TITLE: Cohort Profile: NASA Astronauts as an Occupational Cohort

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ABSTRACT

Purpose

Occupational cohorts are important to understanding the unique exposures of a workforce. The crewmembers selected by NASA to be astronauts experience occupational exposures unlike any other. To better understand the short- and long-term health effects of spaceflight, health and exposure data is collected on this cohort through clinical and other surveillance settings.

Participants

This cohort is comprised of the 360 astronauts who have been selected by NASA from the first selection class in 1959 to the most recent class of 2022. Selection of crewmembers is based on specific skills, education, military experience, and fitness for flight. Due to the stringent and specific selection criteria, this occupational cohort encompasses a population that is more homogenous than other groups. However, with the evolution of selection criteria along with changes to health screening and data collection processes, each selection class has varying baseline health status.

Findings to Date

Data on a variety of health outcomes and risk factors have been collected along with occupational physiological and exposure data, demographic and socioeconomic information, and exposures that occurred prior to selection. Data have been utilized for both research activities, such as studies addressing Spaceflight Associated Neuro-ocular Syndrome (SANS) and venous thromboembolism, and occupational surveillance activities like monitoring cardiovascular health pre-, in, and post-flight.

Characterization of these factors helps not only with current monitoring but also informs future risk reduction decisions for exploration missions.

Future Plans

As NASA plans missions to the Moon and Mars, the evidence base for this cohort will continue to grow through monitoring of current, future, and retired crewmembers. As more data is collected, future research and surveillance activities will continue to be developed both internally and externally.

Strengths and Limitations

Strengths:

- Cohort is closely followed over course of lifetime starting with a rigorous selection exam
- Large amount of data collected for each individual crewmember
- Minimal risk of loss to follow up due to medical monitoring requirements

Limitations:

- Small sample sizes limit ability to address specific
- High health and fitness standards upon selection and resources provided by employment

INTRODUCTION

The first NASA astronauts were selected in 1959 with Alan Shepard becoming the first U.S. astronaut to travel to space in 1961. As of December 31, 2023, NASA has selected a total of 360 individuals into its space program. Early spaceflight missions lasted only minutes, hours or days. Current astronauts spend an average of six months on the International Space Station (ISS), with the longest mission lasting just over one year. On these missions, astronauts endure occupational exposures resulting from the five hazards of spaceflight: altered gravity, radiation, isolation and confinement, hostile closed environment, and distance from Earth.[1] Astronauts spend the majority of their careers on Earth preparing for spaceflight missions and undergo strenuous physical and psychological training in a variety of environments as part of their occupation.

To date, astronaut health research and surveillance studies have focused on detailed reports of consequences resulting from the physiological adaptation to spaceflight for small samples of the astronaut population, often under the constrained conditions of research.[2,3] However, the complete occupational cohort has not been described using validated NASA data sources in over 20 years.[4] Epidemiological literature on the astronauts has relied heavily on outside investigators and media outlets, often compiled with information from public sources with limited access to NASA data, to describe this unique occupational population.[5–8] These reports often use subsets of data, pieced together information from various sources, or are focused on a specific subject area. This report aims to help provide additional information on this occupational population to provide context to those who study NASA astronauts.

The purpose of this report is to describe the demographic characteristics and occupational exposures for all NASA astronauts at the time of selection, using data from validated NASA sources. Astronauts from

NASA's international partners (IP) and private astronauts that have flown on NASA spacecraft are not included in this report. A description of the data collection procedures, throughout the periods of selection, active career, and retirement, as well as a report of their vital status as of the end of 2023 is provided.

As commercial for-profit companies are now conducting fully private space missions and ferrying private astronauts to the ISS, it is important to delineate the unique occupational cohort employed by NASA to conduct its missions. This detailed description of the astronaut cohort will benefit NASA in its occupational surveillance and clinical care, along with mission operations and planning. Outside of NASA, the cohort description will also allow commercial space providers needed information to compare their cohort of space fliers to understand if illnesses and injuries are occurring at expected rates. As demographic characteristics of cohorts change, understanding how different cohorts will be comparable will be necessary. This cohort description will also benefit aerospace medicine researchers, aerospace engineers, the occupational health community, and the general public. Understanding the baseline demographic characteristics of the astronaut cohort allows for incidence, exposures, and other variables will facilitate improved systematic review and meta-analysis of those who have flown in space.

COHORT DESCRIPTION

Astronauts are selected from a pool of applicants based on health characteristics, skills, and educational requirements.[9] The 360 NASA astronauts have been selected in 23 classes between 1959 and 2022. Since the selection of NASA astronauts is based on specific skills, education, military experience, and fitness for flight, the cohort is not representative of the general U.S. population; however, other uniquely selected and followed cohorts may be comparable.[10,11]

Re-use of astronaut data is controlled through the NASA IRB and operational control boards. A non-human subjects research determination was granted by the NASA IRB for use of de-identified data for occupational surveillance purposes.

Data collection

Medical data are collected regularly throughout the astronaut career, providing a comprehensive and detailed source of information regarding the health of this population. Collection of these medical data is similar to a typical outpatient medical facility; care encounters are documented by the technologists, nurses, and physicians employed by the Johnson Space Center (JSC) Flight Medicine Clinic. Data regarding occupational exposures are collected and maintained by respective laboratories or groups (e.g., the Space Radiation Group collects, maintains, and analyzes space radiation exposure data).[12] Although data collection is constant and ongoing, there are four distinct phases of astronaut data collection: Selection, Active Career, Retirement from Flight, and Death. During an astronaut's active career, medical data is collected on an annual basis but also at established intervals prior to, during, and following spaceflight. Collection at these regular intervals facilitates study of the effects of the hazards of spaceflight, especially altered gravity.

