Space & Astronomy | Jul 9, 2026 | 8 min read | By Bryan White

Mars Rotorcraft Phase II: How Skyfall Builds on Ingenuity's Historic Success

Biology * Space * Solar System

From Ingenuity to the Skyfall Aerial Architecture

Extraterrestrial planetary science exploration is transitioning from localized, surface-bound rovers to mobile, regional aerial reconnaissance platforms. Building on the historic 72-flight campaign of the Ingenuity Mars Helicopter between April 2021 and January 2024, NASA has initiated the Skyfall mission, targeted for launch in late 2028.[1] Unlike all prior Martian missions, Skyfall eliminates the static landing platform in favor of a synchronized mid-air deployment of multiple scientific rotorcraft during atmospheric descent.[1][3][15]

To execute this architecture, Skyfall serves as the primary payload aboard Space Reactor-1 Freedom, a pathfinder spacecraft validating Nuclear Electric Propulsion (NEP) for interplanetary transit.[4][6] Protected during Martian entry by a specialized carbon-composite aeroshell built by Firefly Aerospace under a Jet Propulsion Laboratory subcontract, the deployed rotorcraft will use supersonic-capable carbon-fiber blades to carry ground-penetrating radar across the Martian mid-latitudes.[1][3][5] This report analyzes the integrated thermodynamic, plasma-propulsion, aerothermodynamic, and geophysical systems underpinning the Skyfall mission.

Nuclear Electric Propulsion and Closed Brayton Cycle Thermodynamics

Space Reactor-1 Freedom circumvents both the mass-ratio limitations of chemical rockets and the inverse-square irradiance drop-off of solar electric propulsion by pairing an approximately 20-kilowatt electric (20-kWe) fission reactor with Hall-effect electric thrusters.[1][4][6] The reactor concept draws on fission surface power architecture utilizing High-Assay Low-Enriched Uranium (HALEU) fuel isolated from spacecraft avionics by dedicated radiation shielding.[8][9]

Thermal fission energy is converted into electrical power via an Advanced Closed Brayton Cycle recirculating a sealed noble gas working fluid.[7][8] Pressurized working fluid is preheated in a recuperator heat exchanger, heated within the reactor core, and expanded across a turbine shaft coupled to an electrical generator before rejecting waste heat to deep space through composite and titanium radiator arrays.[7][9]

Electrical output drives a hybrid Power and Propulsion Element -- derived from the Lunar Gateway bus -- integrating four 6-kW Busek Hall thrusters and three 12-kW Advanced Electric Propulsion System (AEPS) Hall-effect thrusters developed by NASA Glenn Research Center and Aerojet Rocketdyne (scalable in thrust allocation up to 48 kW depending on reactor operating state and battery buffering).[6][11] Inside each boron nitride ceramic discharge channel, a lanthanum hexaboride hollow cathode injects electrons into a radial magnetic field.[10][11] Trapped in an azimuthal Hall

current by the Lorentz force, these electrons ionize injected xenon propellant, generating an ion plasma that is electrostatically accelerated out of the channel at ~2,800 seconds specific impulse while a secondary cathode electron stream neutralizes the exhaust plume.[10][11]

| Propulsion System Parameter | | Specification |

| Reactor Architecture | | Advanced Closed Brayton Cycle Fission Reactor (~20 kWe output) |

| Fissile Material | | High-Assay Low-Enriched Uranium (HALEU) |

| Primary Thruster Type | | Advanced Electric Propulsion System (AEPS) Hall-effect |

| Electric Power Input per AEPS | | 12 kilowatts |

| Maximum Thrust per AEPS Engine | | 600 millinewtons |

| Specific Impulse (Isp) | | Approximately 2,800 seconds |

| Thruster Operational Lifespan | | 23,000 to 50,000 hours |

| System Propellant | | Xenon (Primary), Krypton/Argon (Alternatives) |

Aeroshell Fabrication, Mid-Air Deployment, and Transonic Rotor Dynamics

Upon reaching Mars in late 2029, Space Reactor-1 Freedom will release the Skyfall entry capsule.[12] Manufactured by Firefly Aerospace under a USD 13 million JPL subcontract at its Briggs, Texas facilities (leveraging Blue Ghost and Alpha composite heritage), the autoclave-cured carbon-composite aeroshell -- comprising a forward heatshield and conical backshell -- maximizes strength-to-weight ratio during hypersonic entry.[3][5] Once supersonic parachutes stabilize descent in the lower atmosphere, the backshell separates and executes the "Skyfall Maneuver": releasing helicopters simultaneously in mid-air to arrest their own vertical descent and fly autonomously to surface coordinates.[1][15] Eliminating landed retro-rockets, Skycrane winches, and egress ramps reallocates structural mass directly to scientific payloads and high-capacity batteries.[5][15]

