Lunar Helium-3 Mining: System Architecture and Extraction-Separation Technologies

Chengdeng Cao, Jiafeng Xie, Lingfeng Sun, Dong Li, Siyu Teng, Yuchen Li, and Long Chen

***Abstract*—As an ideal clean fusion fuel, helium-3 (^{3}He) holds broad application prospects. However, its terrestrial reserves are extremely scarce, whereas lunar regolith contains abundant ^{3}He, making large-scale *in-situ* mining crucial. Because it exists in extremely low concentrations and is primarily enriched within the surface lattices of minerals, such as fine-grained ilmenite, extracting ^{3}He requires a complex and multi-disciplinary engineering system involving physical excavation and thermal processing. This paper presents an architecture for large-scale *in-situ* ^{3}He mining that encompasses four main stages: excavation, sorting, extraction, and purification. It also defines the collaborative operational workflows among these stages. Building on this framework, this paper introduces an integrated lunar regolith collection vehicle capable of large-scale excavation and sorting, alongside a detailed process flow for ^{3}He extraction and purification. The mining architecture and process flows proposed in this paper establish a theoretical foundation and technical reference for the engineering implementation of future *in-situ* lunar ^{3}He mining.**

***Index Terms*—Helium-3 (^{3}He) mining, ^{3}He distribution, mining architecture, lunar regolith collection vehicle, ^{3}He extraction and purification**

I. Introduction

As an ideal clean nuclear fusion fuel, helium-3 (^{3}He) possesses the significant advantage of a low neutron yield [1, 2] and requires only 100–200 t to meet the global energy demand for an entire year [3]. However, the natural reserves of ^{3}He on Earth are extremely scarce (approximately 0.1–20.0 t) [4, 5], whereas the lunar regolith is enriched with millions of tons of ^{3}He because of the long-term bombardment by the solar wind [2, 6]. Therefore, *in-situ* mining of lunar ^{3}He has become a pressing frontier challenge in the field of deep space exploration.

Large-scale *in-situ* ^{3}He mining and extraction constitutes a complex multidisciplinary systems engineering challenge. Since ^{3}He in lunar regolith does not occur freely, but is primarily concentrated on the surfaces and within the crystal lattices of fine-grained minerals such as ilmenite [4, 7], the complete process entails not only physical excavation, but also crucial steps such as regolith sorting, ^{3}He thermal desorption (especially from fine-grained and ^{3}He-rich ilmenite), and ^{3}He purification from massive impurity gases. The extreme lunar environment, notably its low gravity, can cause conventional excavation equipment to fail. To address low-gravity and soft regolith conditions, Green et al. [8] developed CASPER, an auger-propelled lightweight excavation robot that stores raw regolith directly in a hopper. Similarly, Schuler et al. [9] designed IPEx, a planetary soil excavation robot that utilizes a bucket-drum structure to effectively counteract equipment tipping caused by excavation reaction forces, storing the material within the drum. Despite their safe and efficient excavation capabilities, these robots face a critical limitation: ilmenite constitutes an extremely small fraction of the raw regolith. Transporting unprocessed regolith directly leads to a disproportionately high non-target payload, resulting in severe energy inefficiency. Additionally, current studies on ^{3}He sorting, extraction, and purification mostly concentrate on isolated process methods [5, 10, 11], lacking system-level integration.

Currently, a few studies have conducted preliminary explorations on the system architecture for ^{3}He mining, with the primary approach being the high integration of the entire process into a single device. For instance, the Mark III developed by Gajda [12] and the design proposed by the USA company Interlune both concentrate all mining stages onto a single large mobile platform. Although this highly integrated approach eliminates the round-trip transportation of non-target regolith, the mobile platform must carry all processing equipment during operation. This not only results in enormous mobility energy consumption, but also creates a highly coupled internal system with low fault tolerance and a failure in a single stage that will lead to the shutdown of the entire mining system.

To address the aforementioned issues, this paper proposes a

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novel ^{3}He mining architecture, detailing the equipment design concepts for the excavation and sorting stages as well as the operational workflow for the extraction and purification stages under this framework. A schematic diagram of ^{3}He mining is shown in Fig. 1. The integrated lunar regolith collection vehicle primarily collects ilmenite from the raw lunar regolith, which is subsequently transported back to the lunar base by transfer equipment. Equipment within the lunar base then extracts and purifies the ^{3}He. The main contributions are summarized as follows:

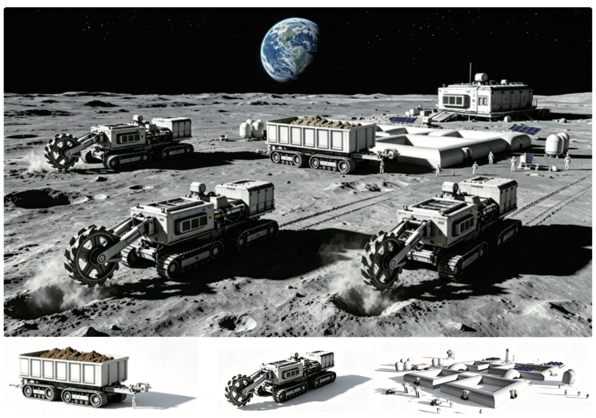

Fig. 1 Schematic diagram of ^{3}He mining. The lunar surface environment is generated by Nano Banana 2.

(1) Regarding the high coupling and low fault tolerance of multi-stage integrated architectures, a decoupled mobile-stationary mining architecture featuring mobile-end excavation and sorting and lunar base-end extraction and purification is proposed. By decoupling excavation and sorting to a mobile platform and stationing extraction and purification at the lunar base, this architecture not only avoids the long-distance transportation of non-target materials, but also achieves physical decoupling between stages. Consequently, a single equipment failure will not paralyze the entire mining process.

(2) Regarding the energy waste associated with transporting raw *in-situ* regolith, a design concept for an integrated lunar regolith acquisition rover is proposed. The *in-situ* processing workflow from raw regolith to ilmenite concentrate, along with the methodology for each step, is defined. This enables the *in-situ* enrichment and volume reduction of target minerals, thereby drastically reducing the energy consumption required for the long-distance transport of non-target materials.

(3) Regarding the ^{3}He extraction and purification processes, a coupled mechanical comminution-pyrolysis extraction and two-stage purification workflow is proposed. Based on the occurrence characteristics of ^{3}He, mechanical comminution is utilized to disrupt the mineral lattice and expose fresh particle surfaces, synergizing with pyrolysis to facilitate ^{3}He release. The purification process is divided into two steps: eliminating non-helium isotope impurity gases and subsequently achieving the preliminary separation and enrichment of ^{3}He/helium-4 (^{4}He).