Selection

After applying to the NASA astronaut corps, highly qualified individuals go through multiple rounds of interviews, and the most qualified are invited to NASA for an extensive battery of physical, physiological, and psychological screening. These rigorous assessments ensure the candidate is physically and mentally fit to endure the rigors of the occupation of astronauts. Exams include documenting demographic factors and baseline health status, screenings for active disease, and assessments of future disease risk.[9,13] The acceptable levels of fitness and health for selecting candidates have changed over time, impacted by changes to clinical practice guidelines, advances in medical technology, and restructuring of the operational needs of NASA. As a result, collection of specific data varies by selection class. While an exhaustive compilation of the past selection standards have not been released publicly, general details of the selection process has been published, [9,13–15] and a recent NASA report details the most recent selection standards.[16] A distinct group of payload specialists were selected for specific missions based on unique skills required to meet mission objectives. Their selection criteria, training, and career trajectories differed from NASA astronauts and as such they are not included in this report.

Active Career

The active career of an astronaut begins when the selection class reports to NASA for employment. Data collection on each astronaut during their active career includes medical visits for primary care such as routine well visits, visits due to injury or illness and subsequent treatment, and monitoring of health status. Additionally, data are collected for occupational surveillance protocols in preparation for spaceflight missions, in-flight monitoring, post-mission screening, and activities as a consented research subject.

Active astronauts receive annual physical exams and primary care services at the JSC Flight Medicine Clinic from NASA flight surgeons. The annual physical exam is the foundation of the astronaut's certification for flight. Components of the annual physical examination include past and interval medical history, vital signs, current medication use, and review of all body systems. This exam may be accompanied by a battery of imaging such as MRI, Optical Coherence Tomography and chest x-rays, laboratory assessments such as blood work and urinalysis, behavioral health assessments, as well as an evaluation of radiation exposures.[17] However, not every one of these tests are run on an annual basis; some may only occur every few years.

During training in preparation for a spaceflight mission, physical exams increase in frequency and depth. This period of enhanced medical testing continues inflight and following the mission. The NASA Medical Requirements Implementation Documents detail the type and frequency of data collected for an astronaut surrounding their mission.[18] This robust data collection around missions enables occupational surveillance and data analysis to understand the effects of spaceflight and its hazards on the human body.

ADD DIFFERENT TRAINING THAT ASTRONAUT UNDERGO HERE. On Earth, astronauts are subject to additional exposures as they train for spaceflight. They undergo strenuous physical and psychological training, in a variety of environments such as the Netural Buoyance Laboratory, NEEMO, Hi-SEAS, etc., along with normal day-to-day physical and technical trainings to properly prepare for their missions. Day-to-day physical training is overseen by a number of athletic trainers and physical therapists, who help design workouts to test and build strength, both physically and cognitively on both an individual and team level.

Once the astronaut is in space, any examination, treatment, or interaction between the crewmember and their assigned flight surgeon is conducted in a telemedicine environment. The frequency, duration, and intensity of these exchanges have varied over the history of spaceflight, primarily commensurate with the risk of the mission. For example, on Shuttle missions, only the Commander or Crew Medical Officer communicated with the flight surgeon on behalf of the crew for the duration of the mission. After landing, the flight surgeon conducted extensive interviews with each crewmember. Current practice on ISS is to hold a weekly status update, known as a private medical conference (PMC). These are held between an astronaut and their assigned flight surgeon, via video and/or audio conference. Frequency of these encounters increases for launch and landing and any Extravehicular Activity (e.g., spacewalks). Any medical events that occur during the mission are documented by the flight surgeon in the crewmember's electronic health record (EHR).

Former Astronauts

Following retirement from active flight status, former astronauts are invited back to the JSC Flight Medicine Clinic annually for a comprehensive physical examination. This exam typically includes medical screenings based on recommendations by the U.S. Preventive Services Task Force as well as additional testing for diseases and conditions possibly associated with spaceflight. For example, dual-energy x-ray absorptiometry (i.e., DXA or DEXA) is a bone densitometry technology that is not typically performed in individuals under age 65 in the U.S. general population; however, it is included in the medical monitoring protocols for active and former astronauts due to the microgravity related physiologic changes to bone density and the subsequent risk for osteoporosis and fractures.[19]

Following retirement from flight, former astronauts receive primary care services and specialty medical services outside of NASA. With authorization from the astronaut, NASA requests medical records from their private providers to include in the medical record system at NASA. This permits the continuous review and analysis of long-term health outcomes that may be related to spaceflight. With the 2017 passage of the To Research, Evaluate, and Treat Astronauts Act (TREAT Act),[20] the U.S. Congress granted NASA additional authorization to expand medical monitoring of former astronauts and payload specialists and to provide diagnostic and treatment services for conditions deemed associated with spaceflight. As NASA enhances the astronaut occupational health program under TREAT, the volume and richness of health data of former astronauts and payload specialists is expected to increase.

Death

Death certificates for deceased astronauts are requested from state or national agencies following a death, regardless of active or former status at the time of death. NASA will also request hospitalization and other interval health records until death. This includes autopsy reports when available. An autopsy program has been established where crewmembers can decide before death to have an autopsy performed by NASA to further understand long-term effects of spaceflight.

Patient Involvement

Participation in the cohort begins at selection and data collected is dictated by requirements set by stakeholders within NASA as part of the Medical Requirements Integration Documents (MRID). However, these requirements change with time and feedback from astronauts is considered as surveillance, clinical, and other operational metrics are identified.

