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Microgravity and the human exploration of space technology challenges

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ABSTRACT

If humans are to explore space beyond low-earth orbit, their health and welfare must be ensured, not only for survival in harsh environments but also so that they can work productively. The requisite technologies, and human physiology itself, are subject to reduced levels of gravity that are indigenous to space travel. Numerous studies have shown that it will require many years of intensive research to develop reliable, efficient, and self-sustaining technologies and to understand the effects of gravity on humans. The research community that was developed to provide crucial specific information has essentially been deactivated because of budget constraints. Thus, the great engineering challenge—to develop advanced and novel technologies that will enable further space exploration—will remain for future generations.

1. Introduction

The human exploration of space is one of the great expeditions of discovery in history and it also presents intriguing challenges and opportunities. Power generation and storage, propulsion, life support, and hazard protection systems are essential to ensure the long-term survival and productivity of the missions and, ultimately, extraterrestrial colonization.

One of the most challenging aspects of human space travel within the solar system is that levels of gravity are very different from terrestrial levels, ranging from microgravity in free fall, such as in low-earth orbit, to greatly reduced gravity on the surface of extraterrestrial bodies. Gravity affects many biophysicochemical phenomena that play a vital role in mission-enabling and -enhancing technologies and in human physiology, and it also suppresses other phenomena that become important as the gravity level is reduced.

The Apollo, space shuttle, and space station programs have shown that humans can live productively in space. In all those missions, however, vital needs such as oxygen, water, and waste management depend entirely on resupply, with associated high costs and up-weight mass requirements. For extended missions on the Moon and beyond low-earth orbit, resupply is not feasible, which means new advanced technologies must be developed that are reliable, efficient, and self-sustaining. Furthermore, they must operate in alien environments under unprecedented conditions. Most processes and systems involved in such technologies are gravity-dependent in ways not completely understood. Thus, the design of systems to sustain humans for space exploration presents enormous challenges to engineers. There is little doubt the development of advanced closed-loop and self-contained technologies for recycling water, air, and waste could help alleviate environmental problems on earth as well.

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Since no databases for designing such technologies exist, requirements-driven research must be performed. The space station was intended for this purpose and eventually the closed-loop systems could be tested on the Moon.

2. Development of NASA's research program

Over the years, NASA has sent people on short forays into orbit to conduct brief scientific and engineering experiments in apparent weightlessness, i.e., microgravity, to understand the role of gravity in the physical universe and on life itself. It was found that many aspects of physics, biology, and chemistry are significantly different in microgravity than they are on Earth. It has also been learned that biological systems, from cells to plants to people, undergo changes as a result of long-term space habitation that are not well understood.

In order to gain a fuller understanding of these effects, in the early 1990s NASA initiated a comprehensive microgravity research program in the areas of fluids, materials, combustion, and fundamental physics. A similar program for life-science research was also established. A rigorous peer review process was instituted, and some 500 highly qualified investigators in the physical sciences were selected in a program that supported 1700 graduate students. The research that emanated from this program included space flight experiments were to be conducted on the International Space Station (ISS), a platform that offers the required microgravity environment for extended periods of time. That this research program was of high quality and extremely productive was affirmed in a 2003 NRC report, "Assessment of the Directions in Microgravity and Physical Sciences Research" [1]. Between 1998 and 2000, research in the field of fluid physics produced several hundred papers that were published in internationally recognized journals. Similar results were obtained for research on combustion, fundamental physics, biotechnology, and materials.

In the mid-1970s I conducted research into surface tension phenomena that are mostly suppressed by gravity [2]. After conducting reviews for scientific value, feasibility, need for space flight, and engineering design of apparatus, my colleague, Y. Kamotani (co-principal investigator) and I received approval to investigate thermocapillary flows, i.e., flows driven by surface tension gradients due to temperature gradients along the free surface of a fluid. The experiments flew on the USML-1 Spacelab mission on *Columbia* in 1992; the second series flew on USML-2 in 1995. Both were performed in fully interactive mode, with direct communication between the science team on ground and the payload specialists in space. Few experiments have been performed this way, and they were to be precursors of the primary mode of operation on the ISS. Eighty hours was allotted for apparatus setup and performing of experiments. The research yielded 17 journal papers describing new and unusual results, a number of Ph.D. dissertations and M.S. theses, and 24 invited lectures. Research on thermocapillarity was dominated by NASA-sponsored investigations for a couple of decades and the approximately 100 articles emanating from it [3] indicate the extraordinary growth of the field in just over 15 years. Research on this topic was also undertaken outside NASA and adapted to other technologies. For example, innovations involving thermocapillarity include liquid positioning in MEMS devices [4–6] and microchip thermocapillary pumps for DNA analysis [7,8].

Billions of dollars went into developing and maintaining a community of high-quality researchers in microgravity sciences in basic and applied scientific areas such as interfacial and multi-phase fluid flows, combustion, crystal growth, and low-temperature physics. During this time, NASA supported more cross-disciplinary research than most other agencies. In addition to its scientific contributions, the research program is vital to the success of human exploration of space because many of the essential technologies involve gravitational phenomena that are poorly understood. This lack of understanding hampers the ability to design devices such as those for heat transfer, fire detection and prevention, fluids handling, welding, life support, and many more.

In the NRC report, "Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies" [9], a survey was made of technologies required for power generation and storage, space propulsion, life support, hazard control, materials production and storage, and construction and maintenance. Their dependence on gravity level was examined by considering the gravity dependence of their subsystems or processes. In many cases, the subsystems (pumps or boilers) or processes (e.g., electrolysis) are common to many technologies, so their underlying phenomena are especially important. As a result, high-priority research was recommended for the following phenomena: surface or interfacial effects, multiphase flow and heat transfer, multiphase system dynamics, fire phenomena, and granular mechanics.

It must be clear that the recommendations made in [9] concern phenomena associated with fluid and material behaviors rather than with the direct development of subsystems and their integration into technologies that can operate in reduced-gravity environments. It was recognized that the blending of conceptual design needs and phenomenological research findings requires considerable communication, coordination, and interdisciplinary collaboration among designers and researchers. Thus, general recommendations were made for coordinating research and design activities [9]. Ultimately, this led to the development of a new paradigm for research, called *Research for Design* (R4D), which is described in Section 3.

Two other observations are important.

1. A long time frame—on the order of decades—would be needed for the evolution of scientific findings into practical applications, and would require sustained commitment from NASA to obtain the requisite understanding of gravity-related issues.