Research on Isolation and Protection Technology for Returning Astronauts of Deep Space Exploration Missions

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Abstract. With the acceleration of deep space exploration missions such as the moon, mars and asteroids, planetary protection has become an important issue that must be faced. In the near future, astronauts will perform extraterrestrial celestial operations in more distant and complex unknown environments, which may lead to a large increasing in probability and uncertainty of carrying unknown microorganisms after the spacecraft returning to the earth. From the perspective of protecting astronauts and the Earth's biosphere, it is necessary to conduct safe isolation and protection for astronauts returning from the outer space. In this paper, biological isolation and protection technologies at home and abroad are studied. For China's future manned deep space exploration missions, we carry out a demand analysis, and propose a design scheme of isolation protection platform.

Keywords: Planetary protection; Deep Space Exploration Missions; Isolation and Protection; Astronaut; Landing Ground.

1. Introduction

nIn recent years, the target of future space exploration has gradually shifted to the moon, Mars, and deep space beyond with the development of near-space exploration. To date, planet protection has been an important issue that human beings must face in conducting deep space exploration activities. Planetary protection mainly involves two aspects: positive pollution and reverse pollution [1]. In future-oriented deep space exploration missions, protecting the Earth from potential reverse pollution is a top priority in planetary exploration. When human-related pollution is found to be controlled and understood can humans only make greater contributions to the biological detection of planets.

So far, the United States is the only country to achieve a successful human landing on the moon [2]. NASA has used the Apollo spacecraft's return capsule, astronauts, and lunar samples as the main risk sources, and has developed a strict isolation and disposal process [3]. These risk sources are equipped with isolation and protection devices [4] and respiratory equipment to realize the function of isolation protection and ensure the safety of rescue workers, but its isolation protection level is low. In addition, there are only a few military enterprises and private enterprises in China to form related products, mainly including the isolation and transport of medical square cabins [5] and mobile biosafety laboratory [6]. The former pays attention to medical treatment guarantees, and the isolation and protection level is low. The latter carries out biosafety experiments, that is, the staff needs to wear personal protective equipment for a long time to carry out work [7], which cannot meet the requirements of long-term exposure on environmental control and life security under the free state.

In manned deep space exploration missions, astronauts' autologous microorganisms and the microorganisms they may carry will increase the complexity of microbial risk control. Therefore, protecting the earth from potential reverse pollution puts forward higher requirements for the landing field system, and it is urgent to carry out targeted research on key technologies such as pollution prevention and control of returning astronauts in manned deep space exploration missions.

2. Space microbes

2.1. The unknown space microbes

In recent years, with the development of microbial detection technology, many known and even several unknown microbial species have been discovered in the space flight activities such as the International Space Station. Taking a joint study by NASA in India and the United States as an example, four microbial [8] species were found in the roof plate, cabin dome, table surface, and highly efficient air filter of the International Space Station in 2015 and 2016, as shown in Table 1.

Table 1: Unknown microbial species detected by the International Space Station

Order	Location	Name	Known or not
1	Space station roof	IF7SW-B2T	Unconfirmed
2	The dome inside the cabin	IIF1SW-B5	Unconfirmed
3	Table surface	IIF4SW-B5	Unconfirmed
4	Air filter	Methylbacterium Roche	Known

The three microorganisms in Table 1 are defined as completely unknown by the scientific community. Its risks are embodied in three aspects: 1) They have ground-unknown gene sequences. Some of the results [9-10] show that the gene fragments of these three microorganisms are similar to a certain bacterial family in-ground soil and fresh water, but they also have surface-unknown gene sequences; 2) They contain fragments of genes similar to human infectious disease pathogens; 3) Their source, harmfulness, and potential risks remain to be studied. It is unclear whether they are unknown microbes in extraterrestrial space or new creatures after the mutation of the International Space Station.

2.2. The known pace microbes

Table 2 summarized the pathogenic microorganism [11] that has been found in low Earth orbit spacecraft based on domestic and foreign literature. It mainly includes bacteria and fungi. The bacteria are mainly Staphylococcus and Bacillus, and the fungi are mainly Aspergillus and Penicillium.