Data changes across time

Since the first NASA occupational health data were collected in 1959, clinical practice standards and medical evidence have changed considerably, along with a concomitant increase in the knowledge of the effects of spaceflight on the human body. With these changes in clinical care practices and knowledge across time, NASA has responded by evolving its monitoring techniques and adopted unique longitudinal methods for analyzing this complex astronaut data. For instance, spaceflight-associated vision changes were once believed to be a normal part of adaptation to microgravity that would resolve following the return to Earth. Following identification of the first cases, extensive eye and brain medical testing was implemented. Analysis of the data collected has found that these changes are not normal, and may not completely resolve, a phenomenon known as Spaceflight-Associated Neuro-ocular Syndrome (SANS).[21] Findings like this from surveillance activities help continuously add to the evidence base and understanding of risk.

Cohort follow-up

Astronauts are employees of the U.S. government and much of the medical monitoring and clinical care an astronaut receives is a requirement for spaceflight assignment. This provides a unique opportunity to gain comprehensive insight into the health of astronauts over the length of their active flight careers. Participation in monitoring and care of active astronauts ensures compliance and consistent follow up. Former astronauts are encouraged, but not required, to return to NASA for an annual physical exam akin to an executive physical.[22] Nearly 75% of retired crew have returned for an annual exam. Former astronauts may elect not to return for follow up for various reasons including health issues not allowing for travel and scheduling conflicts. As mentioned previously, to supplement the annual exam, medical records from external providers are requested to obtain detailed information on significant interval history and medical events, which are integrated into their JSC EHR.

Demographic Characteristics

This report includes a description of the 360 individuals who have been selected by NASA to be astronauts as of December 31, 2023. Table 1 shows a summary of demographics and other basic information collected at selection for crewmembers along with the current status of each astronaut. Among the living crewmembers, 49 are currently active astronauts and 228 are former astronauts. Overall, there have been a total of 61 female astronauts and 299 male astronauts. Individuals who flew on Shuttle missions as payload specialists and now fly to ISS as private astronauts were excluded from this report because selection criteria, data collection, and medical monitoring differ from career NASA astronauts. Table 1 also displays the differences between males and females selected as astronauts.

Female crewmembers were selected at younger average ages than their male counterparts, with mean ages of 33.2 and 35.3 respectively. Likewise, female astronauts are more likely to come from a civilian background with 63% of female selectees being civilians compared to 23% of males. Females were also more likely to have a doctorate at selection, with over half (52%) of female astronauts having a doctorate compared to 31% of males. Until the most recent birth cohort (1980s), males were the predominant group selected. The first female astronaut was selected in 1978, and 2013 was the only class to reach an equal proportion of females and males.

Race and ethnicity in the astronaut population are currently collected by self-report in clinic documentation using the standard categories under the 1997 Revised Standards for the Classification of Federal Data on Race and Ethnicity.[23] Astronauts were only able to report a single race identity within this data, so there are not multi-racial/ethnicity responses. NASA has selected 313 white, 20 Black or African American, 14 Hispanic, 11 Asian or Pacific Islander, and 2 American Indian/Alaska Native astronauts. Early astronaut classes were all individuals who identified as White. The first Black and Asian astronauts were selected in 1978 the first Hispanic astronaut was selected in 1980, and the first American Indian/Alaska Native astronaut was selected in 1996.

Figure 1 displays the age of selection for each NASA astronaut by sex and military status, and test pilot status. The variance in age is shown within each selection class along with the small increase in mean age at selection in both sexes over time. The difference in birth cohorts within selection class and between selection classes is evident. Figure 2 displays the mean age of all astronauts by sex for selection, first mission, and retirement from flight. The mean length of an astronaut's active flight career is 13 years and the mean age at retirement from active flight status is around 48 years. NASA astronaut career length and age of retirement are low compared to a typical career in the US; Many factors may impact this abbreviated career. Astronauts are typically selected after an initial career such as a test pilot, medical doctor, researcher, or engineer, resulting in a mean age of selection being in the early to mid-30s. Active astronaut careers are akin to a military career with deployments for mission. Training, public appearances, and the physical demands of active duty result in extended time away from family. Astronauts may choose to leave their active careers quickly if health reasons prohibit a person from being selected from a mission. Programmatic reasons may also abbreviate an astronaut's career. For example, when NASA programs transition, such as Shuttle to ISS, or flights are halted due to spaceflight accidents, more astronauts leave their active career as their ability to fly a mission may not be eminent. Following retirement from flight status, most astronauts go on to additional careers such as moving to management roles at NASA, or other space companies, or return to careers that they had prior to NASA (e.g., physician, professor, military service).

Education and Military Career characteristics

Most astronauts (n=299; 83%) have obtained an advanced degree prior to selection (Table 1). These advanced degrees include a wide variety of masters', Doctor of Philosophy, Juris Doctor, Medical Doctor, Doctor of Optometry, and Doctor of Veterinary Medicine degrees. Additionally, five astronauts earned dual doctorates (e.g., MD/PhD) before becoming astronauts.

To date, 72% (n=260) of all astronauts were in the military prior to selection; 73% of military astronauts were also graduates of test pilot programs from the U.S. Navy or Air Force. These programs are two-year advanced programs that train elite pilots in the latest military aircraft, systems and technologies.[24] In addition to military careers, astronauts have held a broad range of occupations before o selection including geologists, teachers, microbiologists, biochemists, physicians, and astronomers. The first astronauts with no military background were selected in 1965.

It has been found that education level varies by military test pilot status (Figure 3). Astronauts with a bachelor's or master's degree at selection are also likely to be graduates of test pilot school (88.5% and 69.6%, respectively). However, among individuals with a doctorate, less than 10% are military test pilots. As a large proportion of astronauts are military test pilots, it is important to note that military test pilots have a similar demographic (high proportion of males, high proportion of white, etc.).[25]

Changes over selection classes

Table 2 details the total number of astronauts selected into each class from 1959 to 2022 selection class, by sex. The first NASA astronauts were required to be military test pilots. In the beginning of the NASA space program, the number of astronauts selected was small, increasing in the 1970s and 1980s as more missions were being flown on the U.S. Space Shuttle which could accommodate more crewmembers and fly more often. Since the 1980s, the size of each astronaut selection class has generally decreased, reflecting the ISS era of spaceflight in which only four to six NASA astronauts travel to the ISS annually, although his number has increased in recent years as the U.S. Commercial Crew Vehicles began launching in 2020. In preparation for the low numbers of astronauts who will explore the Moon and Deep Space, the 2017 class selected 12 members followed by the selection of 10 new astronauts in 2022.

