Human Spaceflight

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Introduction

Ever since Yuri Gagarin took the first human step into space on 12 April 1961 humans have been making the journey into outer space. In contrast to the heady pioneering days, spaceflight seems almost routine now. However, spaceflight was, and remains, a hazardous enterprise. Some of the dangers are plain enough, just look at the power of a rocket or fiery re-entry, but the majority are less obvious. This project looks at the hazards faced by those who make, or will make, a trip off the planet.

Pre-Launch

A human flight into space begins long before launch day. Many months of planning, preparation, and training go into any flight. The purpose of such preparation is to ensure that all likely events are addressed with suitable responses. These events are both the desired ones, such as the primary mission, and the undesired ones such as fire aboard the spacecraft or loss of navigation systems.

The training regimen itself can, in fact, pose a threat to the crew's health and well-being. During pre-flight training exercises for the Apollo missions the lives of astronauts Grissom, White, and Chaffee were lost to a cabin fire in ground training (Apollo 1, 27 Jan 1967, [1]). Less directly, the lives of scheduled Gemini 9 astronauts See and Bassett were lost in a T-38 jet crash while flying between training sites (28 Feb 1966). Neil Armstrong was forced to eject from a lunar lander simulator, the so-called Flying Bedstead, before it crashed after a malfunction several months prior to the flight of Apollo 11.

Even when all the training and preparation goes to plan there are potential effects on the participants. The volume of information to be absorbed, and the narrow margins for error, mean that training can be mentally and physically challenging. Pre-launch anxiety is also a potential problem.

NASA, for example, recognise this potential by making one of the stated purposes for the Psychology and Behavior Laboratory at the Johnson Space Center the "Psychiatric, psychological, and psychosocial support for crews, families, and flight controllers before, during, and after extended-duration missions" [2].

Launch

Figure 1: STS-113 Launch. Image Courtesy NASA KSC (KSC-02PP-1818).

When launch day arrives some of the more obvious threats to traveller safety come to the fore. Clearly a space launch is a violent spectacle, with huge amounts of energy released to accelerate the craft against the Earth's gravitational pull. The clearest hazard is the potential for failure in the propulsion system or control system resulting in catastrophic loss of the spacecraft and lives. Elaborate engineering practises have been used in the spacecraft industry, and more generally the aircraft industry, to minimise this potential. Nevertheless, catastrophic failure of a solid rocket booster lead to the loss of seven lives on the space shuttle Challenger (28 Jan 1986, [3]).

Once the engines are fired and the spacecraft leaves the launch pad the crew are subjected to a number of effects. The spacecraft must clear the lower atmosphere as quickly as possible to minimise structural loads and fuel requirements. Until the atmosphere thins, the craft is subject to substantial vibration. As the lower atmosphere is cleared less of the thrust is going into overcoming drag and weight so the craft accelerates more quickly. The crew are subjected to loads on their body related to the acceleration. In the space shuttle this load is deliberately limited to 3-g by controlling the main engine thrust, while the Apollo Saturn V rocket flights reached 4-g. In an aircraft, where g-loads act in the direction from head to toe, there is a strong risk of blood draining from the brain and associated loss of mental faculty during high g-load manoeuvres (there's also a matching issue with pooling in the head). In spacecraft the g-loading issue is mitigated by orienting the crew seating so that they are perpendicular to the direction of the g-load, i.e. horizontal at launch. This attitude is not without its own issue though, with some shuttle astronauts reporting discomfort from their pressure suits while waiting several hours on their back in the spacecraft prior to launch [4].

During launch and boost phase the atmosphere of the spacecraft cabin may be adjusted. In Apollo flights the cabin pressure was maintained at around 5 pounds per square inch ($\simeq$ 34500 Pascals), a little over one third sea-level pressure, and typical for an altitude of 18,000 feet (5500 m). At this altitude some people begin to suffer the effects of hypoxia, something that could be fatal. Consequently, the Apollo atmosphere was oxygen enriched to ensure that sufficient oxygen was available to the crew. Fire risk mitigation (post Apollo 1) had a cabin atmosphere of 60-40 oxygen-nitrogen at launch, but was adjusted to almost pure oxygen over the first 18 hours of the flight [5, §II, Ch5.]. This reduced pressure atmosphere balanced life support needs with keeping total weight down by not carrying inert gas to bulk up the atmosphere. Space shuttle atmospheric pressure is maintained at sea-level pressure with a normal 80-20 nitrogen-oxygen Earth-like atmosphere.