II. Occurrence Mode and Distribution of ^{3}He

Terrestrial ^{3}He typically forms localized enrichments in regions such as mid-ocean ridges and volcanic activity zones, whereas lunar ^{3}He is more widely distributed because of processes such as solar wind implantation. The distribution and occurrence modes of ^{3}He hold significant reference value for the *in-situ* extraction of ^{3}He. The distribution informs the selection of excavation areas and depths, while the occurrence modes guide the choice of sorting and extraction methods. The occurrence mode and distribution of ^{3}He are of crucial importance for its extraction.

A. Occurrence State of ^{3}He

The enrichment level of ^{3}He is influenced by multiple factors, including solar wind flux, mineral composition, particle size, and the physical structure of lunar regolith particles. Lunar regolith comprises various minerals, such as plagioclase, pyroxene, olivine, and ilmenite. Among these, ilmenite exhibits the strongest helium retention capacity [7]. The ^{3}He in ilmenite particles can be 10 to 100 times higher than that in other minerals of comparable particle size [4, 13]. Since ^{3}He is mainly concentrated in the outer layer of ilmenite particles, and because smaller particle size leads to a larger specific surface area, there is an obvious inverse relationship between the ^{3}He content and particle size. Approximately 90% of the helium is concentrated in the fine-grained fraction with a particle size of less than 100 μm [14]. The occurrence modes of helium exhibit diversity. First, after being injected by the solar wind, helium predominantly occupies the vacancies or interstices in the mineral lattice, which represents the most fundamental occurrence mode [6, 15]. Second, the study relying on the samples from the Chang'e-5 mission has discovered that helium bubbles with a size ranging from 5 to 25 nm are commonly present in the amorphous glass layer formed on the particle surface via space weathering [10, 16]. In addition, a small amount of free helium, which has neither entered the crystal lattice nor formed bubbles, remains in the pores of the lunar regolith, though its binding force is extremely weak.

B. Distribution of ^{3}He

This subsection analyzes the distribution characteristics of lunar ^{3}He from both horizontal and vertical perspectives, focusing on its spatial heterogeneity across different geological units and the debated variation pattern with regolith depth.

a. Distribution Characteristics of the Lunar Surface

The distribution of ^{3}He on the lunar surface exhibits spatial heterogeneity, resulting from the synergistic effects of factors such as solar wind flux, mineral composition, and lunar regolith maturity [17, 18]. The injection flux of solar wind is influenced by latitude and the Earth's magnetic tail. First, as the solar wind ion flow is approximately parallel to the lunar orbital plane, the flux per unit area in high-latitude regions decreases because of the increase in the incident angle. Consequently, the equator and the mid-latitude and low-latitude regions (60° S–60° N) serve as the main channels for ^{3}He injection. Second, because of the shielding effect of the Earth's magnetic tail, there are substantial differences in the solar wind exposure conditions between the near side and the far side of the Moon under the same mineral conditions [7]. However, the actual distribution of ^{3}He abundance does not depend solely on the flux. Mineral composition plays a decisive role. From the perspective of geological units, the ^{3}He abundance in lunar mare regions is generally higher than that in the lunar highlands. The fundamental reason is that lunar mare basalts are rich in ilmenite [19, 20]. The ilmenite lattice contains specific structural sites that are conducive to the capture and retention of helium atoms and its capacity to retain helium is significantly greater than that of olivine and pyroxene [21, 22]. Consequently, high-titanium mare regions typically correspond to strong ^{3}He enrichment zones, whereas low-titanium highlands are relatively depleted [4].

When the spatial difference of solar wind flux is superimposed on the mineral distribution, the mineral factor typically plays a dominant role. Although the theoretical injection flux on the far side of the Moon is higher, because of the extensive development of lunar maria rich in ilmenite on the near side, the high-value areas of ^{3}He are still highly concentrated in the high-titanium lunar maria regions at low and middle latitudes on the near side [23], such as the Mare Tranquillitatis, Oceanus Procellarum, Mare Crisium, and Grimaldi Crater [7, 15, 24]. Only a few high-titanium anomaly areas on the far side (e.g., the Mare Moscoviense) exhibit a relatively high enrichment degree. In regions such as Oceanus Procellarum, Mare Orientale, Mare Fecunditatis, Mare Crisium, Mare Moscoviense, and Apollo Basin, the ^{3}He content is generally at a medium level, ranging from 10 to 15 part per billion (ppb). The maximum content can reach approximately 24 ppb, which is mainly distributed in the local lava areas of Grimaldi and Riccioli Craters, the southwestern part of Oceanus Procellarum, the northeastern part of Mare Fecunditatis, the northwestern part of Mare Tranquillitatis, the eastern part of Mare Crisium, and the southern part of Mare Moscoviense. These are core high-titanium zones [24].

b. Vertical Distribution Characteristics

Compared with the horizontal heterogeneity, the vertical distribution of ^{3}He in lunar regolith remains debated. The two prevailing models are exponential decay and approximately uniform distribution [25]. The exponential decay model highlights the shallow penetration of solar wind implantation and the depth limitation of impact gardening. Since the frequency and intensity of the transportation of surface ^{3}He rich materials to the deep by micrometeorite impacts decrease sharply with depth, the degree of reprocessing of the deep lunar regolith is significantly reduced. Therefore, it is theoretically inferred that the ^{3}He content and other substances implanted by the solar wind decrease with depth. This model has also been adopted by some studies for vertical profile characterization and reserve assessment [4, 26]. However, in the lunar environment characterized by the absence of an atmosphere and tectonic activity, the high frequency and random impacts of micrometeorites over a period of up to 4 billion years exert a continuous fragmentation and stirring effect on the lunar surface materials under low gravity conditions, which may weaken the vertical gradient. The analysis of samples retrieved from drill holes approximately 3 m deep, collected during the Apollo 15–17 missions, confirms this. The ^{3}He content in these samples does not exhibit an obvious regular decline as the depth increases [19, 27, 28]. Consequently, homogenization studies apply constant functions to construct vertical profiles and calculate resource quantities [7, 27].