The mean age at selection has remained consistent across time. Mean ages in early selection classes (1959-1987) fluctuated in the low 30s outside of 1984 which had a mean of 37. However, in recent years (post-1990) all selection classes had a mean age over 35, with the 2022 class having a mean age of 38 years old. This homogeneity in age is beneficial as many health outcomes are highly correlated with age.

All members of the first three selection classes (1959, 1962, and 1963, n=30) were in the military prior to or at the time of selection to the astronaut corps, and the first civilian astronauts were selected in 1965. Of the crewmembers who held at most a bachelor's degree at the time of selection, 55 of 65 (85%) were selected before 1990. Since the last individual who had been selected with a bachelor's degree in 2004, the proportion of classes who hold a master's or doctorate degree were similar.

Another way that we can see how the selection of crewmembers has shifted over time is through "selection epochs." These epochs represent larger pools of selection classes that reflect periods of time where selection standards were updated. Figures 4 and 5 show the ages of crewmembers at different milestones based on selection class and their current active status. For active crew, the mean current age is listed instead of the mean retirement age. When grouping crew by selection epochs, female crew from ISS epochs had relatively stable mean age at selection. Within males, these epochs trended older. Current ages and retirement ages are a little difficult to interpret as not enough time has passed for more recent classes; however, for first missions the mean ages increased over the course of late shuttle and ISS missions. When looking at education and military/test pilot status (Figure 6), there is a shift towards higher education. Within the last two selection epochs there have been no astronauts selected with only a bachelor's degree. As with the full cohort as represented in Figure 3, the largest groups are represented by test pilots at master and bachelor levels. After the pre-shuttle epoch, the proportion of selections who were civilians with doctorates remained consistent at between 20 and 26 percent.

Occupational Exposures

There are numerous occupational exposures that astronauts endure across the time of their employment. Following astronaut selection, the first two years are spent in many different types of training, survival skills, and leadership. After this initial astronaut candidacy period, they begin rigorous training for spaceflight. Astronauts spend on average 6 years in training between selection and their first spaceflight, although the range is wide (2-20). This training period exposes crew to an immense amount of physical stress that can result in injuries not unlike those of other occupational athletes such as first responders may experience in training for their line of work. However, diving and survival training provides more specific training for astronauts that are also physically and mentally taxing.

Spaceflight missions encompass the interaction of many different exposures including radiation, isolation and confinement, and microgravity. As of December 31, 2023, 326 of 360 astronauts had flown at least one spaceflight mission for NASA, including 53 women (87% of women selected) and 273 men (91% of men selected). Of those astronauts who never flew a mission, 12 left NASA prior to flight assignment, 8 died before they flew on any spaceflight, and 14 are currently in training to fly a mission. Spaceflight is an inherently dangerous endeavor. Two major spaceflight accidents occurred over NASA's history: the Space Shuttle Challenger disaster minutes after launch, and the Space Shuttle Columbia disaster upon reentry to the Earth's atmosphere. Accidents during training have also occurred including the Apollo 1 fire and several training jet crashes.

The duration of NASA missions has changed over time, ranging from minutes in the early programs to months for the most recent ISS flyers (Figure 7). The mean duration of a mission has increased across time, as has the cumulative time individual astronauts spent in space, ranging from only minutes and hours in the early selection classes to, on average, almost one year of cumulative spaceflight. However, the mean number of missions an astronaut has flown during their career has not changed appreciably over time, ranging from 1.0 to 3.4 by selection class and 0 to 7 for individual astronauts. The number of missions an astronaut has flown and the total time they spend as an active astronaut is driven, at least in part, by NASA programmatic needs, including increased flights for building in space (e.g., increased

Space Shuttle flights while assembling the ISS) or decreased missions following accidents or while a new vehicle is in production.

Figure 8 shows the number of missions and the number of NASA astronauts who flew those missions by program. The first NASA missions on Project Mercury were a matter of minutes flying only to the edge of space before returning to Earth, showing that man could withstand high gravitational forces (g-forces) and safely re-enter the Earth's atmosphere. These missions soon became orbital flights circling the Earth with increasing durations within Low Earth Orbit (LEO), defined as 160 to 1200 miles above the Earth.[26,27] Most spaceflight missions flown by NASA have been only to this altitude as these missions are close enough to Earth that crewmembers can reach their destination quickly, the resupply of needed supplies is more convenient, and return to Earth is possible if there were an emergency. The lack of gravity, as well as living in a hostile closed environment, are the main hazards impacting these missions. Only 24 NASA astronauts have traveled beyond the Van Allen belts (a zone of charged particles held by Earth's magnetosphere)[24,26,28] on nine Apollo missions to the moon, a transit which increases the radiation exposure for astronauts. Twelve of these 24 astronauts set foot on the Moon, which once again changed their microgravity exposure to 1/6th of Earth's, affecting how astronauts ambulated and worked on the Moon's surface. NASA's mission profile will once again be changing as missions to the Moon and its surface are on the horizon with the Artemis program; mission lengths and profiles are expected to shift once again.

