Book, Rev. 7/89; and past JPL tests.

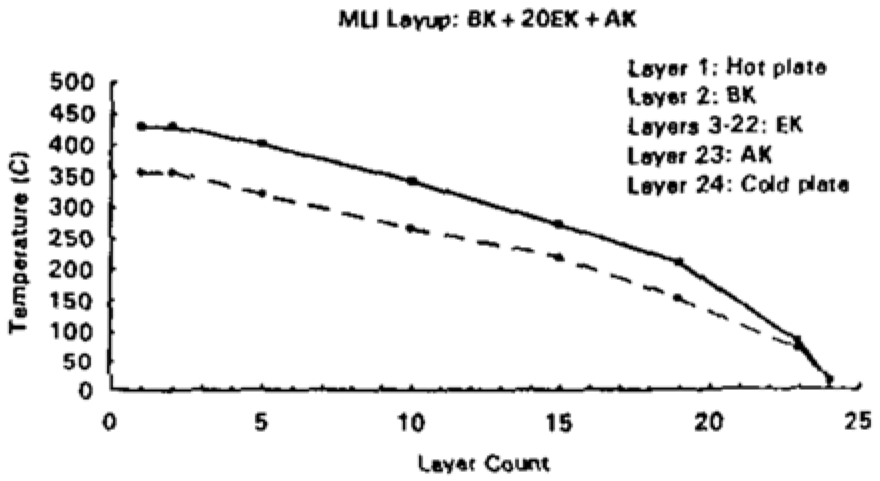

Fig. 7 Steady State Temperature Profiles Across the High-Temperature Layup

Reference: : Lin, Edward, and James Stultz. "Cassini MLI Blankets High-Temperature Exposure Tests." 33rd Aerospace Sciences Meeting and Exhibit, 9 Jan. 1995, https://arc.aiaa.org/doi/pdf/10.2514/6.1995-633

Thermal

Radiators:

- Application: Radiates additional heat generated inside the spacecraft; always faces free space
- Material: 6061 Aluminum with Teflon coating
  - Thickness: 2.5 mm
  - 6061 Aluminum chosen for high strength to weight ratio (115 kN-m/kg)

Louvers:

- Application: Covers exposed radiator surface
- Material: 6061 Aluminum
  - Dimensions: 0.3 m by 0.6 m

Thermal

Summary of Absorptivity and Emissivity

	MLI Outer Layer	Radiators	Open Louvers	Closed Louvers
Absorptivity	0.92	0.15	0.24	0.03
Emissivity	0.80	0.85	0.65	0.15

Thermal

Thermal Energy Balance

Temperature Requirements: 273.15 K (0 ℃) to 313.15 K (50 ℃)

Solar Radiation (W)	Albedo Radiation (W)	S/C Power (W)	Required Radiation Output (W)
379.1	28.4	426.5	834.0

Required Area: 2.5 m^2 and 14 louvers

	Minimum Temperature	Maximum Temperature
Open Louvers	2.4 m^2	4.1 m^2
Closed Louvers	10.2 m^2	17.6 m^2

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Attitude Control Systems

Star Trackers- 2 Hydra Star Trackers from Sodern

- Chosen for high accuracy attitude sensing; deep space heritage
- 2 optical heads, 1 ECU
- tradeoffs: sensitive to sunlight, high mass/power
- Alternatives: horizon sensors or coarse sun sensors

Reaction Wheels- 4 HR12 Reaction wheels from Honeywell

- Chosen for precise 3 axis control, 4 reaction wheels for redundancy
- Tradeoffs: only small maneuvers or corrections
- Alternatives: to use thrusters for higher thrust maneuvers

Digital Sun Sensors

- reliable sun vector, low power
- tradeoffs: need sun visibility
- alternatives: star trackers

Inertial Measurement Unit- LR450 from Northrop

- accurate inertial data during outages/eclipse, proven heritage, includes gyroscopes&accelerometers
- tradeoffs: may be influenced over time- may need correction from star trackers
- alternatives: individual gyroscopes or less precise IMUs

