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Revisiting the needs for artificial gravity during deep space missions

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ABSTRACT

In the past 15 years, several group studies have identified the need to validate the role of artificial gravity (AG) as countermeasure to physiological deconditioning during long duration space missions. AG during centrifugation can be adjusted by varying the rotation rate of the vehicle or the distance of the habitat relative to the axis or rotation. These AG parameters have an impact on vehicle design and on human activities associated with the mission. Mission designers are presently reviewing the technologies and habitats necessary to maintain optimal health, safety, and performance of the crewmembers for missions to destinations beyond the Earth–Moon system. New health concerns during space flight have now emerged, such as the Vision Impairment and Intracranial Pressure (VIIP) syndrome, which appears to be caused by prolonged cranial fluid shifts that persist in the presence of currently available countermeasures. The notion of AG research therefore needed to be revisited to consider what role, if any, AG should play in these missions. This paper describes the engineering aspects of human spacecraft providing AG, what is known of the effects of AG on humans, and the research needed to answer the questions raised by mission designers.

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1. Introduction

As space agencies plan the next generation of human space exploration missions to destinations beyond the Earth–Moon system, it is incumbent on mission designers to review the technologies and habitats necessary to maintain optimal health, safety, and performance of the crewmembers designated to carry out those missions. The primary hazards leading to health and performance risks during these missions are altered gravity levels, isolation and confinement with altered light–dark cycles, a hostile and closed environment, radiation, and distance from Earth. Altered gravity impacts most of the physiological systems, as shown by orthostatic intolerance, muscle atrophy, sensorimotor performance impairment, bone demineralization, immune deficiencies, back pains, and renal stone formation [1]. Lately, a special focus of concern regards changes in vision acuity in astronauts onboard the

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International Space Station (ISS), which are hypothesized to be caused by weightlessness-induced fluid shifts to the upper body leading to intracranial hypertension [2]. Even though vision disturbances have been reported earlier on the shorter Shuttle flights, these effects are of more concern now because if the hypothesis is confirmed, this risk could be an impediment for future long duration deep space missions. Thus an effective countermeasure against these effects will be required, and if it requires re-establishing gravity-induced hydrostatic gradients, artificial gravity might be the most efficient option [3].

With the end of the ISS era less than a decade away, we must consider now what role, if any, AG should play in future exploration missions. According to NASA's flexible path, the next steps in human spaceflight include flyby and orbital missions to the Moon, Mars and near earth asteroids (NEAs), lunar and Martian landings, and combinations of these scenarios. The year for design decisions to be made for the spacecraft is expected in 2022, and the decision criteria will include whether we can protect the health and performance of astronauts.

Space physiologists, crew surgeons, astronauts, vehicle designers, and mission planners need to review, evaluate, and discuss the issues for incorporating AG technologies into the vehicle design. Commitments by spacecraft designers to spin a vehicle, part of a vehicle, an exercise device within a vehicle, or even just a crewmember will only come following acceptance of a well-argued requirement from the life sciences community. Questions that will need answers are: (a) what evidence do we have to support such a requirement; (b) what design parameters would we levy upon the engineers; and (c) what prescriptions would we recommend to the crewmembers? Research needed to address these questions has a timeframe of less than eight years.

The purpose of this paper is to review the current status of AG research, and to discuss the need for and challenges to implementing AG countermeasures in human exploration missions beyond the Earth–Moon system. The objective is to focus on the research plans for using available facilities to answer the key questions in time to influence the decisions for the next generation of space exploration missions.

