Supplementary Information

IMPRESS: A Planetary Penetrator Network for Astrobiology, Prospecting, and Exploration of Mars

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Table S1. Overview of planetary penetrator probes and related literature

Probe / mission	Lead program	Readiness	Notes	Mass (kg)**	Impact Velocity (m/s)	Impact Deceleration (g)	Penetration Depth (m)	Primary references (DOI or website)
Mars								
NASA / Sandia Mars penetrator (1970s)	NASA Ames / Sandia	Built & tested	Detailed Mars subsurface mission architecture with forebody–aftbody split, umbilical, and extensive field and gas-gun testing; not flown.	37.9	150	2,000 (forebody) 20,000 (aftbody)	1–15	Lumpkin / Sandia (1974) NASA-CR-137587 report. https://ntrs.nasa.gov/citations/19750004806 Murphy et al. (1981) NASA Penetrator Study. https://ntrs.nasa.gov/api/citations/19810012471/downloads/19810012471.pdf
Mars-96 penetrators	Roscosmos / Lavochkin Association / Vernadsky Institute	Launched, rocket failed Trans-Mars Injection	Two Mars penetrators launched with Mars-96; mission crashed on Earth after launch vehicle malfunction prevented orbital escape.	125 total 8.8 payload	80	500*	≤ 5	Surkov & Kremnev (1998) Planet. Space Sci. 10.1016/S0032-0633(98)00071-3 Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033
MARSNET	ESA study	Concept	ESA Mars network study which considered both three to four penetrators and three semi-hard landers for geochemical, seismic, and meteorological measurements; remained a study.	65	70–80 (penetrator) 25 (semi-hard lander)	5,700 actual (assuming 70 m/s) 700 experienced ≤100 (semi-hard lander)	Unknown	Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033 Scoon & Whitcomb (1993) Acta Astronaut. 10.1016/0094-5765(93)90164-R Steckemetz et al. (1993) ESA Bulletin. https://www.esa.int/esapub/bulletin/bullet93/DOENGI.pdf
Deep Space 2 (DS2) microprobes	NASA / JPL	Flown, non-responsive upon impact	Two Mars microprobes released from Mars Polar Lander; first Mars penetrator mission to reach Mars; communications were lost after impact due to battery, telecommunications, or landing failure.	2.4 (0.67 forebody, 1.737 aftbody)	190	30,000 (forebody) 60,000 (aftbody)	0.6	Gavit & Powell (1996) Acta Astronaut. 10.1016/S0094-5765(96)00145-2 Smrekar et al. (1999) J. Geophys. Res. Planets 10.1029/1999JE001073 Lorenz et al. (2000) Planet. Space Sci. 10.1016/S0032-0633(00)00016-7 Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033
MetNet (Mars Network Lander / MNL)	Finnish Meteo. Ins./ Lavochkin Association / INTA	Built & tested	Semi-hard Mars lander/penetrator hybrid developed and prototyped for distributed atmospheric and environmental measurements.	24 total 4 payloads	50–70	< 500	0.542	Harri et al. (2017) Geosci. Instrum. Methods Data Syst. 10.5194/gi-6-103-2017

Probe / mission	Lead program	Readiness	Notes	Mass (kg)**	Impact Velocity (m/s)	Impact Deceleration (g)	Penetration Depth (m)	Primary references (DOI or website)
BOLD	WSU-led concept	Concept	Small hard-impact Mars life-detection network concept using six penetrator-like probes to emplace instruments into the shallow subsurface.	78 kg total 7.8 kg payload	Unknown	Undefined; low speed impact.	“a few tens of centimeters”	Schulze-Makuch et al. (2012) Planet. Space Sci. 10.1016/j.pss.2012.03.008
Mars Connect	INTA	Concept	Hard-impact Mars environmental-microprobe network (20–30 probes) for atmospheric observations.	12.5 kg total 7 kg without aeroshell 1 kg payload	90	Unknown	Unknown	Arruego et al. (2024) EPSC. 10.5194/epsc2024-92 Gonzalo et al. (2025) 10th International Planetary Probe Workshop / conference paper. 10.32865/2346/102650
Moon								
LUNAR-A	ISAS / JAXA	Built & tested	Lunar geophysics mission with penetrators for seismology and heat flow; reached qualification-level development but was canceled before launch due to electronics and material quality failures.	12–13	300	4,000 (axial) 5,000–6,000 (lateral)	1–2	Shiraishi et al. (2008) Adv. Space Res. 10.1016/j.asr.2007.08.022 Smrekar et al. (1999) J. Geophys. Res. Planets 10.1029/1999JE001073 Ahrens et al. (2021) Planet. Sci. J. 10.3847/PSJ/abda4f
MoonLITE	UK penetrator consortium	Built & tested	Four-penetrator lunar network concept (one pair on each side of the Moon); full-scale impact trials were reported; not flown.	13 (total) 2 (payload)	300	16,000 (peak axial) 5,000 (smoothed axial) 17,000 (vertical lateral) 4,000 (horizontal lateral)	2–5	Gao et al. (2008) Planet. Space Sci. 10.1016/j.pss.2007.11.005 Gowen et al. (2008) International Astronautical Congress. https://openresearch.surrey.ac.uk/esploro/outputs/journalArticle/An-update-on-MoonLITE/99514483602346 Ahrens et al. (2021) Planet. Sci. J. 10.3847/PSJ/abda4f
LunarEX	UK penetrator consortium	Concept	Lunar penetrator network concept derived from the MoonLITE line; concept study only.	13	300	10,000	2–5	Smith et al. (2009) Exp. Astron. 10.1007/s10686-008-9109-6
Lunar Net	UK penetrator consortium	Concept	Evolution of LunarEX proposal to ESA; modified in response to MoonLITE impact trials.	13	< 300	15,000	2–5	Smith et al. (2011) Exp. Astron. 10.1007/s10686-011-9250-5

Probe / mission	Lead program	Readiness	Notes	Mass (kg)**	Impact Velocity (m/s)	Impact Deceleration (g)	Penetration Depth (m)	Primary references (DOI or website)
Polar Night	NASA / JPL concept	Concept	Lunar volatiles mission concept using three penetrators to access permanently shadowed polar environments.	Unknown	75	3,000	1–2	Mosher & Lucey (2006) Acta Astronaut. 10.1016/j.actaastro.2005.07.033
Small Penetrator Instrument Concept	NASA	Concept	Modern small lunar penetrator concept with compact science payloads for distributed surface and shallow-subsurface investigations.	1.5	"dozens to hundreds"	Unknown	Unknown	Ahrens et al. (2021) Planet. Sci. J. 10.3847/PSJ/abda4f
Mercury								
Mercury penetrator concept	Science Applications, Inc. / NASA study	Concept	Mercury penetrator mission study using active retro-velocity and attitude control because Mercury lacks a substantial atmosphere.	Unknown	150	Unknown	Unknown	Murphy et al. (1981) NASA Penetrator Study. https://ntrs.nasa.gov/api/citations/19810012471/downloads/19810012471.pdf
Galilean satellites								
Galilean satellite penetrator concept	Science Applications, Inc. / NASA study	Concept	Penetrator mission studies for Io, Europa, Ganymede, and Callisto; delivery requirements broadly analogous to Mercury because they lack substantial atmospheres.	Unknown	150	Unknown	Unknown	Murphy et al. (1981) NASA Penetrator Study. https://ntrs.nasa.gov/api/citations/19810012471/downloads/19810012471.pdf
Titan								
Penetrobe	NASA concept	Concept	Adaptable Titan penetrator/probe concept with deployable decelerator studied before Voyager 1 constrained Titan surface conditions.	55	150	1,800 (forebody) 1,800 (aftbody)	1–15	Tindle et al. / Martin Marietta (1976) NASA CR-137847 report https://ntrs.nasa.gov/citations/19760022053
TandEM: Titan and Enceladus mission	Coustenis, LESIA	Concept	Small penetrator seismic network for Enceladus and Titan as part of the TandEM mission concept.	5 total 1.7 payload	Unknown	Unknown	Unknown	Coustenis et al. (2009) Exp. Astron. 10.1007/s10686-008-9103-z
Comet								

Probe / mission	Lead program	Readiness	Notes	Mass (kg)**	Impact Velocity (m/s)	Impact Deceleration (g)	Penetration Depth (m)	Primary references (DOI or website)
CRAF comet nucleus penetrator	NASA concept	Concept	Comet penetrator proposed for in situ composition measurements beneath the nucleus surface; hardware was studied in detail but descoped before flight.	20.35	40	55–420 (surface dependent)	0.35–1 (surface dependent)	Swenson et al. (1987) Acta Astronaut. 10.1016/0094-5765(87)90185-8
Asteroid								
VESTA asteroid penetrators	ESA concept	Concept	Two asteroid penetrators proposed with a deceleration module to slow impact to acceptable velocity during an asteroid flyby.	100 total 10 payload	Unknown	Unknown	Unknown	Langevin (1987) Adv. Space Res. 10.1016/0273-1177(87)90219-5
High velocity penetrators for core rock sampling	University of Washington	Concept	Penetrator designed for emplacement at supersonic velocities on asteroids for geologic core collection.	Unknown	300–900	Unknown	1–2	Winglee et al. (2017) Acta Astronaut. 10.1016/j.actaastro.2017.12.019
Icy moons / outer icy bodies								
SILENUS	Caltech Space Challenge concept	Concept	Multi-lander Enceladus concept using four impact-emplaced penetrators equipped for geophysical measurements.	14	~106	Unknown	Unknown	Nathan et al. (2022) Front. Astron. Space Sci. 10.3389/fspas.2022.995941
Ice Shell Impact Penetrator (IceShIP)	Georgia Tech group	Prototype impact tested	Penetrator designed to emplace into ice shell of planetary moon (Europa, Enceladus, etc.) and conduct laser-induced fluorescence for detection of low concentration organics; fluorometer components impact tested at up to 50,000 g.	Unknown	Unknown	Unknown	1–10	Govinda Raj et al. (2022) Front. Astron. Space Sci. 10.3389/fspas.2022.943594
Penetrator Delivery System for Europa	UK penetrator consortium	Concept	Concept for two penetrators with seismic-focused science payloads targeted at Europa and Ganymede for geophysical and astrobiological observations.	5–15	100–300	40,000	~3.7	Gowen et al. (2011) Adv. Space Res. 10.1016/j.asr.2010.06.026