Communications

Band	Direction	Frequency	Use Case	Mission Context
Ka-band	Downlink	31.5-32.5 GHz	High-rate science data during Saturn orbit and Enceladus flybys	Large data volumes from plume sampling and surface imaging; use when HGA is pointed to Earth
X-band	Downlink	8.2-8.6 GHz	Engineering telemetry, contingency data return, and safe-mode backup/redundancy	Trajectory towards Enceladus, flyby attitude constraints, or Ka-band unavailability
X-band	Uplink (HGA)	7-7.5GHz	Primary command uplink via DSN 34m antennas, use LGA for emergency/safe-mode	Reliable TT&C during cruise to Enceladus, Saturn orbit, flybys, and Earth reentry prep
X-band	Downlink (LGA)	8.4 GHz	Safe-mode or degraded attitude communication/ redundancy	Critical for recovery after anomalies or during cruise anomalies

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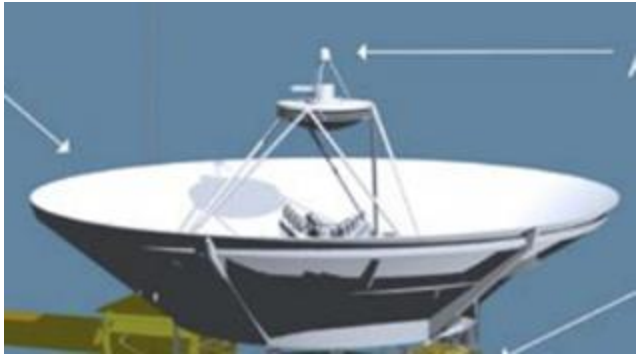
Communications

- Very high prop loss at Enceladus
  - low bandwidth of .1 MHz
  - SNR ~ 11 dB
- 4m diameter HGA
- Smaller LGAs needed to communicate- x band only
- Downlink
  - 200 kbps data rate
  - primarily during scientific research at Enceladus
- Uplink
  - error rate ~ 4*10E-8
  - primarily to HGA, use LGA in safe mode or low data mode
- safe mode and low data mode to be primarily used on trajectory to Enceladus



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Main Structural Material

Using Aerospace Grade Aluminum due to high strength to weight ratio, ability to withstand temperature, and legacy

Alloy	2024	2014	7068
Tensile Strength, Yield	310 MPa	270 MPa	590 MPa
Fatigue Strength	140 MPa	140 MPa	130 MPa
Advantages	- High Tensile Strength - Highest fatigue resistance - Most related legacy	- Easiest to work with	- Highest Tensile Strength
Disadvantages	- Not the easiest to work with or the highest tensile strength	- Lowest Tensile Strength	- Hardest to work with