Short Term Stays

This section addresses the human factors associated with short duration space missions. These are by far the most common space experiences, with durations of one or two few weeks the norm for space shuttle flights.

With the launch over the spacecraft enters Earth orbit. Immediately the crew are subject to micro-gravity - the apparent absence of gravity. Normally, the body is subject to a hydrostatic gradient brought about by the presence of gravity. Under micro-gravity the fluids within their bodies will begin to redistribute, with more fluids than normal pooling around the torso and head, and less around the legs. Crew members become slightly rosey and puffy in the cheeks, an effect called oedema. The body's systems try to compensate for what's perceived as an excess fluid load in the torso by increasing kidney and bladder activity. The net result is that the crew member loses fluid and may suffer the effects of dehydration until processes stabilise.

Red blood cell counts, linked to kidney and bone marrow function, are noticeably lower in astronauts after only one or two days in micro-gravity. Depleted red cell counts, anaemia, can lead to symptoms such as heart palpitations, pallor, lethargy, and breathlessness. The common causes of anaemia on Earth are iron depletion and vitamin B12 (folic acid) deficiency [6], neither of which seems to apply to spacefarers. The precise mechanism of this drop has only recently been uncovered [7]. The body actively removes red blood cells to counter for a reduced blood volume.

The human balance, or vestibular, system relies on the motion of fluid within semi-circular canals in the inner ear to determine up and down. In the absence of gravity the normal function of this system is impeded. The effect is also aggravated by dehydration. While little can be done to provide realistic gravity, spacecraft designers do use a range of visual cues to provide reference. Lighting will be concentrated on the 'ceiling', the 'floor' can be painted differently, and all lettering oriented a certain way.

Another bodily system that appears to be affected by micro-gravity is the proprioceptive system. The proprioceptive system is the nerves in the body's muscles and joints responsible for your sense of where your arms and legs are. In the absence of gravity these responses can become dampened leading to the feeling that arms or legs are not there. One Apollo astronaut recalled that while drifting off to sleep he lost the sense of his arms and legs, but that sensation returned when he moved them, only to fade again when he relaxed [8].

Vestibular and proprioceptive system changes can lead to nausea, a generally short-lived, but common side effect of the transition to micro-gravity. While not generally a major issue, should a crew member vomit while performing extra-vehicular activities (EVA) they risk fouling their life support systems. The possibility of this occurring curtailed elements of the Apollo 9, Earth-orbit mission that required astronaut Schweickart to spacewalk. NASA deliberately avoids scheduling EVAs during the first three days of a flight to mitigate this risk. Various drugs have been tested as means of preventing or treating short-term nausea (e.g. [9]).

The human body has evolved to function in tune with a twenty-four hour day. In low Earth orbit the Sun will rise every 90 minutes or so. The effect of abnormal light-dark cycles can negatively affect sleeping patterns. Tired operators are more prone to accidents with potentially life-threatening results. Sleeping arrangements are carefully controlled to ensure that a reasonable cycle is maintained and the crew receive adequate rest.

Any radiation normally blocked by the Earth's atmosphere becomes a potential hazard in orbit or further afield. Of particular concern is any radiation with sufficient energy to disrupt chemical bonds or remove electrons from atoms, known as ionising radiation. Ultra-violet, X-ray, and gamma radiation, and high energy particles (electrons, neutrons etc.) fall into this category. The potential for radiation damage in the human body is measured in unit of Sieverts and typically falls into the milliSievert range. Spacefarers are subjected to a higher than average radiation doses while outside the majority of the atmosphere as shown in Table 1. Risk mitigation involves the use of radiation shielding material in the structure of the spacecraft or any pressure suit used during EVA. Improved radiation shielding does make a substantial difference: 18 days on Skylab accounts for approximately 36 mSv versus 5.59 for the same time on the space shuttle at comparable altitude.

Long Term Stays

This section addresses the added effects that could be expected from a long term stay in space. Such stays have already occurred, with Valeri Polyakov staying 438 days in orbit on board Mir [12]. Long term exposure to the space environment would be natural consequence of extending human exploration

Types of Exposures	mSv
Transcontinental round trip by jet	0.04
Chest X-ray (lung dose)	0.1
Living one year in Houston, Texas	1.0
Living one year in Denver, Colorado	2.0
Living one year in Kerala, India	13.0
Highest skin dose, Apollo 14 (9-day mission to the Moon)	11.4
Highest skin dose, Skylab 4 (87 day mission orbiting Earth at 272 miles)	178.0
Highest skin dose, shuttle mission 41-C (18-day mission, orbiting Earth at 286 miles)	5.59

Table 1: Comparative radiation doses. Ref: [10]. The differences in exposure values for the various space missions shown here are due to mission characteristics as altitude, duration, and quality of radiation shielding technology. Australian exposure standards for workers in at-risk occupations is "20mSv per year, averaged over a period of 5 consecutive calendar years" [11]

to Mars and other planets.

