Propulsion Options Trade Study for the Mercury "Ice Flayer" Mission

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Purpose. Compare realistic propulsion options for a small satellite Mercury orbiter that targets an elliptical polar science orbit. Evaluate performance, mass and power impacts, operational complexity, heritage, and mission fit. Output is a portfolio ready report that can drop into an Evidence Pack.

Scope. Five candidates are assessed: Aerojet Rocketdyne MR-106L hydrazine (baseline), Aerojet Rocketdyne MR-103G hydrazine, ECAPS LMP-103S green monopropellant thruster, Aerojet Rocketdyne XR-5 Hall thruster, and Busek BIT-3 iodine ion thruster.

1. Context and Assumptions

- Spacecraft wet mass $\approx 190.00\,\mathrm{kg}$ class smallsat consistent with the mission slides.
- Capture strategy: either impulsive chemical burn at arrival or low thrust spiral capture with continuous thrust.
- Representative numbers come from public datasheets and NASA small spacecraft propulsion summaries. Exact values vary with operating point. Where a range exists, a typical operating point is listed for apples to apples comparison.
- No em dashes per style rule. Units and symbols use `siunitx`.

2. Candidate Systems

Chemical, monopropellant. Hydrazine MR-106L ($\sim$22.00 N) is the baseline. MR-103G ($\sim$1.00 N) is a smaller heritage option. ECAPS LMP-103S uses an ADN based green monopropellant in the 5.00 N to 22.00 N class with higher Isp and much safer handling.

Electric propulsion. XR-5 is a 3.00 kW to 4.50 kW Hall effect thruster at 0.17 N to 0.29 N with Isp $\approx$1700.00 s to 2000.00 s. Busek BIT-3 is a 60.00 W class iodine ion thruster at $\sim$1.10 mN and Isp$\sim$2000.00 s to 3500.00 s.

3. Comparative Metrics

System	Thrust	Isp	Power	Dry Mass	Propellant & storability	Heritage
MR-106L hydrazine	22.00 N	228.00 s to 235.00 s	30.00 W to 40.00 W	0.59 kg	Hydrazine, storable, toxic	Very high
MR-103G hydrazine	1.00 N	202.00 s to 224.00 s	10.00 W to 20.00 W	0.35 kg	Hydrazine, storable, toxic	Very high
ECAPS LMP-103S (22 N)	22.00 N	243.00 s to 255.00 s	25.00 W to 50.00 W	1.10 kg	LMP-103S, storable, lower vapor toxicity	Medium to high[a]
XR-5 Hall thruster	0.17 N to 0.29 N	1600.00 s to 2020.00 s	2700.00 W to 4500.00 W	12.30 kg[b]	Xenon, high pressure tank	High
Busek BIT-3 ion	1.10 mN	2000.00 s to 3500.00 s	56.00 W to 75.00 W	1.40 kg[c]	Iodine, solid, no pressure tank	Low to medium

Notes. [a] 1 N HPGP flown repeatedly, 22 N units in qualification on multiple programs. [b] Thruster plus cathode; complete EP string requires PPU, tank, lines, and xenon mass. [c] Dry system including gimbal and feed electronics; wet mass ∼2.90 kg typical with propellant.

Total impulse and thrust to weight. Chemical options have very high thrust to weight and short burn times, at low Isp. Electric options have very low thrust to weight and long burns, at very high Isp. Total impulse is mission limited for EP and lifetime limited for monopropellant catalyst beds.

4. Trade Analysis

Chemical, hydrazine. MR-106L gives decisive impulsive capability. A 22.00 N engine on a 100.00 kg stage yields $\sim 0.22\,\mathrm{m/s^2}$. Capture burns complete in minutes, which limits gravity losses and simplifies GN&C. Penalty is propellant mass, since Isp ≈230.00 s.

Chemical, green mono. LMP-103S improves Isp by roughly 5 to 10 percent and improves density. Handling is far safer. Heavier thruster and longer catalyst preheat demand more electrical energy. For a smallsat that values ground operations simplicity and a few percent mass relief, it is an attractive drop in alternative.