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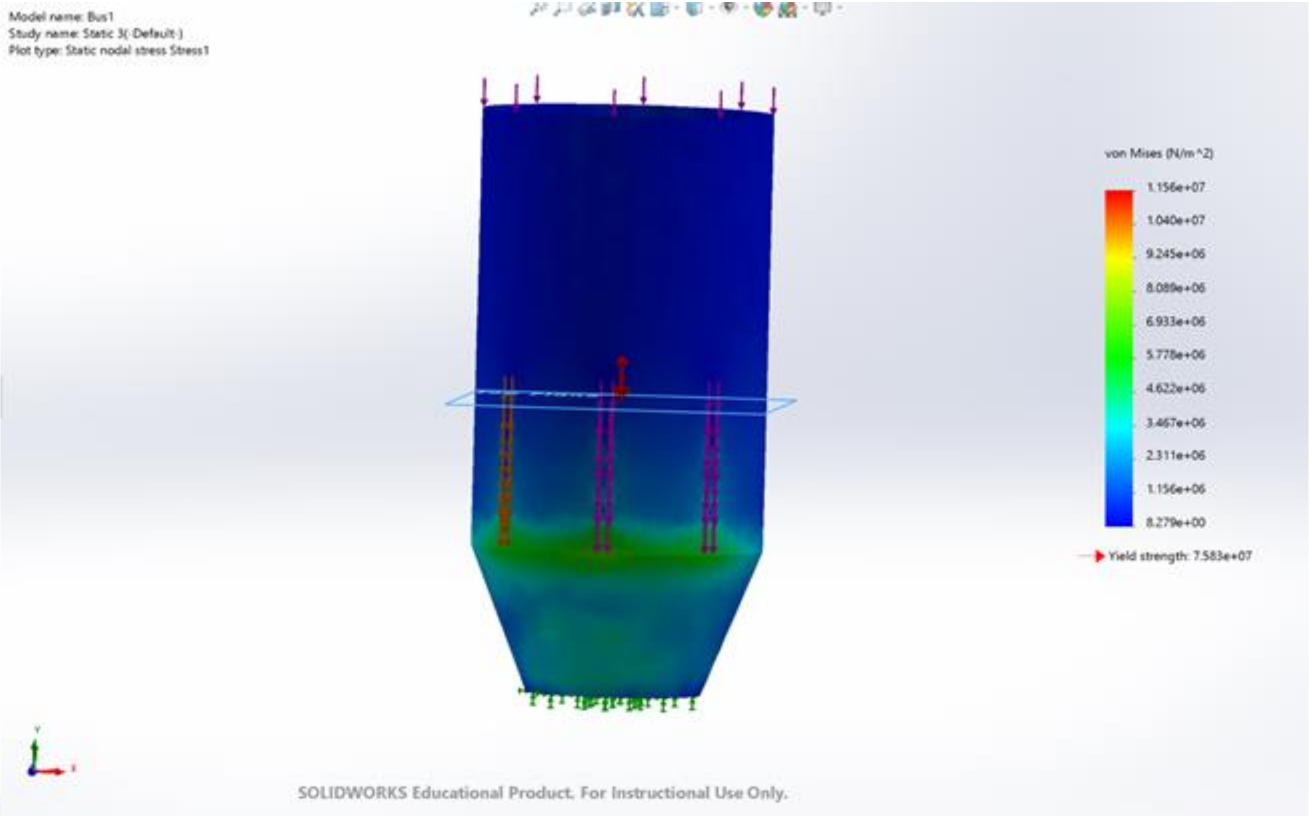
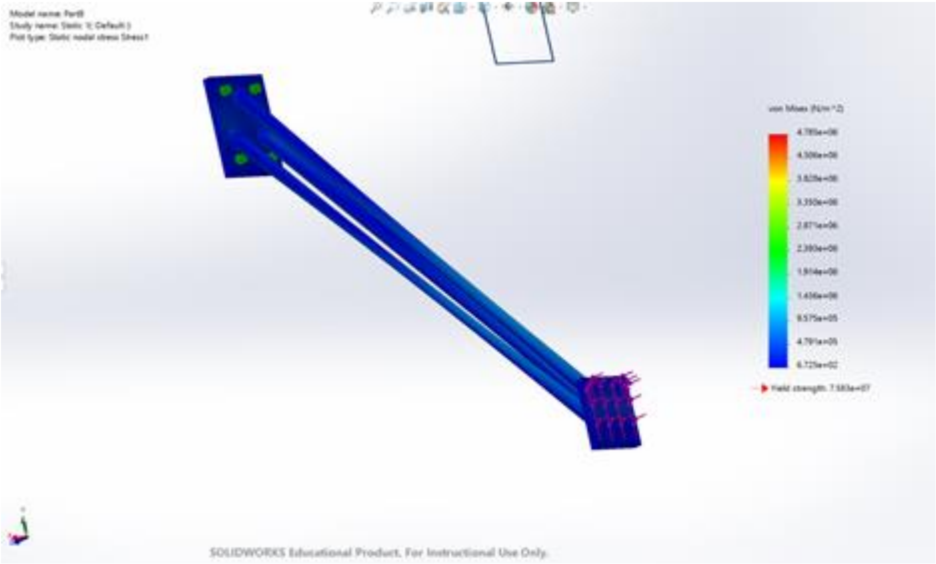
Bus Stress Test (Max Acceleration Launch)

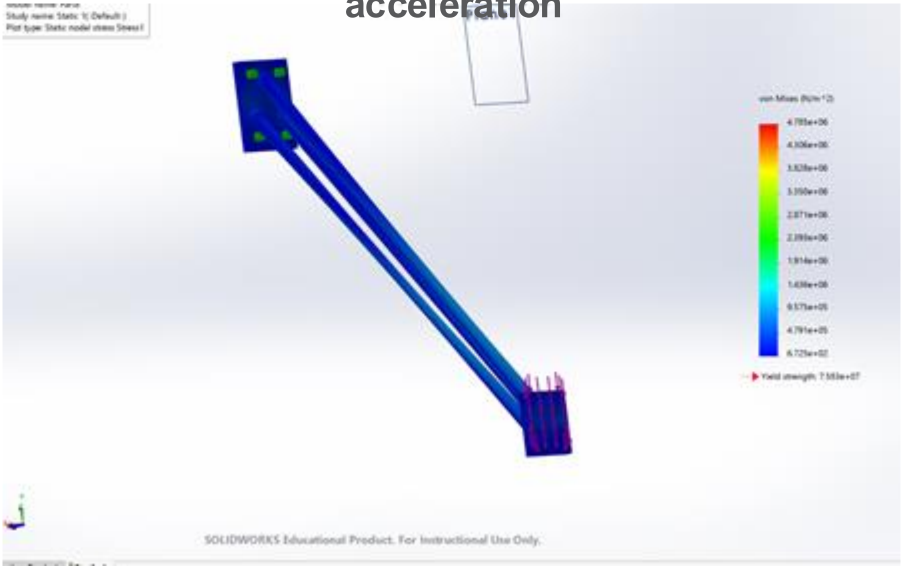


RCS Thruster Arm Stress Test

Simulation under full thruster load



Simulation under full gravitational load of thruster at maximum thrust acceleration



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Summary + Limitations

Master/Mass Equipment List (MEL)

Mass Equipment List (MEL) Launch Vehicle: Falcon Heavy (Expendable)	CBE [kg]	Contingency [%]	MEV [kg]
Total Spacecraft (Wet)	**3274.65**	**18.27%**	**3872.78**
Xenon propellant	161	20.00%	193.2
MMO/NTO Propellant	1172	20.00%	1406.4
Pressurant (He)	15	10.00%	16.5
Total Spacecraft (Dry)	**1926.65**	**17.13%**	**2256.68**
Payload	**118**	**17.42%**	**138.55**
Dust Analyzer	12	15.00%	13.8
Mass Spectometer	18	15.00%	20.7
Infrared Spectrometer (IR)	14	15.00%	16.1
Visible/Near-IR Camera	8	15.00%	9.2
Ice-Penetrating Radar Sounder	25	15.00%	28.75
Stardust Sample Return Capsule (SRC) or OSIRIS-REx Sample Canister	5	30.00%	6.5
TAGSAM (Touch-and-Go Sample Acquisition Mechanism)	4	30.00%	5.2
Stardust Sample Return Capsule (SRV)	30	20.00%	36
406 MHz UHF Locator Beacon (Emergency Locator Transmitter)	2	15.00%	2.3
Power	**569.8**	**24.49%**	**709.36**
16x Advanced Stirling Radioisotope Generator (ASRG)	512	25.00%	640
Li-ion Rechargeable Battery	7.8	20.00%	9.36
Power Connversion & PPU	50	20.00%	60
Cabling	57	20.00%	68
Propulsion	**275**	**13.45%**	**312**
NEXT thruster + gimbal	25	20.00%	30
Xenon tank + feed system	10	15.00%	11.5
Main engine (445 N class)	100	15.00%	115
Auxiliary thrusters (8X RCS)	30	15.00%	34.5
Propellant tanks	60	10.00%	66
Feed system & valves	50	10.00%	55

Mass Equipment List (MEL) Launch Vehicle: Falcon Heavy (Expendable)	CBE [kg]	Contingency [%]	MEV [kg]
Communication	**118.55**	**10.00%**	**130.405**
LGA 30 GHz antenna	0.05	10.00%	0.055
40 GHZ reflector	12	10.00%	13.2
HGA 4m diameter	100	10.00%	110
traveling wave tube amplifier	1.5	10.00%	1.65
ka band deep space transponder	3.2	10.00%	3.52
ultra stable oscillator	1.8	10.00%	1.98
Thermal	**106**	**10.00%**	**116.6**
MLI Thermal Blankets	21	10.00%	23.1
Louvers	17.5	10.00%	19.25
Radiators (Carbon-Carbon Composite with teflon finish)	67.5	10.00%	74.25
Attitude Control System	**39.3**	**13.91%**	**44.765**
star trackers	6.7	15.00%	7.705
reaction wheels	24	15.00%	27.6
Internal measurement unit	4.6	10.00%	5.06
digital sun sensors	4	10.00%	4.4
Structural	**700**	**15.00%**	**805**
Bus/Main Body	700	15.00%	805

Wet Mass w/ contingency: 3872.78 kg
Dry Mass w/ contingency: 3274.65 kg
Overall Contingency: 18.27%

Limitations

Limitations:

- TRL assumptions
  - “Advanced RTGs”
  - Sample Collection Methods
- Trajectory/ACS assumptions
  - No debris/collisions over course of mission
  - No unexpected maneuvers + simplification of maneuvers
- Constant and *consistent* power delivery
- Reliable communication

Q&A