In long-term space missions all of the effects of short-term missions are present. In some cases the risks actually reduce with time spent in the space environment e.g. the potential for space motion sickness. In some cases the existing effects are exaggerated, for example, radiation doses are increased. For extended missions the body's physiological reactions to the loss of gravity become more of an issue. The primary new effects are muscle wastage, bone mass loss, and calcium depletion. These are discussed in the following paragraphs.

In the micro-gravity environment the utilisation of muscles is altered substantially from the normal state. In general the muscles no longer have to work against gravity in order to move. While the muscles are still used in space, they require far less effort in order to achieve desired movement. As with a bedridden patient on Earth, muscles that are underutilised begin to atrophy.

The heart is among the most essential muscles. In micro-gravity environments, the heart is no longer pumping substantial blood to the head against gravity and therefore suffers from wastage. The heart physically shrinks during the extended stay. Heart wastage manifests itself as irregular heartbeats, a lower blood pressure, and reduced aerobic capacity. All of these symptoms are considered worthy of treatment, through medicine or exercise, on Earth. Selection procedures ensure that spacefarers are fit at the time of departure. Even so, after several months in micro-gravity, astronauts return to Earth substantially weakened and incapable of substantial exertion. Periods of rehabilitation, sometimes extending to months, are required to restore normal heart and aerobic function.

The major muscle groups of the legs, back, and hips are required to support and balance the weight of the individual on the ground. These muscle groups atrophy during extended stays in space, up to around 20% mass loss. It's not uncommon for a long-term spacefarer to return to Earth and be unable to stand or sit without slumping, requiring a stretcher or other assistance.

Figure 2: Exercise regime on the ISS [13].

Muscle atrophy and cardiovascular decline can be mitigated to some degree by a rigorous exercise routine. Cosmonauts on board Mir would exercise for at least an hour per day while tethered to a treadmill or exercise bike. Similar regimes are in place aboard the international space station (Figure 2). The tethers pull the body toward the treadmill so that there a force against which the leg muscles can act and running or pedalling is possible. Research is being undertaken, by organisations such as the U.S. National Space Biomedical Research Institute (NSBRI), into various other ways of minimising muscle wastage such as drugs, gene therapy, or hormone therapy.

The human skeleton functions to provide support and mobility to our body, as well as protect inner organs. The removal of the need to support body mass has an effect on the bones of spacefarers. The body, sensing the reduced requirement for rigidity, reduces the mineral content of the bones to reach an equilibrium condition. Russian human post-flight reports indicate that various measures of bone growth are affected, and that there are elevated calcium outputs in human urine. Experiments on rats confirm, more directly, the observations made on humans [10]. Further, the effects on bone growth and maintenance in rats persist for some time after return to the Earth. The changes are not unlike those of the condition osteoporosis on Earth. While in space these changes do pose a risk of stone formation as the calcium aggregates in the kidneys. However, they become a serious problem on return to a normal gravitational field where there is an increased risk of fracture, of particular concern where parachute rather than soft landings occur. Exercise routines, such as the treadmill described above, may go some way toward reducing the effects on the long bones of the human body. Another possibility is the use of dietary or pharmaceutical supplements to bolster the body's bone mineralisation.

The cardiovascular, muscular, and bone changes attributable to extended spaceflight are issues that must be addressed or overcome before manned missions to Mars or elsewhere could occur. Failure to address these issues adequately leaves the spacefarer at serious risk of arriving at their destination physically incapable of achieving their mission.

To date, most human spaceflight has occurred within the near-Earth environment. In this environment, the spacecraft and occupants are still protected from a substantial portion of solar emissions by the van Allen belts. Even so, spacefarers receive higher than usual radiation doses. We know from unmanned missions into the outer solar system that the radiation environment is quite intense. Consequently, long term missions outside the earth's influence will expose the spacefarers to higher does of radiation and potentially longer-lasting effects. Quantifying these risks, and identifying mitigation strategies is a subject for further research.

For a mission of a few days, the possibility of major illness is minimal. Screening for known pathogens and pre-flight isolation can reduce the possibility of carrying a serious bug into space, and this occurs now. For a long-duration mission, the risk of some form of illness occurring increases. The viruses and bacteria present have a chance to multiply and mutate, and the stresses of spaceflight may lower immune responses to them. In the tight confines of a spacecraft, any contagion runs the risk of rapid spread to the entire crew. The crew must be able to fend for themselves medically in this circumstance.