C. Influence of Distribution on ^{3}He Mining

The surface and vertical distributions of ^{3}He have a significant impact on its mining. The surface distribution determines the specific mining locations. For instance, regions with high ^{3}He abundance, such as Oceanus Procellarum, are more suitable for mining. However, within these regions, it is necessary to clarify the vertical distribution characteristics of ^{3}He to determine the mining strategy. The exponential decay equation is given by Refs. [4, 7, 26]

$$\rho(z) = \exp\left(-\frac{z}{3}\right) \tag{1}$$

where z represents the depth, with a maximum value of 3 m. Taking the Chang'e-3 landing site as an example, under the assumption of exponential decay of ^{3}He, approximately 37 ± 2 g of ^{3}He exists in a 445 m^2 area, whereas under the assumption of uniform distribution, there is about 51 ± 2 g of ^{3}He. For the same volume of lunar regolith, the variance between these two assumptions is substantial. Given a constant front-end regolith collection rate, the efficiency of subsequent extraction and purification stages must be determined based on the vertical distribution. Furthermore, at a depth of 2 m, the ^{3}He content attenuates by approximately 48%, and at 3 m, it attenuates by about 68%. The excavation depth shall be dynamically evaluated in real time based on the ^{3}He concentration. For example, when the concentration attenuates by 68%, it is necessary to assess whether the lunar regolith collected by the current excavation equipment can yield sufficient ^{3}He without imposing an excessive processing burden and energy consumption on downstream equipment. Conversely, under the uniform distribution assumption, direct mining in the current area is sufficient. Therefore, during future mining operations, *in-situ* probing of the vertical distribution in the mining area shall be conducted to update the concentration profile information in real time.

III. Overall Architecture of ^{3}He Mining

The ^{3}He content in lunar regolith is extremely low. Samples from the Chang'e-3 mission indicate that the ^{3}He content in the landing area is 6.74 ppb [5]. Based on this value, approximately 148 t of lunar regolith is required to extract 1 g of ^{3}He. Considering the abundance, occurrence mode, and relevant physicochemical properties of ^{3}He, this paper divides the entire lunar surface ^{3}He mining process into four stages: excavation, sorting, extraction, and purification, as shown in Fig. 2. There is no significant operation overlap between these stages. Nevertheless, collaborative operations among the stages are necessary during the mining process. Hence, it is of great importance to design the overall framework for ^{3}He mining based on the operation characteristics of each stage.

A. ^{3}He Mining Stage

Excavation is the starting point of the entire ^{3}He mining process, primarily entailing the large-scale collection of raw lunar regolith from regions on the lunar surface where ^{3}He is

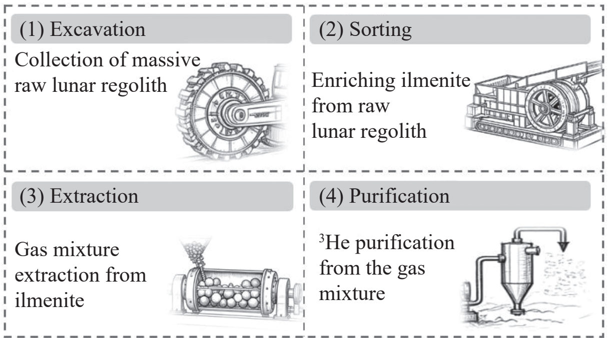

Fig. 2 Process flow of ^{3}He excavation, sorting, extraction, and purification.

relatively concentrated. Given that the content of ^{3}He in lunar regolith is extremely low, the mining capacity directly sets the upper limit of production for all subsequent systems. This stage must be characterized by a high level of automation and fault tolerance. Once the equipment malfunctions and stops operating, the downstream large-scale and energy-intensive systems will be compelled to remain idle.

Sorting involves precisely separating ilmenite rich in ^{3}He from the original lunar regolith with complex components after the enrichment of the raw lunar regolith and removing useless minerals with low helium capture ability, such as pyroxene, plagioclase, and olivine. The significance of this stage is that it can significantly reduce the amount of materials to be processed and the huge energy consumption in the subsequent extraction process, and avoid the interference of useless impurities. In addition, since ^{3}He mainly exists in ilmenite and ilmenite has certain magnetism compared with other minerals, the main task in the sorting process is to enrich ilmenite in the raw lunar regolith.

Extraction is the core step in the mining of ^{3}He. It primarily entails applying external energy (such as pyrolysis at 700 °C or mechanical crushing at room temperature) to disrupt the crystal lattices or bubbles that store ^{3}He in ilmenite, thus releasing ^{3}He. The resulting product is a mixed gas containing ^{3}He, ^{4}He, CO_2, H_2, etc. [29].

Purification is the final stage in the entire ^{3}He extraction process. It primarily centers on the refined separation of the mixed gases, including ^{3}He and ^{4}He, extracted in the previous phase. Given that the properties of ^{3}He and ^{4}He are extremely similar, which makes their separation arduous, the purification process can be mainly divided into two steps. The first step involves separating He isotopes from impurity gases like H_2. The second step is to separate ^{3}He and ^{4}He. This step not only yields highly refined products, but also significantly compresses the volume of the products, effectively reducing the transportation cost between the Earth and the Moon and enhancing the economic value.

B. ^{3}He Mining Architecture

Considering the operational characteristics and collaborative features of the aforementioned stages, this paper proposes a ^{3}He mining architecture. This architecture employs a divergent structure. In this structure, the front-end carries out large-scale beneficiation of ilmenite from the original lunar regolith, while the back-end centrally and flexibly extracts ^{3}He from the ilmenite. This architecture primarily adopts a distributed front-end and centralized back-end structure. The front-end enables large-scale enrichment of ilmenite from raw lunar regolith, while the back-end performs centralized and flexible extraction of ^{3}He from the enriched ilmenite. Specifically, excavation and sorting are highly integrated into large-scale mobile equipment to form an integrated excavation and sorting unit. This unit discards waste minerals directly at the mining site, retaining only ilmenite. Such *in-situ* processing of raw lunar regolith avoids long-distance transportation of barren minerals, thereby eliminating the massive energy consumption otherwise required. Subsequently, the ilmenite will be transported directly back to the lunar base via point-to-point transfer equipment and the same equipment will return supplementary energy to the front-end equipment. In addition, the extraction and purification processes involve complex equipment, high energy consumption, a large footprint, and extremely stringent thermal management requirements. Therefore, they are centrally deployed at the lunar base. Leveraging the base's inherent storage capability, these processes can flexibly schedule operations according to the lunar surface's environmental conditions (e.g., using solar concentrating heating for extraction during the lunar day and passive pre-cooling to ultra-low temperatures for purification during the lunar night). This approach minimizes overall transportation costs and mobile energy consumption while simultaneously optimizing mining efficiency, process flexibility, and energy utilization. During the purification process, the separation process is complex because of the similar properties of ^{3}He and ^{4}He. Additionally, the mass ratio of ^{3}He to ^{4}He in the mixed gas extracted at a high temperature of 700 °C is extremely low, approximately 1:3100 [5]. Therefore, equipment with controllable complexity and cost can be employed to perform preliminary purification of ^{3}He and ^{4}He on the lunar surface, and subsequently, the crude products can be transported back to the Earth for refined purification.