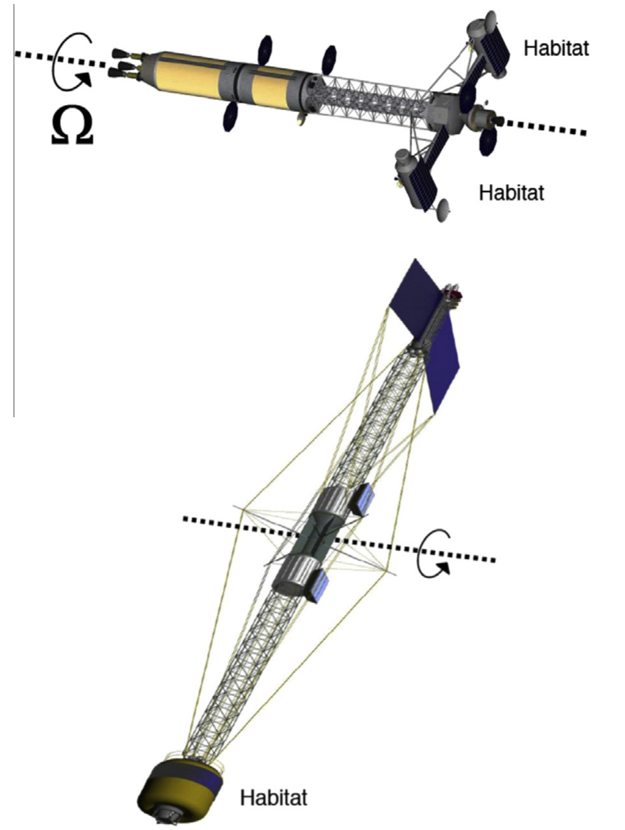

Fig. 1. *Top*. Mars transfer vehicle using conventional nuclear thermal propulsion rocket (NTR) for rotating two habitats along its long axis. The vehicle also utilizes photovoltaic arrays for auxiliary power. *Bottom*. The bimodal BNTR spacecraft configuration – long and linear – is naturally compatible with AG operation. Distance between the habitat and the axis of rotation is 56 m. An AG environment of 1 G can be provided to the crew by rotating the BNTR vehicle about its center of mass at about 4 rpm. Photo courtesy of NASA.

2. Artificial gravity concepts

Providing AG on board deep space human exploration vehicles using centrifugation has received surprisingly limited engineering assessment. This is most likely due to a number of factors: (a) the lack of definitive design requirements, especially acceptable AG levels and rotation rates; (b) the perception of high vehicle mass and performance penalties; (c) the perception of complications associated with vehicle spin-up and spin-down, such as antennae and photovoltaic arrays; and (d) the expectation of effective alternative gravity-replacement countermeasures [4].

A number of AG spacecraft concepts have been proposed with a variety of habitat module orientations. Human factor issues associated with each of these concepts have been identified along with mitigation strategies [5,6]. Transfer vehicles equipped with high thrust nuclear thermal rocket (NTR) engines, which use photovoltaic arrays for spacecraft auxiliary power, and "bimodal" NTR (BNTR), which uses the engines to generate the spacecraft's electrical power during the coast phase, are attractive options and are currently under study [7]. Both space transfer vehicle concepts can readily be adapted for AG operation, for example by placing the engines at one end of a structure and the habitat at the other end and rotating the entire structure around its center of mass (Fig. 1).

The NTR's high specific impulse of approximately 900 s (100% higher than LOX/LH_2 chemical rockets) is particularly attractive for AG missions because it can more readily accommodate the heavier payload mass and the increased reaction control system propellant required for multiple spin-up/spin-down cycles. Also very important is the fact that NTR can enable shorter transit times (3–6 months) to and from Mars that can help reduce the crew's exposure to galactic cosmic radiation and solar flares. Indeed, the ultimate countermeasure is in fact speed, flying faster and minimizing the weightless cruise time to mitigate the physiologic deficits along with the radiation acquired dose associated with deep space travel [4].

NTR is a proven technology successfully demonstrated in ground tests. This technology is receiving increased attention at NASA through the Nuclear Cryogenic Propulsion Stage (NCPS) project. Ground testing of a NTR engine could occur in the early 2020s, in time to support long duration crewed missions to NEAs, Mars and its moons in the 2028–2033 timeframe. A recent study has tried to understand the implications of and potential solutions for incorporating AG in the design of a vehicle for 18–24 months of round trip and three months stay on Mars using NTR [6]. The habitat would spin at 4 rpm, thus generating 1 G at a radius of 56 m (Fig. 1, left). The trade-off advantages of this design are that it would: (a) reduce the Mars transit time; (b) not require excessive propellants; (c) not require long duration 0 G tests; (d) not require massive de-spun joints; and (e) constitute a good convergence between power system mass and habitat as counterweight [4].

One alternative to spinning the entire vehicle is rotating one vehicle segment only, such as depicted in Kubrick's movie "2001: