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EDITORIAL

Extraterrestrial *in-situ* resource utilization: from technology demonstrations to long-term planetary infrastructure

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In-situ resource utilization (ISRU) beyond Earth is moving from a peripheral task in deep-space exploration to a foundational capability for future missions to the Moon, Mars, Venus, and small bodies. Its significance is not limited to reducing the launch cost of materials transported from Earth. More fundamentally, ISRU enables long-duration presence, regional mobility, resilient energy supply, *in-situ* construction, sample return, and the sustainable expansion of planetary exploration. In this sense, ISRU is no longer a single-device or single-process problem. It is becoming a long-term system that connects planetary science, deep-space engineering, and the emerging space economy.

Internationally, ISRU has become a strategic theme in the renewed era of deep-space exploration. NASA's Artemis program frames sustainable lunar exploration as a pathway toward Mars, with lunar polar volatiles, solar power, oxygen production, and local construction materials among its central concerns. On Mars, the MOXIE experiment aboard Perseverance has demonstrated oxygen production from the Martian atmosphere, marking an important transition from terrestrial validation to planetary-surface operation. The European Space Agency and commercial actors are also advancing technologies for oxygen extraction from lunar regolith, *in-situ* construction, robotic processing, and polar resource prospecting. Across these efforts, the field is shifting from demonstrating that a process can work to demonstrating that it can operate continuously, reliably, and maintainably within a mission architecture.

China's ISRU research is closely linked with the Chang'E lunar exploration program, deep-space exploration, and the planning of the International Lunar Research Station (ILRS). The Chang'E-5 and Chang'E-6 sample-return missions have greatly advanced studies of lunar regolith mineralogy, volatiles, and space weathering. Chang'E-7, Chang'E-8, and subsequent missions are expected to further emphasize the lunar south-polar environment, resource prospecting, surface construction, and *in-situ* utilization demonstrations. Chinese research teams are already active in regolith sintering, microwave and laser processing, lunar energy systems, robotic construction, volatile detection, and planetary atmospheric spectroscopy, forming a broad technical foundation for future resource-oriented missions.

The next stage of ISRU research will be shaped by four closely related challenges. The first is resource ground truth: remote-sensing signatures, returned-sample properties, and *in-situ* recoverability must be connected through more quantitative frameworks. The second is process robustness: dust, vacuum, thermal cycling, radiation, low gravity, rough terrain, and equipment degradation can all affect resource processing efficiency. The third is system closure: energy supply, thermal control, logistics, construction, maintenance, and waste recycling must be optimized together rather than treated as isolated subsystems. The fourth is governance: resource utilization must develop in parallel with scientific preservation, environmental disturbance assessment, planetary protection, and international norms.

The enduring significance of Planet's regular column lies in its capacity to follow ISRU through a continuous arc of development—from theoretical conception to flight-ready hardware, from ground-based experiments to *in-situ* missions, and from lunar pioneering to multi-planet infrastructure. Future contributions may further address lunar polar

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ice and volatile prospecting, oxygen and metal extraction from regolith, standards for *in-situ* construction materials, energy networks in extreme environments, autonomous resource operations, Martian CO_2 conversion, Venusian atmospheric chemistry utilization, and resource assessment for small bodies.

The durability of extraterrestrial ISRU derives from the durability of humanity's deep-space ambitions. Its integrative character derives from the fact that no resource can be separated from energy, environment, hardware, mission design, or governance. The papers in this column illustrate this point through diverse technological pathways and planetary settings. As the ILRS, Artemis, lunar south-polar exploration, Mars oxygen-production demonstrations, and Venus atmospheric investigations continue to advance, ISRU will increasingly stand at the intersection of planetary science and space engineering, and will become one of the defining themes of deep-space exploration in the coming decade.