Regarding the uncertainty in the vertical distribution of ^{3}He, it is essential to deploy mobile ^{3}He measurement devices (e.g., quadruped robots) on the lunar surface to measure its vertical profile in real time and to update the lunar surface ^{3}He distribution on the basis of remote sensing data. The resulting high-resolution ^{3}He distribution map can guide the selection of excavation areas and depths, thereby avoiding inefficient energy consumption caused by uncertainty in deep subsurface ^{3}He distribution.

IV. Lunar Regolith Collection Vehicle Design

A. Lunar Regolith Enrichment and Processing Technology

Because of the low content of ^{3}He in lunar regolith, a large amount of raw lunar regolith needs to be collected to enrich a certain amount of ^{3}He. Therefore, in the excavation stage, high-efficiency continuous excavation shall be the primary goal and priority shall be given to the excavation of high-titanium mare and other enriched areas. At the same time, since about 90% of ^{3}He is highly concentrated in fine-grained lunar soil with a particle size of less than 100 μm, the operation process must be equipped with a strict dust prevention and sealed collection mechanism to prevent the escape of the target product. In addition, *in-situ* coarse screening shall be introduced to remove large waste rocks in advance to reduce the processing load in subsequent stages. After the enrichment and initial screening of raw lunar soil, all lunar regolith shall be processed for ilmenite enrichment. Since ^{3}He is mainly present in ilmenite with certain magnetic properties, magnetic sorting can be used to remove pyroxene, plagioclase, and olivine, and other coarse-grained useless minerals with extremely low helium capture capacity, and only retains fine-grained ilmenite concentrate with high helium content. Zhang et al. [30] utilized magnetic sorting to enrich ilmenite from lunar regolith under vacuum conditions. For a particle size of 50 μm, the concentrate grade reaches 98.6% with a recovery rate of 93.2%. For a particle size of 100 μm, the concentrate grade is 98.0% with a recovery rate of 100.0%. This indicates that magnetic sorting can achieve excellent sorting results on the lunar surface, making it well-suited for integration into the current system. This integrated architecture of excavation and sorting can significantly reduce the huge volume of raw lunar soil to a small volume of enriched materials at the source, avoiding the huge energy consumption caused by the long-distance transportation of useless minerals.

B. Integrated Lunar Regolith Collection Vehicle

Based on the lunar regolith enrichment and processing technologies described above, we design an integrated lunar regolith collection vehicle capable of performing both mining and sorting operations. The front-end of the collection vehicle can be equipped with a wide bucket-wheel device to ensure continuous collection of large quantities of raw lunar regolith. Immediately following it are a series of multi-stage vibrating screens and magnetic separation modules, which enable immediate capture of fine-grained ilmenite and *in-situ* separation of impurity minerals. After enrichment, the ilmenite is either retained in a vehicle-mounted sealed cabin or discharged via conveyor belts, whereas the remaining minerals are directly backfilled. The workflow design of the integrated lunar regolith collection vehicle is shown in Fig. 3. Operationally, equipped with sensors and artificial intelligence (AI) technologies, the integrated lunar rover exhibits highly autonomous navigation and robust fault tolerance, traversing the worksite according to the ^{3}He distribution map. The enriched ilmenite is then transferred to specialized transport equipment either during or upon completion of excavation, which subsequently hauls it back to the lunar base.

V. ^{3}He Thermal Extraction and Gas-Solid Separation Systems

After ilmenite enrichment, the solar-wind-implanted volatiles stored in lunar regolith must be released and separated to obtain usable ^{3}He. During extraction, multiple gaseous species, including H_2, CO, CO_2, H_2O, CH_4, N_2, ^{4}He, and other volatile products, are simultaneously generated [5, 31]. Therefore, efficient *in-situ* gas-solid separation is a critical prerequisite for lunar ^{3}He utilization, as it directly determines extraction purity, recovery efficiency, and the operational stability of downstream storage and transport systems.

At present, lunar ^{3}He extraction technologies can be broadly divided into three categories according to their energy-input mechanisms: high-temperature thermal desorption extraction, microwave-assisted extraction, and room-temperature mechanical extraction, as shown in Fig. 4. Among them, thermal desorption and microwave-assisted extraction belong to thermal desorption methods, in which volatile release is achieved through heating, while mechanical extraction relies on physical fracture of surface bubbles and amorphous layers to release weakly bound helium. These technologies are not strictly sequential processes, but rather alternative technical routes designed for different energy conditions and engineering requirements. Future lunar mining systems may also combine multiple approaches, such as mechanical pretreatment followed by thermal extraction, to improve the overall recovery efficiency.

A. High-Temperature Thermal Desorption Extraction Technology

High-temperature thermal treatment is considered a promis-

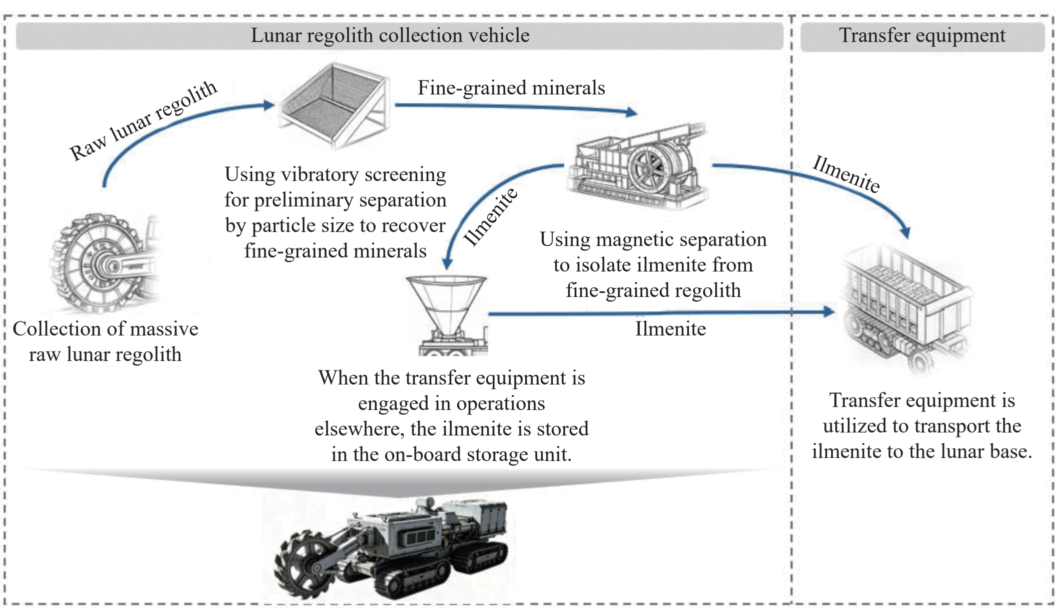

Fig. 3 Workflow design of the integrated lunar regolith collection vehicle.

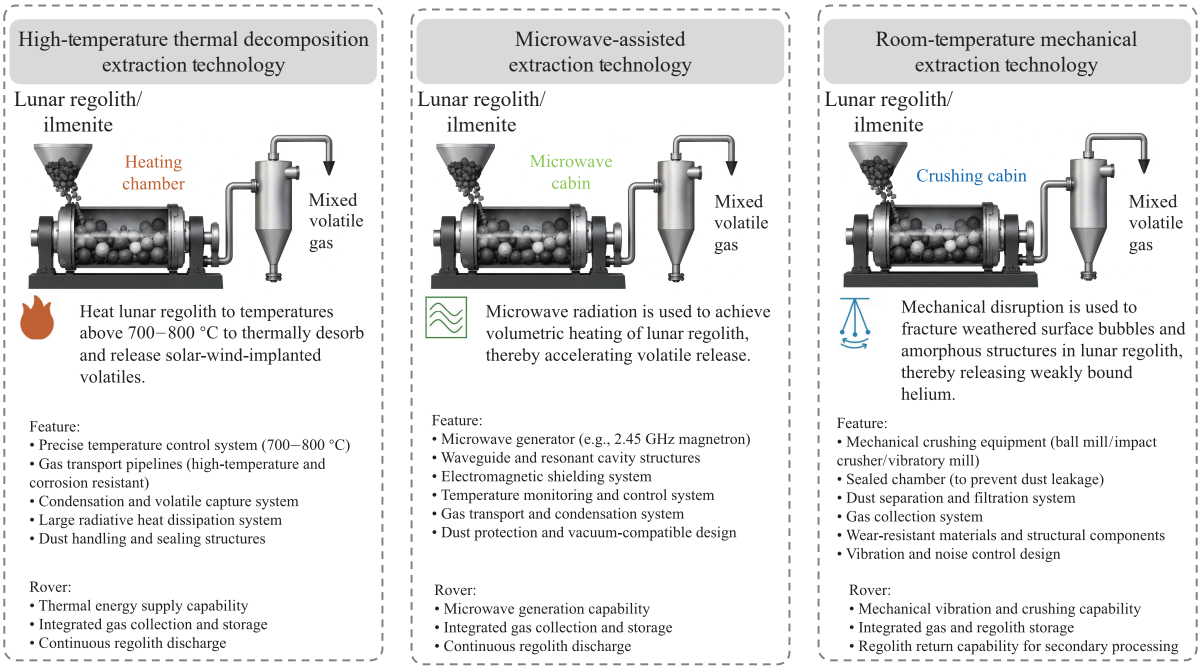

Fig. 4 Conceptual comparison of three lunar ^{3}He extraction approaches, illustrating the corresponding extraction mechanisms, required equipment architectures, and volatile gas release characteristics of each method.

ing approach for releasing solar-wind-implanted ^{3}He from lunar regolith. The release mechanism is governed by the thermally activated diffusion of ^{3}He atoms trapped in lattice vacancies and interstitial sites within helium-bearing minerals such as ilmenite. As the heating temperature increases, ^{3}He atoms acquire sufficient energy to overcome lattice binding energies and migrate toward the mineral surface, resulting in enhanced release. Molecular dynamics simulations indicate that the cumulative release of ^{3}He increases rapidly with temperature and gradually approaches a plateau. The study further suggests that a heating temperature of approximately 700 °C provides an optimal balance between release efficiency and energy consumption, yielding a cumulative ^{3}He release of about 86% [5]. The primary advantages of this method are high extraction efficiency and relatively mature engineering basis. However, the process requires continuous high-power heating and generates substantial waste heat. Since lunar regolith has very low thermal conductivity and the lunar surface lacks atmospheric convection, thermal management becomes a major engineering challenge. Large radiative cooling systems and high-temperature-resistant materials are therefore required to ensure long-term operational stability.

The extraction process can be approximately described as a thermally activated desorption process

$$R(T) = R_0 \exp\left(-\frac{E_a}{kT}\right) \tag{2}$$

where $R(T)$ is the helium release rate, R_0 is the pre-exponential factor characterizing the intrinsic attempt frequency of helium diffusion and desorption from trapping sites within the mineral lattice, E_a is the activation energy of trapped helium, k is the Boltzmann constant, and T is the absolute temperature. According to the reported measurements of lunar regolith volatiles, heating one metric ton of regolith may release on the order of tens to hundreds of grams of volatile species, including H_2, CO, CO_2, H_2O, CH_4, N_2, and ^{4}He [31]. In contrast, the abundance of ^{3}He is typically only on the order of several to several tens of milligrams per metric ton of regolith, highlighting the need for efficient isotope recovery and enrichment processes [7].

B. Microwave-Assisted Extraction Technology

Microwave-assisted extraction is an enhanced thermal extraction approach, in which microwave radiation is used to achieve volumetric heating of lunar regolith. Unlike conventional conductive heating, microwaves penetrate directly into regolith particles and generate internal dielectric heating, thereby significantly improving heating efficiency and temperature uniformity. Microwave systems typically operate at frequencies such as 2.45 GHz using magnetrons, waveguides, and resonant cavities. Because of the volumetric heating mechanism, microwave extraction can reduce heating time and partially overcome the low thermal conductivity limitation of lunar soil. Consequently, this method is regarded as a promising high-efficiency extraction technology for future *in-situ* resource utilization systems.

However, microwave-assisted extraction also faces several technical difficulties. The first challenge is the complexity of high-power microwave systems, which require stable microwave generation, transmission, and electromagnetic (EM) shielding under lunar vacuum and dust environments. In addition, the dielectric properties of lunar regolith vary significantly with mineral composition, iron content, and particle size distribution, potentially causing nonuniform heating and localized overheating. Electromagnetic interference with nearby communication and control systems must also be considered during engineering implementation.

C. Room-Temperature Mechanical Extraction Technology

Room-temperature mechanical extraction is a low-energy-consumption approach that releases ^{3}He through physical disruption of amorphous surface bubbles generated by space weathering. Analyses of Chang'e-5 lunar samples reveal that helium-bearing nanoscale bubbles are widely distributed within weathered layers on ilmenite surfaces. Since part of the implanted helium is concentrated near the particle surface, mechanical fracture methods can release a fraction of ^{3}He without requiring high-temperature heating. Typical extraction methods include ball milling, impact crushing, and vibrational grinding. Compared with the thermal extraction technologies, mechanical extraction offers lower energy consumption, simpler equipment architecture, and reduced thermal management requirements, making it suitable for small lunar outposts or early-stage resource utilization missions.

Nevertheless, the extraction efficiency of this method remains relatively limited because only near-surface ^{3}He can be effectively released, while ^{3}He trapped within deeper crystal defects and mineral lattices remains difficult to extract. In addition, the highly abrasive nature of lunar regolith may cause severe mechanical wear and dust contamination during long-term operation, reducing equipment reliability and operational lifetime.

D. Comparison of the Three Extraction Technologies

Regarding energy consumption, room-temperature mechanical extraction does not require high-temperature conditions and relies solely on mechanical energy [10], making it the least energy-intensive among the three techniques. Although both microwave-assisted extraction and high-temperature thermal desorption rely on heating for extraction, the low thermal conductivity of lunar regolith results in substantial differences in their energy requirements [32]. Microwave-assisted extraction primarily utilizes volumetric heating, which effectively mitigates the bottleneck of low thermal conductivity and minimizes thermal losses, thereby consuming less energy than thermal desorption. Conversely, thermal desorption relies on surface heating. The difficulty of inward heat transfer readily forms steep thermal gradients near the surface, leading to significant thermal dissipation into the environment and consequently demanding substantially higher energy consumption. Furthermore, since Mark III has demonstrated the feasibility of thermal desorption using solar thermal energy [29], it logically follows that the other methods, which require lower energy consumption, are also viable from an energy perspective. A more detailed comparison of the three technologies can be found in Table 1.

Accordingly, future lunar ^{3}He mining vehicles may adopt modular processing chambers capable of operating in thermal heating, microwave heating, or mechanical vibration modes. For thermal and microwave extraction systems, volatile release and gas-solid separation can be performed directly onboard, allowing processed regolith to be continuously discharged. In contrast, mechanically processed regolith will still need to be transported to a centralized processing station for secondary thermal treatment and further volatile recovery. Therefore, future lunar ^{3}He mining systems will likely adopt integrated architectures combining mechanical pretreatment with thermal deep-release extraction to balance recovery efficiency, energy consumption, and engineering feasibility.

VI. ^{3}He Isotope Separation and Transport Architecture

Following lunar regolith extraction, the released gaseous products contain not only ^{3}He, but also significant quantities of ^{4}He, H_2, CO_2, H_2O vapor, and other solar-wind-derived volatiles. Since the abundance of ^{3}He in the extracted gas mixture is extremely low, direct transportation of all released gases will result in substantial storage and transportation penalties. Therefore, gas processing after extraction generally includes three stages: non-isotope volatile separation, preliminary *in-situ* helium isotope enrichment, and Earth-based high-purity isotope purification. The first stage mainly removes non-helium volatile species through moderate cryogenic cooling, while the second stage performs coarse ^{3}He enrichment on the lunar surface. Finally, high-purity isotope separation is completed using terrestrial cryogenic infrastructure after transportation back to Earth. The workflow can be seen in Fig. 5.

A. Non-Isotope Volatile Separation

As shown in Table 2, the liquefaction temperatures of H_2O, CO_2, CH_4, CO, and N_2 are substantially higher than those of helium isotopes. Consequently, these species can be removed through staged cryogenic condensation prior to helium recovery. Under such conditions, helium isotopes remain in the gaseous phase, while most heavier volatile components are condensed. Based on the assumed volatile composition, the residual gas stream is expected to consist primarily of H_2, ^{4}He, and trace amounts of ^{3}He, providing a suitable feed stream for subsequent helium enrichment and isotope separation processes.

Considering the severe constraints of lunar infrastructure, energy supply, and cryogenic equipment deployment,

Table 1 Comparison of lunar ^{3}He extraction technologies.

Extraction technology	Mechanism	Efficiency	Maturity	Implementation difficulty
High-temperature thermal desorption	Heating regolith to 700 °C to thermally desorb volatiles	86% at 700 °C	Validated by Apollo samples	Requires continuous high-power heating and large radiators, posing severe waste heat management challenges in vacuum.
Microwave-assisted extraction	Microwave radiation achieves volumetric heating of regolith to release volatiles.	The specific data require further verification.	Promising but requires further validation.	Requires complex high-power microwave systems and EM shielding, as variable dielectric properties may cause localized overheating.
Mechanical extraction	Mechanical disruption fractures weathered surface bubbles to release volatiles.	Low, only releases near-surface He while deep lattice He remains trapped.	Validated by Chang'e-5 samples	Lower energy consumption, but suffers from severe mechanical wear and dust contamination from abrasive regolith over long durations.