FINDINGS TO DATE

Select medical data and NASA funded research findings on NASA astronauts are available upon request through an online platform[29]. Data collected on astronauts may be utilized for clinical and surveillance purposes. As such, much of this data may often be shared between research and occupational communities. Research studies have evolved over time and differed based on the types of missions being flown. The earliest programs, Mercury and Gemini, developed life support systems for spaceflight and demonstrated that humans could survive in space; these missions flew humans up to 14 days and found “physiological functions remaining within normal tolerances.”[30(p3)] With the shift to landing humans on the Moon, the Apollo program built on these successes and continued to study humans “performing useful work in the space environment.”[30(p5)] Biomedical objectives studied included ensuring crew safety by working to identify, minimize, or eliminate anything posing a threat to the health of the crew as well as further understanding biomedical changes experienced during spaceflight. These operational studies employed both a pre-post design to look at any changes to biomarkers that occurred during spaceflight as well as a case-control study to understand if these changes differed from humans who remained on Earth. The studies laid the foundation for the longer duration spaceflight of the Skylab era. The studies on these missions focused mainly on the changes to the human physiology that comes with spaceflight such as changes to the vestibular system, bone mineral density, muscular deconditioning, and cardiovascular adaptations,[31] as well as living in space, such as food studies and exercise capabilities.

Missions again shifted with the beginning of the U.S. Space Shuttle program in the early 1980s; larger crews and the reuse of vehicles allowed for a larger pool of astronauts to study the effects of spaceflight. Specific life science studies have been detailed, and many of these results are available publicly.[15] Space shuttle missions had various objectives across its lifespan. During the midst of the Space Shuttle era in the mid-1990s, the space shuttle also transported crewmembers to the Russian Mir space station. These long-duration missions laid the foundation for the ISS. In the late 1990s, the focus of Space Shuttle missions shifted to the assembly and operations of the ISS.[15] The Space Shuttle era lasted until 2011 after 135 missions over 30 years.

Human research on ISS focuses on living and working in space. Research to date has centered on the relationship of longer duration spaceflight exposure to changes to human anatomy and physiology, behavioral health, and team performance. Understanding these health outcomes along with countermeasure testing are the primary focus of these studies. Health outcomes that have been studied include SANS eye and vision changes,[21] SANS brain changes,[32,33] venous thromboembolism,[34,35] possibly precipitated by slow venous outflow in the internal jugular,[36] cardiovascular physiology changes,[2,37] bone health,[19] and headaches related to carbon dioxide levels during spaceflight.[38] Behavioral health and performance are also regularly studied including behavioral conditions, team functioning, sleep loss, and circadian desynchrony. While many studies assess the effects of spaceflight on humans, many also aim to study the effect of possible countermeasures on these identified risks to the human [bisphosphonates, exercise, lower body negative pressure, orthostatic intolerance (OI) garments]. The Human Research Program routinely publishes evidence reports, or a collection of evidence-based risk reports, or cited journal articles for these identified risks to human health.[39]

Comparison to Other Cohorts

NASA's astronaut corps has many unique facets in terms of occupational exposures, although they are not without compare. There are other cohorts of astronaut-like cohorts, such as Russian cosmonauts, and occupations such as military pilots and first responders (career fire fighters in particular) that share similar experiences. Cosmonauts are the most directly comparable as they endure similar spaceflight exposures, although they have different geographic exposures, including differences in healthcare across the lifespan. Aspects such as the extended periods of isolation with small teams, physical training required, exposure to unique/dangerous environments that astronauts endure can be compared to other occupational or general population cohorts. By understanding the population that data are collected from, contextualized comparisons can occur. Comparison cohorts have been used in the past to focus on long-term health outcomes and their possible relationship to spaceflight. The Longitudinal Study of Astronaut Health was conducted from the early 1990s through 2010 and was as a case-control study where astronauts were matched to a Civil Service cohort employed at Johnson Space Center.[40] Each group was monitored for health outcomes via annual physical exams. Early results found a possible increase in cancer mortality but not cardiovascular disease than the control group.[4] Ade et al.[41] found that there was no difference between the two groups for cardiovascular outcomes. The Longitudinal Study concluded when the Institute of Medicine deemed the match to be insufficient and recommended that NASA shift to occupational surveillance of their astronauts.[42] Identification of comparable cohorts with similar subject pools, data collection methods, and chronology has been ongoing. The NASA Study of Cataract in Astronauts compared astronauts who flew at least one mission with three control groups: 1) astronauts with no spaceflight; 2) military air crew; 3) non-aircrew. Cross-sectionally, astronauts with spaceflight had more extensive cortical opacification.[43] Laughlin et al.[11] used a cohort comparison of individuals in a capitated insurance contract to understand if NASA astronauts were at a higher risk of shoulder injuries due to the occupational exposures. While astronauts had a higher rate of shoulder injury consultations, they did not have a higher rate of surgeries. Charvat et al.[10] used a well-matched cohort from the Cooper Center Longitudinal Study and found that there may be a higher incidence of cardiovascular events, but not cardiovascular mortality. While this study was produced by LSAH, this is one example of how this cohort profile can help facilitate future cohort comparisons internally and in collaboration with external researchers. The more knowledge available on the population allows for better informed studies in the future.

STRENGTH AND LIMITATIONS

The NASA astronaut occupational cohort is unique. Each class of astronauts is selected from a pool of thousands of applicants, narrowed through a rigorous screening process that looks not only at the health of the prospective astronaut but what skills, personality traits, team compatibility, and leadership ability they have.[9,13] Astronauts have extensive contact with the Flight Medicine Clinic at JSC throughout their active careers and retirement, providing a wealth of data for investigation, but with distinct analysis challenges.

The vast amount of data collected on each member of this population across time is a major strength of this cohort, even though the population is small. The richness of these data allows for detailed study of occupational health exposures and health outcomes. For instance, one potential astronaut occupational health risk currently under study is bone changes during spaceflight. The changes to bone density are closely monitored after missions to understand how the bone architecture is rehabilitating. Data systems have also matured and allow for replicable data and expedited requests.