Table 2: The known microbial species detected

Order	Classification	The microbial name	The spacecraft detected with microbes
1	Bacterium	Colibacillus	Salyu and Mir space station
2		Staphylococcus aureus	ISS, Apollo, Mir space
3		Bacillus	Widely distributed in all kinds of spacecraft
4		Klebsiella pneumoniae	ISS, Salyu
5	Fungus	Aspergillus	ISS, Apollo, Skylab
4		Penicillium notatum	ISS, Apollo, Skylab

Among the above microorganisms, Colibacillus, Bacillus, Staphylococcus aureus, Klebsiella, Aspergillus, and Penicillium are microorganisms that need to be focused on. They are widely distributed and highly abundant in spacecraft, and are potentially harmful to the human body. The complex microecological environment is easy to reduce the astronauts' physiological function and immune function [12]. Toxins secreted by Staphylococcus aureus can cause symptoms like nausea, vomiting, stomach cramps, and diarrhea [13]. Klebsiella is the most common pathogen of pneumonia, and Aspergillus and Penicillium are also one of the main pathogenic genera causing respiratory infectious diseases. At the same time, space microorganisms produce acidic metabolites, which can

cause damage to spacecraft and related equipment and materials, and cause pollution to the air, food and water.

2.3. Space-variant microbes

Some microorganisms that are originally harmless to the human body and the environment have experienced a long-term in-orbit environment, and their virulence, pathogenicity, and antibiotic sensitivity may be significantly changed. As shown in Table 3, the effects of spatial mutagenesis on the virulence of Escherichia E. coli and K. pneumoniae. The experiment was performed in two groups: ground control strains and spatial mutagenic strains. By comparing the half-lethal doses of the two groups, it was found that spatial mutagenesis can enhance the virulence of E. coli and K. pneumoniae [14].

Table 3: Half of ground control and spatial mutagenic strains

Order	Classification	Test team	Half-lethal dose (LD50)
1	E. coli	Ground control strains	$10^{7.5}$CFU/mL
2		Spatial mutagenic strains	$10^{7.25}$CFU/mL
3	K. Pneumoniae	Ground control strains	$10^{7.75}$CFU/mL
4		Spatial mutagenic strains	$10^{7.25}$CFU/mL

2.4. Transmission of space microorganisms

When the astronauts enter the spacecraft after completing the planetary surface operation, stardust such as stardust attached to the outer space suit and boots also enter the spacecraft. The life of some microorganisms in outer space is very tenacious, even if the sterilization of the outer cabin space suits. However, the spores of some bacteria and the spores of fungi are difficult to eliminate by general disinfection and sterilization measures. These microbes or spores that avoid sterilization and enter the spacecraft will continue to grow and reproduce when they encounter suitable conditions, and spread to the various environment of the spacecraft, thus introducing microbial contamination into the spacecraft [15].

Microbial pollution in the environment of extraterrestrial bodies usually has the characteristics of strong unknown, strong variability, strong lag, and strong concealment [16]. Once it enters the earth's environment under uncontrolled conditions, it will threaten the safety of the earth's biosphere. Therefore, it is necessary to take corresponding isolation measures for the astronauts returning to Earth to improve the risk prevention and control of extraterrestrial microorganisms.

3. Isolation and protection requirements and research

3.1. Task requirements for isolation and protection

Driven by the manned space program, China has built a three-level medical rescue support system for astronauts in the landing site, an emergency hospital and a Beijing Support hospital. China has a relatively complete capability of normal and emergency return medical aid for astronauts in low Earth orbit, and has successfully guaranteed all its manned flight missions.

The isolation and protection requirements of returning astronauts in manned deep space exploration missions are mainly reflected as follows:

1) It provides a reliable means to eliminate the risk of unknown microbial pollution in space. Through strict input and output control of material flow, a safe isolation space is formed, thus minimizing the risk of astronauts polluting the earth's environment while returning to the ground with space viruses and unknown microorganisms.

2) It provides a suitable environment for the astronauts' isolation and recovery. This is helpful to establish the basic conditions required for astronaut medical examination and assessment, psychological and physical recovery, and physical training activities. It is also helpful to create and

maintain a comfortable living space, provide various living support equipment during the isolation and recovery period, and solve the issues of astronauts' food, drinking water, and personal hygiene.

3) It provides effective tools for the safe transfer of astronauts after leaving the cabin. It can transport the astronauts from the landing point (sea or land) after returning to the ground to the designated receiving sites such as the recovery training center. It also provides the necessary living support and isolation protection for the astronauts during the transportation process.