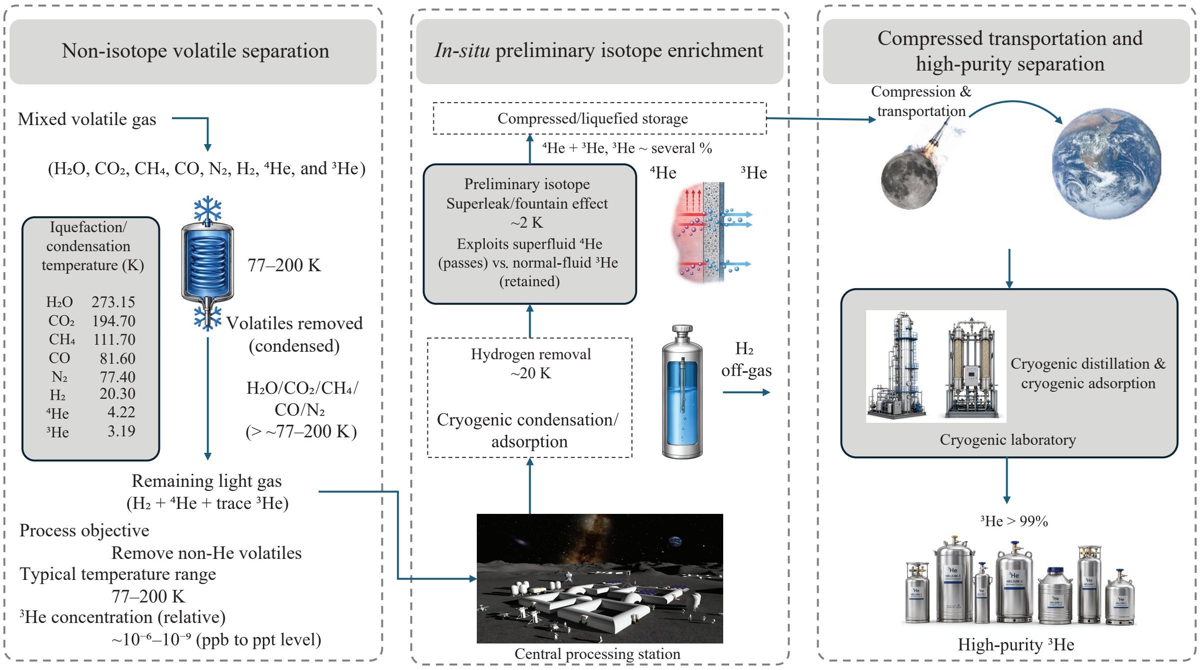

Fig. 5 Conceptual architecture of lunar ^3He gas processing, isotope enrichment, and Earth-return purification. The process consists of three major stages: (1) non-isotope volatile separation onboard lunar mining vehicles through staged cryogenic condensation and volatile removal; (2) preliminary *in-situ* helium isotope enrichment at centralized lunar cryogenic stations using superleak or fountain-effect separation; and (3) compressed or liquefied helium transport to Earth for high-purity ^3He purification via cryogenic distillation, adsorption, and membrane-based separation technologies. This figure also illustrates the corresponding temperature ranges and relative ^3He concentration evolution throughout the entire processing chain.

Table 2 Liquefaction temperatures and estimated mass fractions of major volatile gases released from lunar regolith.

Gas species	Liquefaction (K)	Temperature (°C)	Mass (%)
H_2O	273.15	0.0	17.9000
CO_2	194.70	−78.5	9.3400
CH_4	111.70	−161.5	8.5600
CO	81.60	−191.5	10.5000
N_2	77.40	−195.8	3.1100
H_2	20.30	−252.9	33.4600
^4He	4.22	−268.9	17.1200
^3He	3.19	−269.9	0.0050

complete high-purity isotope separation directly on the Moon is currently unrealistic. A more feasible strategy is to perform preliminary volatile removal and coarse isotope enrichment on the lunar surface, followed by transportation of enriched helium products to Earth for large-scale cryogenic purification. In such an architecture, helium mixtures may first be liquefied or stored in high-pressure form to reduce transport volume and improve storage stability during Earth-return missions. After transport, terrestrial facilities with mature cryogenic infrastructure can perform deep isotope purification to obtain high-purity ^3He suitable for fusion, scientific, or medical applications.

Based on the separation mechanism and engineering maturity, current ^3He isotope separation technologies can be broadly divided into four categories: superleak and fountain-effect separation, cryogenic distillation, cryogenic adsorption separation, and membrane-based quantum separation.

B. *In-Situ Preliminary Isotope Enrichment*

After preliminary volatile removal, the remaining gas mixture is mainly composed of H_2, ^4He, and trace amounts of ^3He. Since H_2 and helium possess significantly different liquefaction temperatures, hydrogen can be separated relatively easily through moderate cryogenic cooling. In contrast, ^3He and ^4He are isotopes of the same element and therefore exhibit nearly identical chemical properties, making isotope separation substantially more difficult. Consequently, helium isotope enrichment becomes one of the most challenging stages in the overall lunar ^3He utilization architecture [5].

At present, cryogenic superleak separation and fountain-effect separation are among the most extensively studied approaches for preliminary helium-isotope enrichment. Cryogenic superleak separation relies on the distinct superfluid transition temperatures of helium isotopes. ^4He undergoes a superfluid transition at approximately 2.17 K, while ^3He remains in a normal fluid state at this temperature. Under such conditions, superfluid ^4He can pass through porous superleak materials with nearly zero viscosity, whereas ^3He is largely blocked, thereby enabling isotope enrichment. Similarly, fountain-effect separation utilizes thermally induced counterflow between superfluid and normal-fluid helium components, causing ^3He to gradually accumulate in the colder region.

Although both methods possess relatively simple structures and have demonstrated feasibility for low-abundance enrichment, they are mainly suitable for coarse isotope separation rather than high-purity purification. In practical applications, these techniques can provide preliminary isotope enrichment prior to high-purity separation. However, both approaches require operating temperatures near 2 K, where space cryogenic systems currently suffer from limited cooling power, large mass, and high energy consumption. As a result, implementing such ultralow-temperature systems directly onboard mobile mining vehicles is highly impractical. Therefore, future lunar architectures will likely employ centralized cryogenic processing stations, where gases collected by mining vehicles are transported for preliminary *in-situ* isotope enrichment and subsequent purification.

C. Compressed Transportation and High-Purity Separation

After preliminary *in-situ* enrichment, the ^{3}He concentration in the helium mixture may increase from trace levels to several percent. At this stage, the remaining gas mainly consists of ^{4}He and enriched ^{3}He, allowing the mixture to be compressed or liquefied for transportation back to Earth. Since helium gas possesses a relatively low density, preliminary enrichment on the lunar surface is essential for reducing storage volume and transportation cost. Compared with ultralow-temperature isotope purification directly on the Moon, transporting partially enriched helium mixtures to Earth is currently considered more practical and energy efficient. High-purity ^{3}He purification generally requires highly stable cryogenic systems, precise temperature and pressure control, and large-scale continuous processing capability. Such systems are difficult to implement under lunar constraints including limited power supply, restricted cooling capacity, and low-gravity operation. Therefore, deep isotope purification is more suitable for terrestrial facilities with mature cryogenic infrastructure and industrial-scale processing capability.

At present, cryogenic distillation remains the most mature large-scale helium isotope separation technology. This method utilizes the slight vapor-liquid equilibrium difference between ^{3}He and ^{4}He at ultralow temperatures. Through repeated vapor-liquid contact and multistage mass transfer processes inside distillation columns, ^{3}He gradually becomes enriched in the vapor phase, enabling purification from several percent concentration to reactor-grade purity levels exceeding 99%. In addition to cryogenic distillation, cryogenic adsorption and membrane-based separation technologies have attracted increasing attention in recent years. These methods rely on quantum adsorption differences, zero-point energy effects, and quantum tunneling behavior inside nanoporous materials such as metal-organic frameworks, porous graphene, and graphdiyne membranes [33–35]. Compared with conventional cryogenic distillation systems, adsorption and membrane-based approaches potentially offer lower energy consumption and simpler system architectures. However, most of the current studies remain at the laboratory or theoretical stage and simultaneously achieving high selectivity and high throughput remains a major engineering challenge.