EP, XR-5. Isp ∼1700.00 s to 2000.00 s reduces propellant mass by a large factor. The price is kilowatt class continuous power, large deployable arrays, thermal rejection, and months of thrust time. For a smallsat, this shifts the bottleneck from tank mass to power system mass and operations.

EP, BIT-3. Very compact and efficient. Thrust is only ∼1.10 mN. Even with clustering, spiral capture at Mercury would require many years. Useful for fine orbital energy trimming or very small spacecraft, but not viable as the sole capture engine for this mission class.

5. Spacecraft Impacts

Mass budget. Chemical systems are light dry mass with heavy propellant. EP systems are heavy dry mass with light propellant. For XR-5, include PPU, gimbal, xenon tank, harness, and array structure in the dry mass rollup.

Power budget. Chemical burns draw tens of watts for heaters and valves. XR-5 draws 2.70 kW to 4.50 kW while thrusting. BIT-3 draws 60.00 W. Continuous EP thrust requires persistent array pointing and thermal control.

Mission duration. Chemical capture is impulsive. EP capture is a slow spiral. Either approach still uses gravity assists. With sufficient power, XR-5 can trade propellant for time and reduce the number of flybys.

6. Recommendation

For a ∼190.00 kg Mercury smallsat:

- **Primary alternative: XR-5 Hall thruster** when program can support kilowatt class power, large arrays, and multi month thrust operations. This option enables the largest total Δv within a small wet mass.
- **Pragmatic upgrade: LMP-103S green mono in the 22.00 N class** as a drop in for MR-106L. Gains are modest in Isp and strong in safety and operations. Pair with an aggressive gravity assist profile.
- **Not recommended as primary: MR-103G and BIT-3** for main capture. MR-103G lacks thrust margin. BIT-3 lacks thrust by orders of magnitude, which drives mission time and risk.

7. Traceable Assumptions and Sources

Values reflect typical operating points from vendor datasheets and NASA small spacecraft propulsion summaries. Use this list in your portfolio to cite specific PDFs:

- Aerojet Rocketdyne MR-106L data sheet: thrust range, Isp, mass, heater and valve power.
- Aerojet Rocketdyne MR-103G data sheet: nominal thrust, Isp, mass.
- ECAPS LMP-103S thruster notes: 5 to 22.00 N class, Isp, preheat and handling characteristics, density benefit.
- Aerojet Rocketdyne XR-5 Hall thruster summary: thrust versus power, Isp at 300 to 400.00 V, thruster mass and heritage.

- Busek BIT-3 product brief: iodine propellant, thrust, power, system dry and wet mass, typical Isp.
- NASA Small Spacecraft Propulsion State of the Art reports: cross checks and lifetime remarks.

8. Appendix: Back of the Envelope Checks

Chemical burn time scaling. Burn time $t \approx m_0\,\Delta v/T$. For $m_0 = 120.00\,\mathrm{kg}$, $\Delta v = 300.00\,\mathrm{m/s}$, $T = 22.00\,\mathrm{N}$, we get $t \approx (120 \cdot 300)/22 \approx 1636.00\,\mathrm{s}$ which is about $27.00\,\mathrm{min}$.

EP spiral rate estimate. Constant thrust acceleration $a = T/m$. For XR-5 at 0.25 N on 150.00 kg, $a \approx 0.00\,\mathrm{m/s^2}$. One month of thrust gives $\Delta v \approx a\,t \approx 0.00167 \times 2.63 \times 10^6 \approx 4390.00\,\mathrm{m/s}$. This is an upper bound that ignores duty cycle and pointing losses. It shows why kilowatt class EP is viable and why millinewton class is not for capture.

Usage note for the portfolio. This document is self contained and compiles with `pdflatex` or `xelatex`. To adapt for the Evidence Pack, keep Section 3 and Section 6, then convert Section 7 into footnotes tied to figure callouts and a one page trade grid. Avoid sensitive or proprietary data. Keep claims measurable and traceable.