Probe / mission	Lead program	Readiness	Notes	Mass (kg)**	Impact Velocity (m/s)	Impact Deceleration (g)	Penetration Depth (m)	Primary references (DOI or website)
Cryo-braking penetrator concept	University of Washington	Built & tested	First-stage hypervelocity penetrator concept for icy bodies that creates ejecta to brake a second-stage payload; lab fabrication and testing reported.	12 total 4 impactor 8 science payload	4,000 impactor	< 10,000 impactor	"Several meters deep"	Winglee et al. (2017) Acta Astronaut. 10.1016/j.actaastro.2017.12.019
Earth / terrestrial reconnaissance								
Igloo White: Acoustic and Seismic Intrusion Detector (ACOUSID)	US Air Force / Sandia	Flown, successful	Air-dropped seismic/acoustic intrusion detectors used operationally over the Ho Chi Minh Trail; key terrestrial heritage for instrumented penetrators.	20	Unknown	< 2,000	Unknown	Igloo White (1967) Museum Exhibit. https://www.nationalmuseum.af.mil/Visit/Museum-Exhibits/Fact-Sheets/Display/Article/195948/igloo-white/ Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033
Tabasco surveillance pod	CIA / Sandia	Flown, non-responsive	Instrumented reconnaissance penetrator dropped from U-2 flights to monitor Chinese nuclear tests; at least one pair was dropped, but no telemetry was recovered.	Unknown	Unknown	Unknown	Unknown	Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033
Sea-ice penetrometer	Sandia	Built & tested	Air-dropped Earth penetrator for sea-ice thickness measurements; dual-use terrestrial heritage closely related to later planetary penetrator thinking.	23	Unknown	Unknown	Unknown	Young & Keck (1971) Sandia Technical Report. https://apps.dtic.mil/sti/html/tr/AD0739991/index.html Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033

*500 g is load experienced by instruments, lessened via shock absorber; real deceleration experienced by Mars96 probe is likely higher
**total refers to the masses of individual penetrators; payload refers to the mass of scientific instruments only

Table S2. Penetrator instrument table

Instrument / payload	Description / use / size*	Penetrator relevance / heritage	Readiness for IMPRESS**	Primary references (DOI + link)
EDL / emplacement				
Combined 3-axis accelerometer / 3-axis gyrometer IMU	Inertial measurement unit for descent control and landing reconstruction. Size: compact 6-axis package within the precursor payload; exact size not given in Harri et al. 2017.	MetNet payload element. May be used for post-landing orientation knowledge.	Integrate-ready	Harri et al. (2017) Geosci. Instrum. Methods Data Syst. 10.5194/gi-6-103-2017
Tiltmeters	Determines final probe attitude and local surface slope; important for correcting seismic and thermal measurements. Size: XS.	LUNAR-A and LunarEX payload element.	Integrate-ready	Shiraishi et al. (2008) Adv. Space Res. 10.1016/j.asr.2007.08.022 Smith et al. (2009) Exp. Astron. 10.1007/s10686-008-9109-6
Descent accelerometer	Measures atmospheric-entry deceleration; can constrain atmospheric density; pressure/temperature require modeling. Size: XS.	Flown on Deep Space 2; standard penetrator EDL diagnostic.	Integrate-ready	Smrekar et al. (1999) J. Geophys. Res. Planets 10.1029/1999JE001073
Impact accelerometer / penetrometer	Records deceleration during impact and burial; constrains target strength, layering, and penetration dynamics. Size: XS.	DS2 and LUNAR-A payload element. Flown on DS2.	Integrate-ready	Smrekar et al. (1999) J. Geophys. Res. Planets 10.1029/1999JE001073 Lorenz et al. (2000) Planet. Space Sci. 10.1016/S0032-0633(00)00016-7 Shiraishi et al. (2008) Adv. Space Res. 10.1016/j.asr.2007.08.022 Langevin (1987) Adv. Space Res. 10.1016/0273-1177(87)90219-5 Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033
Descent camera	Provides last-minute terrain context and deployment verification for interpreting subsurface measurements. Size: S.	Proposed for LunarEX	Requalification needed	Smith et al. (2009) Exp. Astron. 10.1007/s10686-008-9109-6
Imaging / context				
Subsurface mineralogy / astrobiology camera	Images mineralogical textures and possible astrobiology context at close range in Titan/Enceladus penetrators. Size: S–M	Named as a penetrator-specific complementary payload option in the TandEM study.	Concept	Coustenis et al. (2009) Exp. Astron. 10.1007/s10686-008-9103-z
Surface context camera	Images terrain morphology around the penetrator post-impact for geological and environmental context; mounted on aft body. Size: S	Various surface context cameras included in payloads for the SILENUS and MetNet penetrator concepts. Included in Mars-96 payload.	Concept	Nathan et al. (2022) Front. Astron. Space Sci. 10.3389/fspas.2022.995941 Harri et al. (2017) Geosci. Instrum. Methods Data Syst. 10.5194/gi-6-103-2017 Surkov & Kremnev (1998) Planet. Space Sci. 10.1016/S0032-0633(98)00071-3
Meteorology / atmosphere				
Radiative-balance / radiometer package	Measures surface energy balance and thermal environment. Size: XS (25 g + 56 g processor for ExoMars DREAMS; ~114 g MetNet heritage radiometer).	Miniature environmental-network payload for Mars Connect, with MetNet heritage.	Integrate-ready	Arruego et al. (2024) EPSC. 10.5194/epsc2024-92 Gonzalo et al. (2025) 10th International Planetary Probe Workshop / conference paper. 10.32865/2346/102650
Relative humidity sensor	Tracks water vapor activity, frost/deliquescence conditions, and near-surface habitability windows. Size: S (124 cm^3, 45 g Perseverance)	Perseverance MEDA payload element (MEDA-HS). Compact	Integrate-ready	Polkko et al. (2023) J. Geophys. Res. Planets 10.1029/2022JE007447 Hieta et al. (2024) Geosci. Instrum. Methods Data Syst. 10.5194/gi-13-337-2024

Instrument / payload	Description / use / size*	Penetrator relevance / heritage	Readiness for IMPRESS**	Primary references (DOI + link)
		enough for penetrator environmental packages.		
Wind sensor	Measures wind speed and direction for boundary-layer dynamics, dust lifting, aeolian transport, and engineering risk assessment. Size: S (foil cylinder—Phoenix)/M (850 cm³ 305 g fixed boom—Perseverance)	Phoenix and Perseverance (MEDA) payload element. Relevant to distributed penetrator networks.	Requalification needed (shock-fragile)	Taylor et al. (2008) J. Geophys. Res. Planets 10.1029/2007JE003015 Rodriguez-Manfredi et al. (2021) Space Sci. Rev. 10.1007/s11214-021-00816-9
Dust sensor	Measures in situ dust flux and saltation for atmospheric loading and near-surface transport studies. Size: XS (35 g in Mars Connect).	Explicit payload element for MetNet and carried forward as Mars Connect heritage.	Integrate-ready	Harri et al. (2017) Geosci. Instrum. Methods Data Syst. 10.5194/gi-6-103-2017 Gonzalo et al. (2025) 10th International Planetary Probe Workshop / conference paper. 10.32865/2346/102650
Integrated meteorology station	Integrated weather/environment package in aft body combining pressure, temperature, humidity, and thermal sensors for networked atmospheric monitoring. Some variations include extra sensors for wind velocity/direction, photosynthetic active radiation, UV irradiation, and acoustic sound.	Mars-96 penetrator payload element, main payload element on MetNet and Mars Connect miniature probes, core experiment in BOLD probe concept.	Requalification needed	Harri et al. (2017) Geosci. Instrum. Methods Data Syst. 10.5194/gi-6-103-2017 Gonzalo et al. (2025) Mars Connect conference paper. 10.32865/2346/102650 Schulze-Makuch et al. (2012) Planet. Space Sci. 10.1016/j.pss.2012.03.008 Surkov & Kremnev (1998) Planet. Space Sci. 10.1016/S0032-0633(98)00071-3
Geophysics				
MOURA magnetometer / gradiometer	Three-axis magnetometer/gradiometer for local crustal-field and environmental magnetic measurements. Size: ~72 g.	MetNet precursor payload element with direct heritage into later Mars network concepts.	Integrate-ready	Díaz-Michelena et al. (2016) Geosci. Instrum. Methods Data Syst. 10.5194/gi-5-127-2016 Harri et al. (2017) Geosci. Instrum. Methods Data Syst. 10.5194/gi-6-103-2017 Bennett et al. (2021) Sensors. 10.3390/s21165568
Traditional Triaxial Seismometer	Three-axis seismic package on multi-cm scale. Options include adapted Viking triaxial seismometer, compact 4.5 Hz geophone implementation, or Mars-96 OPTIMISM spherical seismometer. For Martian internal-structure studies. Size: M (7.6 cm diameter Sandia, 729 cm³ 405 g Mars-96).	Detailed baseline/candidate seismic instrument in the original NASA/Sandia Mars penetrator study.	Requalification needed	Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033 Lumpkin / Sandia (1974) NASA-CR-137587 report. https://ntrs.nasa.gov/citations/19750004806
Microseismometer	Measures local and regional seismic vibrations; especially powerful when deployed as a time-synchronized network. Size: XS/S (12 cm³ Pike, 2150 cm³ Lunar-A)	Penetrator heritage in LUNAR-A and LunarEX; MEMS NANO-G seismometers compatible with small penetrators.	Integrate-ready	Pike et al. (2009) Transducers. 10.1109/SENSOR.2009.5285413 Yamada et al. (2009) Planet. Space Sci. 10.1016/j.pss.2008.12.004 Nathan et al. (2022) Front. Astron. Space Sci. 10.3389/fspas.2022.995941
Seismometer / thermal sensors / geochemistry core suite	Payload suite proposed as common to Enceladus and Titan penetrators, comprising seismometers, geochemistry package, thermal sensors, accelerometers, and descent camera. Size: L–XL	TandEM study.	Concept	Coustenis et al. (2009) Exp. Astron. 10.1007/s10686-008-9103-z
Heat-flow probe	Measures subsurface temperature gradient and thermal conductivity to estimate planetary heat flow and volatile stability. Size: S.	Planned for DS2 successors; major science objective of LUNAR-A penetrators; also	Integrate-ready	Yen et al. (1999) Lunar and Planetary Science Conference https://www.lpi.usra.edu/meetings/LPSC99/pdf/1870.pdf