3.2. Research on the key technologies of isolation and protection

Given the isolation and protection needs of astronauts in the mission after returning to the ground, the key issues such as sealed isolation, space microbial risk control, astronauts' living support and human engineering comfort can be divided into four aspects.

1) Seal and isolation space construction technology. The sealed isolation space construction technology aims to study the space construction scheme of the safe isolation astronauts, and establish the physical isolation between the internal environment and the external environment of the isolation protection platform, thus ensuring biological security. It mainly includes negative pressure isolation technology research and sealing design technology research. Negative pressure isolation technology adopts negative pressure isolation measures to ensure the safety of the environment and personnel and prevent the continued spread of potentially pathogenic microorganisms. The sealing design mainly includes the main structure and interface of the isolation and protection platform.

2) Environmental control and life support technology. For astronauts' isolation and living to provide comfortable environment conditions and sufficient life support, it needs to carry out research on confined space environment control and life support technology, mainly to solve the problems of spatial atmospheric environment control, temperature and humidity control, water resources supply and waste treatment inside the isolation and protection platform, thus forming a new environmental control and life protection scheme in confined space.

3) Determination technology. To ensure the safety of astronaut isolation and prevent the reverse pollution of space microorganisms to the earth's environment, it is necessary to study the space microbial elimination technology and select the appropriate isolation technology combined with the characteristics of the astronaut isolation and protection platform.

4) Multiple comfort-level design technology. To create a safe and comfortable environment for astronauts' physical and psychological recovery, it is necessary to carry out the life function design of the isolation and protection platform, and carry out the comfort design of daily life and function guarantee based on the human factor engineering, so as to solve the problems of astronauts' living, eating, drinking and personal hygiene.

4. Isolation and protection scheme design

4.1. Overall design ideas

The return capsule may return to land or splash to the sea landing zone. To ensure the health of the astronauts after returning to the earth and the safety of the earth's ecological environment, the scheme is designed according to the land and sea search and rescue modes for the rescue workers, the return capsule, and the astronauts.

1) When the astronauts leave the capsule, the rescue workers with direct exposure risk with astronauts should wear external protective clothing to ensure that the rescue workers are not contaminated by potential extraterrestrial microorganisms.

2) Ding sterilization solution for parts that the rescuers have direct contact with the re-entry capsule.

3) The astronauts need to replace the biological isolation suit before leaving the cabin and directly enter the isolation protection platform after leaving the cabin.

Combined with the actual situation of the manned deep space exploration mission, the isolation and protection platform is flexibly settled according to the three layout methods near the landing point area in the emergency hospitals and in the salvage and recovery ships. It should be integrated into the

three-level medical rescue guarantee system of on-site medical supervision, medical rescue team, emergency hospital, and Beijing support hospital already built with the space station mission, thus forming a new system of astronaut isolation and protection, medical supervision, medical insurance, and medical rescue.

4.2. Isolation and prevention

4.2.1 Basic requirements

In order to meet the different requirements of returning to manned deep space exploration missions on land or sea landing sites, deploying the isolation and protection platforms nearby or rear, and the transportation capacity of different carrier platforms, the isolation and protection platform should have good environmental adaptability and convenient transportation. In order to meet the long-cycle isolation of astronauts, the isolation and protection platform should have good environmental control and life support requirements. Specifically, it includes the following.

1) Personnel size. The isolation and protection platform is designed in accordance with the rescue standards for the three astronauts.

2) Application scenarios. The isolation and protection platform should be characterized by miniaturization and lightweight to meet the needs of astronaut transfer, on-road isolation or local isolation.

3) Medical function. For the risk of carrying microorganisms after returning, the isolation and protection platform shall be capable of microbial sampling, detection and prevention and control, and shall have the capability to support the astronaut's medical examination, medical aid and medical assessment according to the life and health support needs of the astronauts.

4) Isolation function. According to the requirements of group isolation by astronauts, the first is to design safe isolation space construction scheme based on the principle of reliable sealing and negative pressure isolation. And the second is to design a new atmospheric environment and temperature and humidity control mode based on the development of modified functional materials and advanced sensing technology, and combine with microbial sterilization technology to ensure the atmospheric environment, water quality index and waste disposal in the region meet the biosafety requirements.

5) Life function. Based on the human factor project to carry out the comfort design of life and function guarantee, it needs to solve the issues of astronauts living, eating, drinking and personal hygiene, thus creating a safe and comfortable environment for astronauts physically and psychologically.

4.2.2 Isolation and protection period

The purpose of isolation and protection is to eliminate the diffusion risk of carrying unknown microorganisms and other pollutants from space after returning to earth on flight missions, and also helps to promote the astronauts' re-adaptation to the earth's environment and physical recovery.

Usually, the 7~21 d continuous isolation side [17] is used to ensure the astronauts' physical condition for the next stage of recovery. The isolation cycle is generally determined according to the longest incubation period of pathogenic microorganisms. Based on the current types of microorganisms detected in outer space and the existing experience of preventing and controlling infectious diseases, it is usually limited to the three-week (21 d) isolation period. The first week can follow the level III infectious disease prevention and quarantine system. From the second week to the third week, the grade II infectious disease prevention and quarantine system can be implemented. During this period, it is necessary to carry out medical supervision and inspection, work and rest and diet adjustment, and exercise function rehabilitation for the astronauts, so that their psychological and physiological states can adapt to the earth's environment.

4.2.3 Isolation and protection level

Referring to the joint biosafety classification standards by the US Centers for Disease Control and Prevention (CDCP), US National Institutes of Health (NIH), and US Department of Health and

Human Services (DHHS), there established the level of isolation and protection for the biosafety issues. The standard is divided into four levels from P1 to P 4 [18].

Considering the task requirements, technical difficulties and economic costs, the P2 grade isolation and protection facilities or buildings are the current mainstream research and application direction. The P2 grade can be divided into common type and enhanced type (i. e., P2 +). The common type is suitable for isolation and protection of traditional viruses such as hepatitis B, and the enhanced type is suitable for isolation and protection of pathogenic factors with airborne transmission routes such as novel coronavirus.

According to the mission profile of the astronaut isolation and protection platform, the severity and risk of carrying space pollutants to healthy adults, animals and the earth environment are evaluated. Considering the technical feasibility and economic cost, it is recommended that P2 + level isolation and protection standard should be used as the design basis of the isolation and protection platform.

4.3. Design of the isolation and protection platform

4.3.1 System composition

The isolation and protection platform is mainly composed of an isolation and sealing compartment, fresh air treatment system (including temperature regulation), supply system, waste management system, disinfection system, intelligent control system, microbial detection module, sampling and transmission device, and supporting equipment and other parts.

4.3.2 Operation process

The platform takes the standard cabin as the main body, and it is sealed and isolated by designing an independent physical space, thus s controlling the material input and output channels to ensure the safety of medium exchange. In addition, the fresh air treatment system in the equipment area makes the resultant negative pressure gradient of the medical functional area and the living functional area to scientifically control the flow direction of the air flow organization, purify the inhaled gas, and eliminate the discharged gas. In this way, the personnel and the surrounding environment can be effectively protected, and the environmental parameters in the cabin can be regulated to provide comfortable isolation conditions for the astronauts.

When the astronauts enter the isolation protection platform inside, they first pass through the buffer room and then into the living room. In the process of platform transfer, the astronauts mainly work and rest in the living room. After transferring to the designated area or after the isolation period expires, the astronauts will leave the platform from the living room through the buffer room. Special maintenance channels are set up in the equipment room, and the physical partition from the living functional areas and medical functional areas is carried out to reduce the impact of external factors such as cross-pollution risk and noise on the internal environment of the platform.

The platform provides effective and convenient solutions for the safe isolation and transfer of astronauts. The maximum width and height of the cabin, electrical and foot seat fixation mode are consistent with the international standard size. Existing container trucks, roll-off ships, military large transport aircraft and other vehicles with container transport function can be used for direct transport, and the port and airport standardized lifting equipment can be used for rapid transfer.

5. Summary

For reverse microbial pollution prevention and control, from the perspective of the astronauts' safety and health protection and the earth's ecological environment protection, it suggests speeding up the isolation protection scheme design and key technology research in advance, introducing a new isolation and protection system suitable for missions such as manned lunar exploration and manned fire exploration. These attempts will support the top-level design and system construction of deep space exploration missions and enhance the comprehensive capabilities of manned lunar exploration.

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