VII. Engineering Challenges and System Feasibility

Although lunar ^{3}He extraction has attracted significant interest as a potential long-term energy resource pathway, the realization of a complete industrial-scale mining architecture still faces substantial engineering and operational challenges. Based on the preceding discussions of lunar regolith excavation systems, ^{3}He distribution modeling, extraction technologies, and isotope separation architectures, the feasibility of lunar ^{3}He utilization depends not only on extraction efficiency but also on the coordination between mining scale, energy consumption, transportation capability, and system reliability. Therefore, future lunar ^{3}He exploitation shall be regarded as an integrated engineering system rather than an isolated extraction process.

A. Large-Scale Regolith Excavation and Resource Accessibility

One of the primary engineering challenges is the extremely low concentration of ^{3}He in lunar regolith. Even within high-titanium mare regions, the average abundance generally remains at the ppb level, meaning that enormous quantities of lunar soil must be excavated and processed to obtain usable amounts of ^{3}He. Consequently, the efficiency and operational lifetime of large-scale excavation vehicles become critical factors affecting the overall system feasibility. Future mining systems must therefore achieve continuous autonomous excavation, regolith transport, and preprocessing under harsh lunar conditions including vacuum, abrasive dust, radiation exposure, and large thermal cycles. In addition, excavation efficiency strongly depends on accurate geological modeling and resource prediction. High-resolution ^{3}He distribution models derived from orbital remote sensing, sample analysis, and *in-situ* measurements are essential for identifying high-abundance mining regions and reducing unnecessary excavation workload.

B. High-Temperature Heating and Cryogenic Separation Challenges

One of the major engineering challenges in lunar ^{3}He utilization lies in the coexistence of sustained high-temperature extraction and ultralow-temperature separation processes within the same industrial architecture. Thermal extraction technologies generally require continuous operation above 700 °C to release solar-wind-implanted volatiles from lunar regolith, while subsequent hydrogen removal and helium isotope enrichment may require cryogenic environments approaching 20 K or even below 4 K. Consequently, future lunar processing systems must simultaneously support high-temperature heating, ultralow-temperature refrigeration, and stable long-duration operation under vacuum conditions.

Solar energy is currently considered the most accessible lunar energy source, although the approximately fourteen-day lunar night severely restricts continuous operation of solar-powered systems unless large-scale energy storage infrastructure is available. Nuclear power systems may therefore become necessary for long-term industrial-scale operation. Meanwhile, thermal management on the lunar surface is fundamentally difficult because heat transfer can only occur through radiation and conduction in vacuum conditions. Continuous high-temperature processing generates substantial waste heat, while cryogenic separation systems require highly stable low-temperature environments with minimal thermal leakage. Therefore, large radiators, thermal shielding structures, multilayer insulation systems, and high-efficiency cryocoolers are all essential components of future lunar ^{3}He processing facilities.

In addition, maintaining stable operation of electronic systems and cryogenic equipment under simultaneous high-temperature and ultralow-temperature environments introduces significant engineering complexity. The combination of strong thermal gradients, lunar dust contamination, radiation exposure, and long-duration operation may severely affect material reliability, thermal stability, and overall system lifetime. As a result, the integration of high-temperature extraction and cryogenic separation remains one of the most critical technological bottlenecks for future lunar ^{3}He industrialization.

C. Long-Term Operation under Harsh Lunar Environments

Future lunar ^{3}He mining systems must operate autonomously for extended periods under highly hostile environmental conditions, making long-term operational stability a critical engineering challenge. Large-scale mining architectures will require coordinated control of excavation vehicles, regolith transport systems, extraction units, cryogenic processing facilities, and power-management systems, all operating continuously under vacuum, extreme thermal cycles, and limited maintenance capability.

In addition to the substantial energy demand associated with high-temperature extraction and cryogenic separation, lunar environmental hazards further complicate system reliability. Because fine lunar dust particles can degrade mechanical and optical systems and solar radiation and electromagnetic disturbances threaten electronic stability, future systems must incorporate robust hardware mitigation strategies alongside multi-layered fault-tolerant control architectures. At the system level, the proposed distributed front-end vehicles and clustered back-end units shall ensure graceful degradation, isolating single-unit failures without paralyzing the workflow. A demand-driven scheduling algorithm shall dynamically regulate active units to minimize energy and thermal risks, while safety-prioritized docking protocols govern inter-stage transfers. At the process level, mobile equipment requires anti-slippage and anti-sinkage mobility control and excavation shall utilize risk-aware collision avoidance. Sorting must integrate thermal-aware and clogging-aware modules to prevent overheating and blockages, and extraction/purification units need predictive scheduling to avoid degradative dry-running. Furthermore, internal equipment modularization is essential to ensure fault isolation and prevent cascading interference.

Communication delays between the Earth and the Moon also limit the practicality of continuous human teleoperation. Consequently, future lunar industrial systems will likely rely heavily on AI, autonomous navigation, adaptive process control, and distributed robotic cooperation.

VIII. Conclusion

Lunar ^{3}He is widely regarded as a potential strategic resource for future advanced fusion energy systems because of its high energy density and relatively aneutronic fusion characteristics. This study reviews the major technological components of lunar ^{3}He utilization, including regolith excavation, resource distribution modeling, extraction technologies, isotope separation methods, and transportation architectures. Given the constraints of lunar infrastructure, energy supply, and system complexity, the feasible near-term strategy shall involve deploying a limited number of regolith collection vehicles for excavation, followed by preliminary *in-situ* enrichment and subsequent terrestrial deep purification, relying exclusively on solar energy. Conversely, the long-term vision entails deploying large-scale integrated mining fleets to form sophisticated architectures capable of complete high-purity ^{3}He extraction on the lunar surface. This will be supported by a robust hybrid power supply of solar and nuclear energy, thereby establishing a stable and resilient mining system. Overall, lunar ^{3}He exploitation shall be viewed as an integrated engineering system requiring coordinated development of excavation, extraction, cryogenic processing, transportation, and autonomous operational technologies before the large-scale industrial implementation becomes feasible.

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