Instrument / payload	Description / use / size*	Penetrator relevance / heritage	Readiness for IMPRESS**	Primary references (DOI + link)
		carried forward in LunarEX concepts.		Mizutani et al. (2003) Adv. Space Res. 10.1016/S0273-1177(03)00542-8 Smith et al. (2009) Exp. Astron. 10.1007/s10686-008-9109-6
Magnetometer / plasma monitor	Measures local magnetic field and plasma environment; useful for crustal magnetism and space-weather coupling at the surface. Size: S–M (315 cm^3 219 g Mars-96, ≤ 1 kg with 60 cm deployable boom Rosetta).	Mars-96 and Rosetta/Philae payload element.	Requalification needed	Auster (2007) Space Sci. Rev. 10.1007/s11214-006-9033-x Biele (2002) Earth Moon Planets 10.1023/A:1021523227314 Surkov and Kremnev (1998) Planet. Space Sci. 10.1016/S0032-0633(98)00071-3 Kuhnke et al. (1997) Planet. Space Sci. 10.1016/S0032-0633(98)00010-5
Thermoprobes	Temperature sensors distributed vertically along penetrator to measure passive heat variations with depth. Used to compare surface and subsurface temperatures on planetary/icy bodies. Size: XS–M (Built into penetrator walls DS2, 0.5 kg retractable probes Mars-96).	DS2 and Mars-96 penetrator payload element, potential VESTA payload, candidate comet penetrator payload, recommended baseline instrument for Titan Penetrobe concept.	Integrate-ready	Surkov & Kremnev (1998) Planet. Space Sci. 10.1016/S0032-0633(98)00071-3 Smrekar et al. (1999) J. Geophys. Res. Planets 10.1029/1999JE001073 Langevin (1987) Adv. Space Res. 10.1016/0273-1177(87)90219-5 Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033 Swenson et al. (1987) Acta Astronaut. 10.1016/0094-5765(87)90185-8 Tindle et al. / Martin Marietta (1976) NASA CR-137847 report. https://ntrs.nasa.gov/citations/19760022053
Thermal conductivity / temperature string	Active measurement where known heat pulse is applied to determine thermal properties of penetrated material; useful for ice content, soil texture, and heat-flow interpretation. Size: S.	Deep Space 2 and LUNAR-A heritage.	Integrate-ready	Smrekar et al. (1999) J. Geophys. Res. Planets 10.1029/1999JE001073 Tanaka et al. (1999) Adv. Space Res. 10.1016/S0273-1177(99)00535-9
Volatiles / water / physical properties				
^3He neutron spectrometer	Uses ambient neutrons to non-invasively detect hydrogen-rich materials/volatiles; especially useful for mapping shallow ice or hydrated regolith with a penetrator array (e.g. permanently shadowed lunar regolith or mid-latitude subsurface ice on Mars.) Size: S–M.	Proposed for various planetary penetrator missions including Polar Night lunar penetrators; survived 1,400 g impact test.	Requalification needed	Lawrence et al. (2025) Earth Space Sci. 10.1029/2024EA004091 Mosher & Lucey (2006) Acta Astronaut. 10.1016/j.actaastro.2005.07.033
Cavity ringdown spectrometer	Laser spectrometer which uses precisely aligned mirror cavities for detailed volatile composition versus depth in lunar regolith. Size: S–M (CubeSat model is just over IMPRESS-345 payload size but must be heavily miniaturized for 1.5 kg SPIC penetrator).	SPIC Lunar penetrator payload option.	Requalification needed (shock-fragile)	Ahrens et al. (2021) Planet. Sci. J. 10.3847/PSJ/abda4f Gibson (2019) Appl. Opt. 10.1364/AO.58.001941
Evolved gas analyzer	Heats acquired regolith and measures trace volatile abundance and possibly isotopic ratios (e.g., D/H). Size: S	DS2 (flown, water-specific) and SPIC payload element. SPIC extends to broader volatile and isotopic analysis.	Integrate-ready	Ahrens et al. (2021) Planet. Sci. J. 10.3847/PSJ/abda4f Smrekar et al. (1999) J. Geophys. Res. Planets 10.1029/1999JE001073
Calorimetric volatile analyzer	Detects endothermic/exothermic phase changes or reactions during sample heating; useful for volatiles and bound-water screening. Size: S.	Part of LunarEX volatile analysis concepts.	Concept	Smith et al. (2009) Exp. Astron. 10.1007/s10686-008-9109-6

Instrument / payload	Description / use / size*	Penetrator relevance / heritage	Readiness for IMPRESS**	Primary references (DOI + link)
				Smrekar et al. (1999) J. Geophys. Res. Planets 10.1029/1999JE001073
Tunable-diode-laser volatile sensor	Optical sensing of released water vapor or other evolved gases after heating or exposure of subsurface samples. Size: S.	LunarEX volatile-analysis payload option.	Integrate-ready	Smith et al. (2009) Exp. Astron. 10.1007/s10686-008-9109-6
Permittivity meter	Electrical-property probe intended to constrain dielectric properties of asteroid material.	VESTA payload element.	Requalification needed	Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033 Langevin (1987) Adv. Space Res. 10.1016/0273-1177(87)90219-5
Geochemistry				
Laser-Induced Breakdown Spectroscopy	Elemental/mineralogical properties of subsurface minerals are derived from light spectra from cooling plasma after material is vaporized by laser. Size: S.	SPIC Lunar penetrator payload option.	Requalification needed	Ahrens et al. (2021) Planet. Sci. J. 10.3847/PSJ/abda4f
X-ray fluorescence spectrometer	X-ray bombardment causes outer-shell electrons to replace inner-shell electrons, causing characteristic fluorescence. Used to analyze major, minor, and trace elements in rocks, minerals, and regolith for prospecting, petrology, and context for biosignature interpretation. Size: S.	MoonLITE payload element; modern XRF instruments flown on planetary missions could be repurposed for penetrator use.	Requalification needed	Beck et al. (2020) Planet. Space Sci. 10.1016/j.pss.2020.104990 Yin & Trombka (1986) Nucl. Instrum. Methods Phys. Res. A 10.1016/0168-9002(86)90463-8 Gao et al. (2008) Planet. Space Sci. 10.1016/j.pss.2007.11.005 Smith et al. (2008) LPSC XXXIX abstract 1238. https://www.lpi.usra.edu/meetings/lpsc2008/pdf/1238.pdf
Laser-ablation mass spectrometer	Direct in situ elemental/isotopic analysis of solids with minimal sample handling using ultraviolet laser pulses to remove mineral layers from sample material; useful for exposed fracture surfaces or sample cups. Size: S–M.	Miniaturized planetary version demonstrated for in situ planetary work. May be adapted for penetrators.	Concept (shock-fragile)	Arevalo et al. (2014) Planet. Space Sci. 10.1016/j.pss.2013.09.007
X-ray/α/neutron spectrometer suite	Combined X-ray, alpha, and neutron spectrometers for elemental composition, water/ice indications, and physical-property interpretation. Size: L	Mars-96 science package element.	Requalification needed	Surkov & Kremnev (1998) Planet. Space Sci. 10.1016/S0032-0633(98)00071-3
Alpha Proton X-ray Spectrometer	Contact elemental analyzer with strong flight heritage where sample is bombarded with alpha particles which backscatter (light element detection) and excite X-ray fluorescence (heavy element detection); suitable where a penetrator exposes or contacts fresh subsurface material. Size: S–M.	Mars-96, Pathfinder, MER, MSL, and Philae heritage; not unique to penetrators but highly compatible.	Integrate-ready	Rieder et al. (1997) J. Geophys. Res. 10.1029/96JE03918 Biele (2002) Earth Moon Planets 10.1023/A:1021523227314 Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033 Lumpkin / Sandia (1974) NASA-CR-137587 report. https://ntrs.nasa.gov/citations/19750004806 Surkov & Kremnev (1998) Planet. Space Sci. 10.1016/S0032-0633(98)00071-3
Gamma-ray spectrometer	Remotely detects natural radioactivity and induced gamma lines for bulk elemental composition measurements of planetary minerals, volatiles, and comet material; housed in	Explicit Mars-96 science package element, core payload of the CRAF comet penetrator concept.	Requalification needed	Surkov & Kremnev (1998) Planet. Space Sci. 10.1016/S0032-0633(98)00071-3 Swenson et al. (1987) Acta Astronaut. 10.1016/0094-5765(87)90185-8

Instrument / payload	Description / use / size*	Penetrator relevance / heritage	Readiness for IMPRESS**	Primary references (DOI + link)
	the buried afterbody cylinder immediately below the surface. Size: XS–S			Swenson et al. (1985) AIAA/NASA NTRS report. https://ntrs.nasa.gov/citations/19850037614 Evans et al. (1986) J. Geophys. Res. 10.1029/JB091iB04p0D525 Becker et al. (2014) Nucl. Instrum. Methods Phys. Res. A 10.1016/j.nima.2014.05.096
Mass spectrometry / organics				
Raman and heterodyne fringe spectrometers	Compact spectrometers proposed for water chemistry, trace gases, organics, and mineralogical assessment in lunar penetrators. Size: small penetrator payload elements in the SPIC options table. Size: S–M	SPIC Lunar penetrator payload option; Raman spectrometry has non-penetrator heritage on Mars2020 and the upcoming Rosalind Franklin rover.	Concept	Ahrens et al. (2021) Planet. Sci. J. 10.3847/PSJ/abda4f Hutchinson et al. (2026) Nat. Rev. Methods Primers. 10.1038/s43586-025-00458-z
Ion-trap mass spectrometer	Analyzes evolved gases or sampled volatiles for isotope ratio analysis with good sensitivity in a compact package; a simplified ion-trap approach has been discussed specifically for penetrator and mole-based subsurface sampling. Size: M.	Ruggedized miniaturized instrument already flown in Ptolemy/Rosetta heritage; directly cited in LunarEX volatile-analysis work and explicitly discussed for high-speed penetrator and mole-delivered subsurface sampling.	Requalification needed	Sheridan et al. (2010) EGU General; ADS abstract. https://ui.adsabs.harvard.edu/abs/2010EGUGA..1215415S/abstract Todd et al. (2007) J. Mass Spectrom. 10.1002/jms.1147 Smith et al. (2009) Exp. Astron. 10.1007/s10686-008-9109-6
Volatile mass spectrometer	In situ volatile analyzer for identifying composition and abundance of cold-trapped volatiles (frozen gases and/or organics 10–300 amu) via m/z ratio and molecular weight on worlds like Mars, the moon, and Titan. Size: M–L (~1800 cm^3 in Polar Night test).	Principal instrument for Polar Night Lunar penetrators and Titan Penetrobe concept.	Requalification needed	Mosher & Lucey (2006) Acta Astronaut. 10.1016/j.actaastro.2005.07.033 Lawrence et al. (2025) Earth Space Sci. 10.1029/2024EA004091 Tindle et al. / Martin Marietta (1976) NASA CR-137847 report. https://ntrs.nasa.gov/citations/19760022053 Langevin (1987) Adv. Space Res. 10.1016/0273-1177(87)90219-5
Gas chromatograph	One of the asymmetric payload items proposed on the second VESTA penetrator for volatile/organic separation. Also included in the Titan Penetrobe concept as a complement for the mass spectrometer. Size: M–L (part of a < 4 kg payload).	VESTA and Titan Penetrobe payload element.	Concept	Langevin (1987) Adv. Space Res. 10.1016/0273-1177(87)90219-5 Lorenz (2011) Adv. Space Res. 10.1016/j.asr.2011.03.033 Tindle et al. / Martin Marietta (1976) NASA CR-137847 report. https://ntrs.nasa.gov/citations/19760022053
Differential scanning calorimeter	Candidate thermal-analysis instrument for phase/reaction signatures in Titan atmospheric and surface samples. Size: not specified; likely S due to programmable heater, temperature controller, and data acquisition + micro-sensors.	Candidate instrument in the Titan penetrator study.	Concept (shock-fragile)	Tindle et al. / Martin Marietta (1976) NASA CR-137847 report https://ntrs.nasa.gov/citations/19760022053
Chemically sensitive quartz microbalance array	Candidate chemical-sensing array discussed for Titan's atmospheric composition. Size: not specified in the report; likely S.	Candidate instrument in the Titan penetrator study.	Concept	Tindle et al. / Martin Marietta (1976) NASA CR-137847 report https://ntrs.nasa.gov/citations/19760022053
Sample acquisition / handling				

Instrument / payload	Description / use / size*	Penetrator relevance / heritage	Readiness for IMPRESS**	Primary references (DOI + link)
Sample acquisition drill and analysis chamber	Proposed sample-handling subsystem with miniature drill to bring local regolith into a common analysis chamber in probe forebody. Size: S	Flown DS2 science subsystem and payload element on proposed MoonLITE mission.	Integrate-ready	Gao et al. (2008) Planet. Space Sci. 10.1016/j.pss.2007.11.005 Smith et al. (2008) LPSC XXXIX Abstract 1238. https://www.lpi.usra.edu/meetings/lpsc2008/pdf/1238.pdf Smrekar et al. (1999) J. Geophys. Res. Planets 10.1029/1999JE001073 Lorenz et al. (2000) Planet. Space Sci. 10.1016/S0032-0633(00)00016-7
Communications / fields				
Charged-particle detector	Detector for cosmic rays and solar-wind particles, relevant to polar environments and lunar magnetic anomalies. Size: S	SPIC Lunar penetrator payload option.	Integrate-ready	Ahrens et al. (2021) Planet. Sci. J. 10.3847/PSJ/abda4f
Radio science package (SPIC, lunar penetrator concept)	Low-frequency radio / radio-science payload for libration studies, shallow subsurface investigations, and communications-network demonstrations. Size: XS–S	SPIC Lunar penetrator payload option.	Integrate-ready	Ahrens et al. (2021) Planet. Sci. J. 10.3847/PSJ/abda4f

*XS: micro-components
S: small instrument for IMPRESS-345 class ≤305 cm^3 volume
M: medium instrument for 12 kg classes
L: large instrument for 30+ kg classes

**Integrate-ready = plausible near-term integration to penetrator (size-independent) after IMPRESS packaging/interface work
Requalification needed = heritage exists but high-g/thermal/interface testing is required
Concept = proposed but not yet demonstrated for penetrator use.
Shock-fragile = payload is potentially shock-fragile and likely needs modification to withstand high-g-forces

Table S3. Astrobiology-relevant payloads

Table S3 expands on the astrobiology-relevant subset of instruments surveyed in Table S2 and adds life-detection-specific payloads not covered in S2. Development stage labels describe the maturity of the detection method itself, distinct from the penetrator-integration readiness assessed in Table S2.

Payload / development stage	Description / use / size	Target Biosignature	Null Hypothesis	Controls for Abiotic Factors	Penetrator relevance / heritage	Suitability for Penetrator***	Primary references (DOI + link)
Astrobiology / Biosignature Detection							
Microscope (Concept; optics heritage tested)	Images crystal/grain structure and regolith texture at microscopic scale; especially useful when paired with compositional spectrometers. Size: S.	May support morphology studies (e.g. microbial sheaths, and precipitated microfossils)	Morphology is due to abiogenic structures resembling microfossils	Confirm mineralogy via spectrometer; compare with Earth analogue samples; check chirality	SPIC Lunar penetrator payload option, may be adapted for biosignatures.	**Suitable**: Imaging optics plausible; no complete microscope high-g demo.	Ahrens et al. (2021) Planet. Sci. J. 10.3847/PSJ/abda4f Govinda Raj et al. (2022) Front. Astron. Space Sci. 10.3389/fspas.2022.943594
Icy Moon Penetrator Organic Analyzer (IMPOA)	Laser fluorometer for detection of biomolecules, pigments; useful as a rapid low-mass life-screening payload. Combine with chirality assay or Raman spectrometer to determine biogenicity. Size: S.	Polycyclic aromatic hydrocarbons, amino acids, other organic molecules, antibody-bound biomarkers	Fluorescence from organics delivered by meteoric infall or synthesized by abiotic processes or from contamination	Blanks; contamination control; Raman/chirality confirmation.	Allows rapid biosignature screening with minimal sample handling; Laser-Induced Fluorometer tested as penetrator payload for organic detection on icy moons	**Suitable**: In preliminary tests LIF optics mostly survived; glass microfluidics and laser packaging need redesign.	Smith et al. (2014) J. Biol. Eng. 10.1186/1754-1611-8-16 Govinda Raj et al. (2022) Front. Astron. Space Sci. 10.3389/fspas.2022.943594 Parro et al. (2011) Astrobiology 10.1089/ast.2010.0501 Parro et al. (2008) Astrobiology 10.1089/ast.2007.0126
Multispectral Microscope (Concept)	Microscopic color / multispectral imaging of grains, films, textures, and putative cellular morphologies in collected samples. Size: S.	Geometric patterns combined with chemical spectra	Morphology and mineralogy formed abiotically	Compare with Earth analogue samples; check chirality	Proposed for BOLD penetrator concept.	**Conditionally suitable:** Complex optics require high-g testing; power may limit use.	Núñez et al. (2014) Astrobiology 10.1089/ast.2013.1079 Schulze-Makuch et al. (2012) Planet. Space Sci. 10.1016/j.pss.2012.03.008
Chiral labeled-release / chirality assay (Concept)	Tests differential metabolism or reaction of L- and D-substrates to discriminate biological from abiotic reactivity. Size: S.	Chiral metabolism: Life is likely to have enantiomer-selective metabolism	Abiotic enantioselective chemistry or contamination	Label release of both enantiomers could be due to abiotic chemistry, or due to lack of life preference. Use multiple chiral substrates.	Viking-successor concept compatible with penetrators. Included as a chirality experiment in BOLD concept.	**Suitable:** Chiral label release is designed for penetrator use; simple sample collection and reagent release	Anbar and Levin (2012) LPI abstract https://www.lpi.usra.edu/meetings/marsconcepts2012/pdf/4319.pdf Schulze-Makuch et al. (2012) Planet. Space Sci. 10.1016/j.pss.2012.03.008

Payload / development stage	Description / use / size	Target Biosignature	Null Hypothesis	Controls for Abiotic Factors	Penetrator relevance / heritage	Suitability for Penetrator***	Primary references (DOI + link)
Astrobiology / Biosignature Detection							
TWEEL Metabolic incubation package (Concept)	Tests for metabolism via integrated sample handling, wet chemistry, and incubation while maintaining cleanliness. Size: M–L.	Metabolic gas or chemical change after sterile incubation	Abiotic reaction, leakage, or contamination.	Replicate sterile analyzers; abiotic blanks; varied substrates.	Classic low-mass life-detection architecture relevant to larger penetrators or penetrator-delivered sample modules.	**Suitable:** TWEEL architecture is meant to gather sterile samples by ejecting from lander and emplacing in the subsurface; potentially adaptable; needs high-g validation.	Levin and Miller (2003) Proc. SPIE. 10.1117/12.457312
Urey organic and oxidant detector (Mature method, not impact hardened)	Extracts organics and detects oxidants to characterize both trace organic abundance and the oxidizing environment that may destroy them. Size: M–L.	Trace organics, including amino acids, via subcritical-water extraction.	Organics may be introduced or not be biogenic.	Pair with GC-MS/Raman.	Strong reference architecture for compact life-detection chemistry payloads that can be adapted to larger penetrators; however, it has many complex parts.	**Needs significant development:** The original Urey experiment is likely too complex.	Aubrey et al. (2008) Astrobiology 10.1089/ast.2007.0169 Bada et al. (2008) Space Sci. Rev. 10.1007/s11214-007-9213-3
Antibody microarray immunoassay (Mature method, not impact hardened)	Detects biomolecules and broad molecular targets using multiplexed antibodies; powerful for targeted biosignature surveys. Size: S–M.	Detects array of selected organic molecules via fluorescent immunoassay with specific binding properties	Antibody binding is highly specific. Contamination and cross-reactivity.	Strict control for forward contamination and onboard null control with a sterile sample to subtract background signal.	Well-developed Mars-life-detection platform (SOLID2, ExoMars LMC). May be compatible with planetary penetrator.	**Suitable:** Antibody detection further developed after ExoMars descoping, robust and miniaturized (≤1 kg), Intended for use on Enceladus	Parro et al. (2008) Astrobiology 10.1089/ast.2007.0126 Rix et al. (2011) Astrobiology 10.1089/ast.2011.0662 Sims et al. (2012) Planet. Space Sci. 10.1016/j.pss.2012.04.007
BOLD-style integrated penetrator biology package (Concept)	Bundles imaging, chirality, nanopore, fluorescence, and environmental sensing into a combined biology payload for a small penetrator mission. Size: M–L.	See individual experiments (multispectral imager, chirality assay, fluorescent stain, nanopore)	See individual experiments (multispectral imager, chirality assay, fluorescent stain, nanopore)	Concordant positives across orthogonal assays reduce false positives.	BOLD proposes larger lander/penetrators. For IMPRESS, the BOLD suite could be distributed across multiple probes for a holistic analysis of a given area.	**Suitable**: Fluorescence and microfluidics have precedent in IceShIP testing. Other instruments may require downscaling	Schulze-Makuch et al. (2012) Planet. Space Sci. 10.1016/j.pss.2012.03.008 Schulze-Makuch et al. (2007) Proc. SPIE 10.1117/12.732155

Payload / development stage	Description / use / size	Target Biosignature	Null Hypothesis	Controls for Abiotic Factors	Penetrator relevance / heritage	Suitability for Penetrator***	Primary references (DOI + link)
Astrobiology / Biosignature Detection							
Fluorescent stain / viability microscopy (Concept)	Uses fluorogenic stains to distinguish cells or biomaterial from the mineral background; relevant to low-biomass life-detection screening. Size: S.	Activation of membrane permeable dyes that fluoresce via esterase activity, redox activity, or DNA binding.	Fluorescence signal is due to abiotic mineral fluorescence, non-biological organic matter, or contamination.	Pair with microscope/spectrometer for morphological and chemical context. False negatives are more likely than false positives; Martian cells may lack analogous esterases or polyelectrolyte binding sites, so negative results should be interpreted cautiously.	Included in the BOLD concept penetrator payload suite.	**Suitable**: Stains are widely used; fluorescence hardware has gas-gun heritage from IceShIP project.	Govinda Raj et al. (2022) Front. Astron. Space Sci. 10.3389/fspas.2022.943594 Schulze-Makuch et al. (2012) Planet. Space Sci. 10.1016/j.pss.2012.03.008
Nanopore-ARROW biosensor (Concept)	Single-molecule optofluidic biosensor concept for detecting biopolymers or other macromolecular targets in minute sample volumes. Size: S.	Detection of polyelectrolytes + polypeptides	False positives possible: contamination, abiotic polymers, artifacts	Pairing with a Raman spectrometer and/or chirality assay could provide molecular context and help assess biogenicity.	Proposed for the BOLD penetrator concept.	**Suitable:** Microfluidic channels may be adapted for use with planetary penetrators.	Deamer et al. (2007) Proc. SPIE. 10.1117/12.732235 Schulze-Makuch et al. (2012) Planet. Space Sci. 10.1016/j.pss.2012.03.008

*** Suitable = detection method and hardware are compatible with penetrator delivery with minor adaptation.
Conditionally suitable = method is promising but requires substantial engineering development or high-g qualification.
Needs significant development = method is too complex for current penetrator platforms without major redesign.