Generating lift in an atmosphere composed of 95% carbon dioxide at less than 1% of Earth's sea-level density requires high rotor angular velocities.[2][13] Because cold, low-pressure CO2 lowers the Martian speed of sound to ~540 mph (versus ~760 mph on Earth), Ingenuity capped its rotor speed at 2,700 RPM (Mach 0.7 tip speed) to avoid transonic shockwaves, boundary-layer separation, and drag divergence on the advancing blade.[13][14] To lift Skyfall's heavier payload within the aeroshell's diameter constraints, NASA JPL and AeroVironment tested next-generation carbon-composite blades across 137 runs inside JPL's 25-Foot Space Simulator backfilled with low-density CO2 and artificial headwinds.[16][17][18] Spinning up to 3,750 RPM (three-bladed) and 3,570 RPM (two-bladed), the rotors operated stably at Mach 1.08 without delamination, yielding a 30 percent increase in aerodynamic lift.[16][17][19][20]

| Aerodynamic and Physical Parameters | | Ingenuity Heritage Baseline | | Skyfall Next-Generation Design |

| Target Atmosphere Composition | | 95% Carbon Dioxide | | 95% Carbon Dioxide |

| Local Speed of Sound | | ~540 miles per hour | | ~540 miles per hour |

| Total Mass | | 1.8 kilograms | | Higher than baseline |

| Maximum Allowable Tip Speed | | Mach 0.7 | | Mach 1.08 |

| Maximum Rotational Velocity | | 2,700 RPM | | 3,570 - 3,750 RPM |

| Aerodynamic Lift Capability | | Baseline Reference | | +30 percent over baseline |

| Scientific Payload Suite | | Optical cameras | | Ground-penetrating radar, environmental sensors |

Drone-Borne Ground-Penetrating Radar and Subsurface Ice Prospecting

Traversing several kilometers per day -- and scalable in AeroVironment architectures up to six-helicopter swarms -- the Skyfall rotorcraft are designed to map shallow subsurface water ice in the Martian cryosphere for future In-Situ Resource Utilization, supporting water extraction, electrolytic oxygen production, and chemical rocket propellant synthesis.[1][12][15] Each helicopter carries a miniaturized Ground-Penetrating Radar (GPR) that records two-way travel times, amplitudes, and phase shifts of high-frequency electromagnetic pulses reflected at dielectric boundaries between dry silicate regolith and buried water ice.[1][21][23]

Flying at 10 to 50 meters altitude bridges the resolution gap between orbital radar (such as Mars Reconnaissance Orbiter's SHARAD, which suffers ionospheric attenuation and coarse footprints above 250 km) and boulder-constrained surface rovers.[21][24][25] Field validation using 80-MHz MALA Geodrone GPR over debris-covered rock glaciers in Alaska (Sourdough Rock Glacier) and Wyoming (Galena Creek Rock Glacier) successfully minimized surface boulder clutter, mapped supraglacial debris overburden thickness, identified internal englacial dust layers recording paleoclimate cycles, and resolved solid ice cores exceeding 40 meters in depth.[22][23]

| Subsurface Prospecting Parameters | | Orbital Radar (SHARAD) | | Drone-Based Aerial Radar |

| Operational Altitude | | >250 kilometers | | 10 to 50 meters |

| Shallow Stratigraphic Resolution | | Low | | High |

| Signal Attenuation | | High (Ionospheric interference) | | Low (Proximity to surface) |

| Mobility and Terrain Limitations | | Global coverage, no terrain limits | | Regional coverage, no terrain limits |

| Primary Capability | | Deep-seated planetary mapping | | High-resolution localized ISRU mapping |

Establishing a Scalable Martian Reconnaissance Architecture

By uniting Space Reactor-1 Freedom's ~20-kWe Nuclear Electric Propulsion, Firefly Aerospace's composite aeroshell and mid-air Skyfall Maneuver, Mach 1.08 transonic rotors, and low-altitude GPR sounding, the 2028 Skyfall mission establishes a

high-mobility reconnaissance framework capable of pinpointing accessible water-ice reservoirs and low-risk landing zones for future human outposts on Mars.[1][6][15][23]

Updates... (Nov 21, 2026): Added verified publication years and exact publication dates across all 25 references -- including AeroVironment, Space.com, NASA mission briefs, NASA NTRS reports (with primary author attribution), ZME Science, New Atlas, Vertical Magazine, Bioengineer.org, LPSC 2025, and SPH Engineering. (Prior Nov 19, 2026 update corrected Space Reactor-1 Freedom's rating to ~20-kWe electrical output and upgraded third-party links.)

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