While a life-threatening accident is possible in Earth orbit, Earth is not far away if required. For long duration missions, or even Moon missions, Earth may be too far away to be of assistance. In this circumstance surgical skill and equipment may be required to save a life. The practicality of sending a dedicated physician on every flight is questionable. Therefore, as a mitigation strategy, the long-duration crew must have some form of medical training in order to deal with eventualities. Equipment for minor surgery and first aid must be provided. Facilities for tele-conferencing with Earth-based physicians could be used to bolster the crew's capability, but that may become impractical with, for example, a 10 min round-trip lag in communication.

Space crews are, by necessity, small groups of people. Small groups lack the complex social interactions and support networks that we normally experience on Earth. Consequently, the possibility of psychological effects of spaceflight must be considered, especially for long periods flights. The possible effects are:

- Loneliness. Spacefarers may feel deprived of contact with loved ones.
- Stress. The workload during a space flight could be quite high, is constantly present, and there's little chance of getting away from work

for a break.

- Depression. Monotony of environment and work, failure of missions objectives, or other events could lead to psychological effects such as depression.

Careful pre-flight selection processes can ensure, to a reasonable degree, that crew members are mutually compatible and unlikely to be at each other's throats. Careful attention to human factors in the design of the spacecraft environment and the mission in general could mitigate against the possibility of serious psychological problems.

Extra-Vehicular Activity

EVA exposes the spacefarer to an added range of increased risks. The only protection they have from the near-vacuum of space is their space suit. Apart from the obvious requirement to provide life support, this suit must provide protection from:

- extreme light-dark temperatures and associated gradient;
- radiation exposure; and
- micrometeorite impacts which, despite the small particle size involved, carry a high energy load.

Loss of suit pressurisation through suit failure can be mitigated by thorough pre-use and pre-egress testing of the suit. Micrometeorite impact could, in principle, puncture a suit, but suitable materials design can reduce this risk. The risk due to extreme temperatures is met with strong insulating materials and an internal heating/cooling system to redistribute heat around the suit. Radiation exposure is difficult to prevent, but rudimentary protection is afforded by layers in the suit material that are designed to absorb harmful wavelengths.

Return to Earth

Having spent some time adapting to the micro-gravity environment, the spacefarer must ultimately return to the surface of Earth or elsewhere. This presents the last of the hazards.

The spacecraft must re-enter the atmosphere before the return can be effected. In a successful re-entry the spacecraft is subject to extreme temperatures which the occupants must be protected from. There are substantial loads associated with the deceleration from orbital speed. The ballistic re-entry of Apollo and Soyuz capsules is designed to keep these loads inside tolerances suitable for human survival. The space shuttle more actively manages these loads by adjusting attitude during descent. In the event of catastrophic failure, such as befell the shuttle Columbia in February 2003, there is little that can be done to protect the crew.

Having reached the ground, adaptations made for life in space, in general, work against the individual. Muscle wastage makes it difficult to move limbs or support the body's weight, which may be life threatening in an emergency setting. The vestibular system must readjust to gravity and the spacefarer can suffer giddiness, putting them at risk of falls. Bone mass loss increases the likelihood of fracture in the event of a fall. The return of gravity redistributes the diminished bodily fluids, which move away from the upper body, and may leave the astronaut light headed and short of breath. The heart, which has atrophied during flight, must suddenly work harder to move fluids to the head, and low blood pressure results. Long term fliers need to be assisted out of the spacecraft on landing, and are usually confined to a chair or stretcher (Figure 3).

Figure 3: ESA astronaut Haigneré after six months on Mir. Unable to stand, he's confined to a chair. Image courtesy ESA/CNES.

It may take minutes for some effects to pass, and days, weeks, or months for others. For long term flights the risk may extend substantially into the future. In general, extended radiation exposure increases the risk of cancer, cataracts, and tissue damage related disease.

Conclusion

Travel into space may be relatively frequent but it is far from risk-free. Risks to traveller health and wellbeing start before the launch and continue after return. While the human body's ability to adapt to the changed conditions of micro-gravity allows us to function in space it is also a weakness on return to Earth. Some hazards, such as radiation or immune system suppression, may have lasting and hard to quantify effects. Psychological effects may play just as important a role as physical effects in long duration missions. Most hazards faced by human space travellers can be minimised if not removed. If humankind is to venture far into space then the hazards, whether external or internal, must be addressed and minimised.

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