A caveat of the richness of these astronaut data is the consideration of astronauts as a healthy worker population. Astronauts are selected, in part, on their physical health and fitness, and are commonly healthier when compared to the general population. Further, resources are invested for them to remain healthy and eligible for spaceflight. This may result in a health worker effect,[44] since the astronaut population is heavily screened to be selected and throughout the active career (in many cases at younger ages and more frequently than recommended by the United States Preventive Services Task Force to ensure mission success. Higher incidence rates compared to the general U.S. population may be the result of a screening bias.

Further, during the active phase of an astronaut's career there is minimal concern of loss to follow up. In order to maintain their flight status, astronauts obtain care on site at JSC or from outside providers who partner with NASA. This has led to the establishment of a substantial compilation of astronaut medical and research data providing an evidence base to characterize short- and long-term health risks of the astronaut occupation.

The principal limitation of the NASA occupational cohort is the small population size. Any studies using these data must consider the small sample along with the homogeneity of certain selection classes; large proportion of the crew was selected during the Shuttle mission program which results in data having a bias towards white males with a military background born in the 1950's. Thus, when these data are stratified by characteristics such as sex, race, and spaceflight exposure, they become even more limited. Specifically, characterizing the health effects of long-duration missions is critical to identifying the potential risks of future deep space and planetary missions. However, as of the end of 2023, only 76 of the 360 NASA astronauts have launched a mission to the ISS, and only 20 are female and 12 are a race other than white. Age is another critical element to consider when studying the impacts of spaceflight, particularly long-duration spaceflight where the mean age at first mission is 42. For example, the development of health outcomes may be related to spaceflight exposures or due to the normal aging process. The interaction of age and exposures and outcomes is difficult to study among the small population and the smaller sample of long-duration flyers who have not yet aged enough to evaluate the impact of space travel on long-term health. It is also difficult to overcome the inherent bias that any health outcomes an astronaut experiences must be due to the effects of spaceflight. Causation in small samples is very difficult to discern.

Studying the astronaut cohort is complicated by changes in the collection, management, and provision of the data that have occurred over time. Unlike other populations, such changes in astronaut data collection methods are primarily based on the clinical needs of the population and the operational needs of NASA, with less attention to how such changes may impact the ability to investigate the effects of spaceflight. Further, as spaceflight mission profiles have changed over time so the exposure to hazards of spaceflight have also changed. As a result, it can be exceedingly difficult to compare differences in health risks across potential risk factors and across time with findings only generalizable to a small subset of the entire population. While there is homogeneity of the demographics typically within a selection class, the change in trends over time due to program needs limits the internal validity of data when generalizing a sample of astronauts to the larger cohort. Additionally, the external validity of astronauts compared to the general population and other non-astronaut populations may be limited.

COLLABORATION

Authors encourage the reuse of astronaut medical and research data for retrospective study. Because of the employee and employer relationship between astronauts and NASA, the Privacy Act of 1974 governs release of this data, which requires that federal agencies develop a System of Record for each type of record maintained.[46] A System of Record Notice, SORN, is available for the public to understand appropriate collection, use, and sharing of different types of data. Astronaut health data are part of the NASA SORNs 10HERD and 10HIMS, Human Experimental and Research Data Records and Health Information Management System.[47] Release of data for research is also governed by 45CFR, Code of Federal Regulations, and requires human subject review and approval along with written informed consent of the participants.[48] Opportunities for external investigators to obtain data are subject to these ethical and technical approvals. Requests for data can be made to nlsp.nasa.gov. Appropriate populations to compare this highly select group are always sought.

FUNDING

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Tables and Figures

Table 1. Demographic Characteristics of Crewmembers at Selection by Sex

Characteristic	**Total,** N = 360[1]	**Female**, N = 61[1]	**Male**, N = 299[1]
Current Status	*n (%)*	*n (%)*	*n (%)*
Active	49 (14%)	20 (33%)	29 (9.7%)
Deceased	83 (23%)	7 (11%)	76 (25%)
Retired	228 (63%)	34 (56%)	194 (65%)
Race			
African American	20 (5.6%)	6 (9.8%)	14 (4.7%)
Asian	11 (3.1%)	3 (4.9%)	8 (2.7%)
Hispanic	14 (3.9%)	2 (3.3%)	12 (4.0%)
Native American	2 (0.6%)	1 (1.6%)	1 (0.3%)
Other	1 (0.3%)	0 (0%)	1 (0.3%)
White	312 (87%)	49 (80%)	263 (88%)
Birth Cohort			
1920s	14 (3.9%)	0 (0%)	14 (4.7%)
1930s	60 (17%)	0 (0%)	60 (20%)
1940s	58 (16%)	6 (9.8%)	52 (17%)
1950s	111 (31%)	19 (31%)	92 (31%)
1960s	77 (21%)	18 (30%)	59 (20%)
1970s	23 (6.4%)	9 (15%)	14 (4.7%)
1980s	17 (4.7%)	9 (15%)	8 (2.7%)
Education			
Bachelor	61 (17%)	4 (6.6%)	57 (19%)
Masters	184 (51%)	25 (41%)	159 (53%)
Doctorate	115 (32%)	32 (52%)	83 (28%)
Military and Test Pilot Status			
Civilian	100 (28%)	41 (67%)	59 (20%)
Military - Not a Test Pilot	69 (19%)	10 (16%)	59 (20%)
Test Pilot	191 (53%)	10 (16%)	181 (61%)
	Mean (SD)	*Mean (SD)*	*Mean (SD)*
Age at Selection	34.6 (3.7)	32.9 (3.5)	34.9 (3.7)

Table 2. Demographic Characteristics of Crewmembers at Selection by Selection Class

Characteristic	Sex		Military and Test Pilot Status			Education			Age at Selection
	Female	Male	Civilian	Military - Not a Test Pilot	Test Pilot	Bachelor	Masters	Doctorate	
1959, N = 7[1]	0 (0%)	7 (100%)	0 (0%)	0 (0%)	7 (100%)	7 (100%)	0 (0%)	0 (0%)	34.7 (1.9)
1962, N = 9[1]	0 (0%)	9 (100%)	0 (0%)	1 (11%)	8 (89%)	6 (67%)	3 (33%)	0 (0%)	33.0 (1.3)
1963, N = 14[1]	0 (0%)	14 (100%)	0 (0%)	5 (36%)	9 (64%)	7 (50%)	6 (43%)	1 (7.1%)	31.5 (1.9)
1965, N = 6[1]	0 (0%)	6 (100%)	2 (33%)	4 (67%)	0 (0%)	0 (0%)	0 (0%)	6 (100%)	31.9 (2.5)
1966, N = 19[1]	0 (0%)	19 (100%)	0 (0%)	5 (26%)	14 (74%)	5 (26%)	12 (63%)	2 (11%)	33.3 (2.3)
1967, N = 11[1]	0 (0%)	11 (100%)	9 (82%)	2 (18%)	0 (0%)	0 (0%)	1 (9.1%)	10 (91%)	31.6 (4.7)
1969, N = 7[1]	0 (0%)	7 (100%)	0 (0%)	0 (0%)	7 (100%)	4 (57%)	3 (43%)	0 (0%)	33.2 (1.8)
1978, N = 35[1]	6 (17%)	29 (83%)	10 (29%)	6 (17%)	19 (54%)	7 (20%)	14 (40%)	14 (40%)	32.5 (3.6)
1980, N = 19[1]	2 (11%)	17 (89%)	4 (21%)	4 (21%)	11 (58%)	0 (0%)	15 (79%)	4 (21%)	33.1 (2.6)
1984, N = 17[1]	3 (18%)	14 (82%)	4 (24%)	3 (18%)	10 (59%)	4 (24%)	10 (59%)	3 (18%)	34.4 (3.7)
1985, N = 13[1]	2 (15%)	11 (85%)	4 (31%)	1 (7.7%)	8 (62%)	6 (46%)	5 (38%)	2 (15%)	32.2 (2.8)
1987, N = 15[1]	2 (13%)	13 (87%)	4 (27%)	1 (6.7%)	10 (67%)	3 (20%)	9 (60%)	3 (20%)	33.9 (2.7)
1990, N = 23[1]	5 (22%)	18 (78%)	7 (30%)	4 (17%)	12 (52%)	2 (8.7%)	11 (48%)	10 (43%)	34.1 (2.8)

1992, N = 19[1]	3 (16%)	16 (84%)	7 (37%)	7 (37%)	5 (26%)	1 (5.3%)	7 (37%)	11 (58%)	35.9 (3.7)
1995, N = 19[1]	5 (26%)	14 (74%)	4 (21%)	4 (21%)	11 (58%)	1 (5.3%)	13 (68%)	5 (26%)	35.8 (2.6)
1996, N = 35[1]	8 (23%)	27 (77%)	11 (31%)	7 (20%)	17 (49%)	2 (5.7%)	22 (63%)	11 (31%)	36.3 (4.1)
1998, N = 25[1]	4 (16%)	21 (84%)	11 (44%)	1 (4.0%)	13 (52%)	2 (8.0%)	15 (60%)	8 (32%)	36.5 (4.0)
2000, N = 17[1]	3 (18%)	14 (82%)	5 (29%)	1 (5.9%)	11 (65%)	3 (18%)	9 (53%)	5 (29%)	35.6 (3.6)
2004, N = 11[1]	2 (18%)	9 (82%)	6 (55%)	3 (27%)	2 (18%)	1 (9.1%)	7 (64%)	3 (27%)	37.6 (3.9)
2009, N = 9[1]	3 (33%)	6 (67%)	3 (33%)	2 (22%)	4 (44%)	0 (0%)	5 (56%)	4 (44%)	37.4 (4.5)
2013, N = 8[1]	4 (50%)	4 (50%)	2 (25%)	1 (13%)	5 (63%)	0 (0%)	5 (63%)	3 (38%)	36.7 (1.9)
2017, N = 12[1]	5 (42%)	7 (58%)	5 (42%)	3 (25%)	4 (33%)	0 (0%)	7 (58%)	5 (42%)	34.7 (4.6)
2022, N = 10[1]	4 (40%)	6 (60%)	2 (20%)	4 (40%)	4 (40%)	0 (0%)	5 (50%)	5 (50%)	38.2 (3.6)

[1] n (%); Mean (SD)

Figure 1. Age at selection by sex and military/test pilot status across selection classes

Ages of astronauts on date of selection into the NASA Astronaut corps by sex (male circles; female squares) and military/test pilot status (civilian red; green military but not a test pilot; blue military test pilot) overlaid with the average age of each class by sex (black, open circle/square)

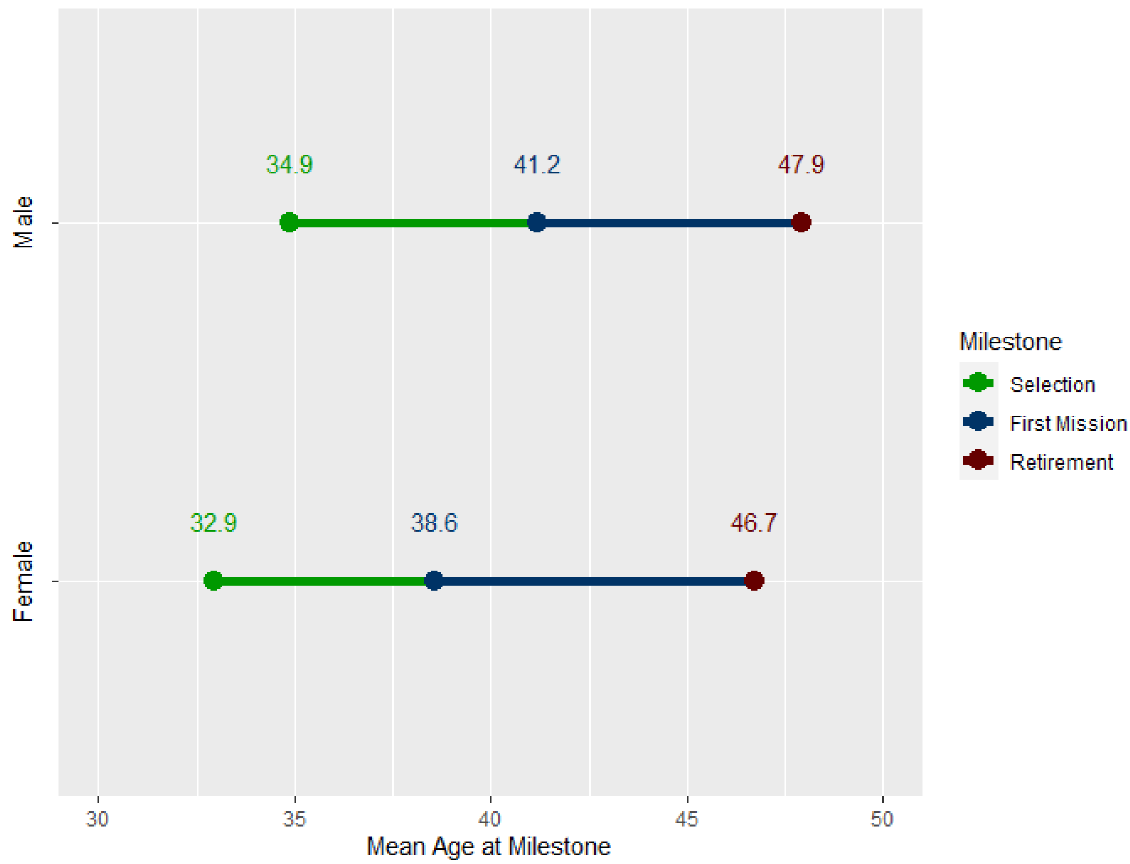

Figure 2. Age at career milestones by sex

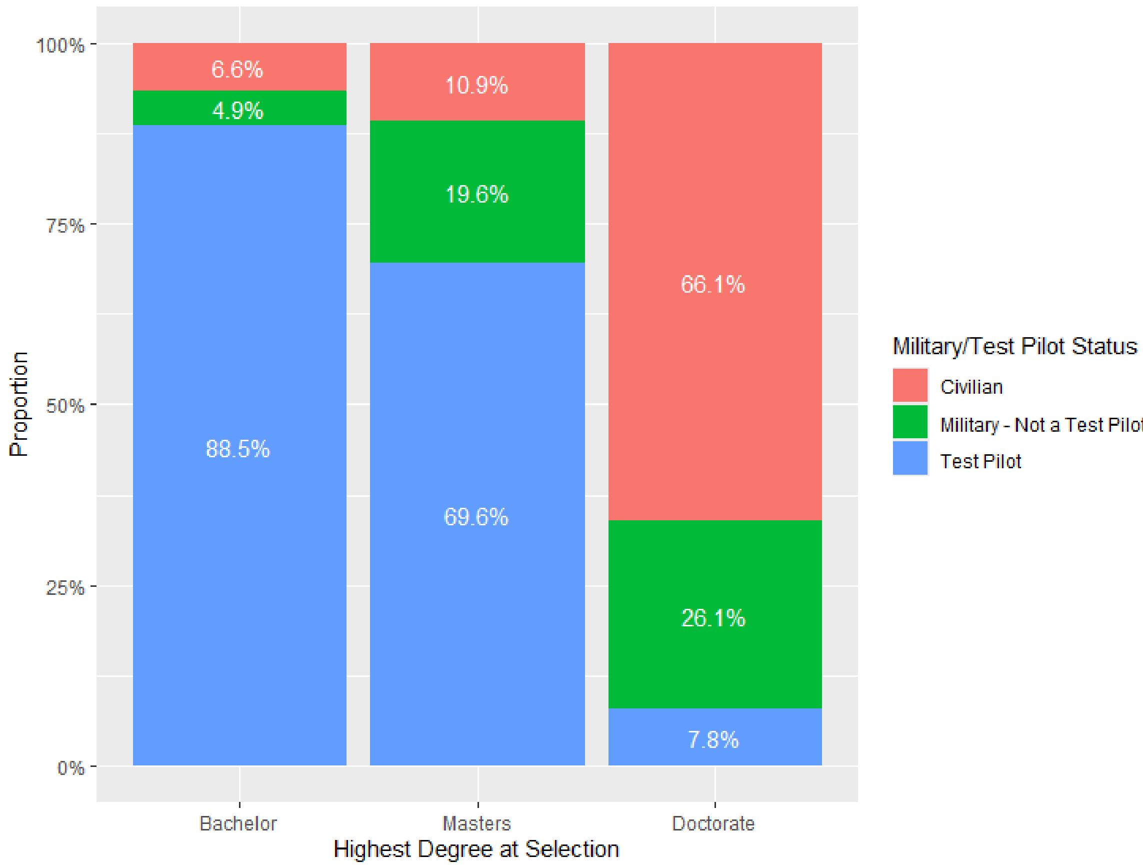

Figure 3. Highest achieved degree at selection by civilian, military, and test pilot status

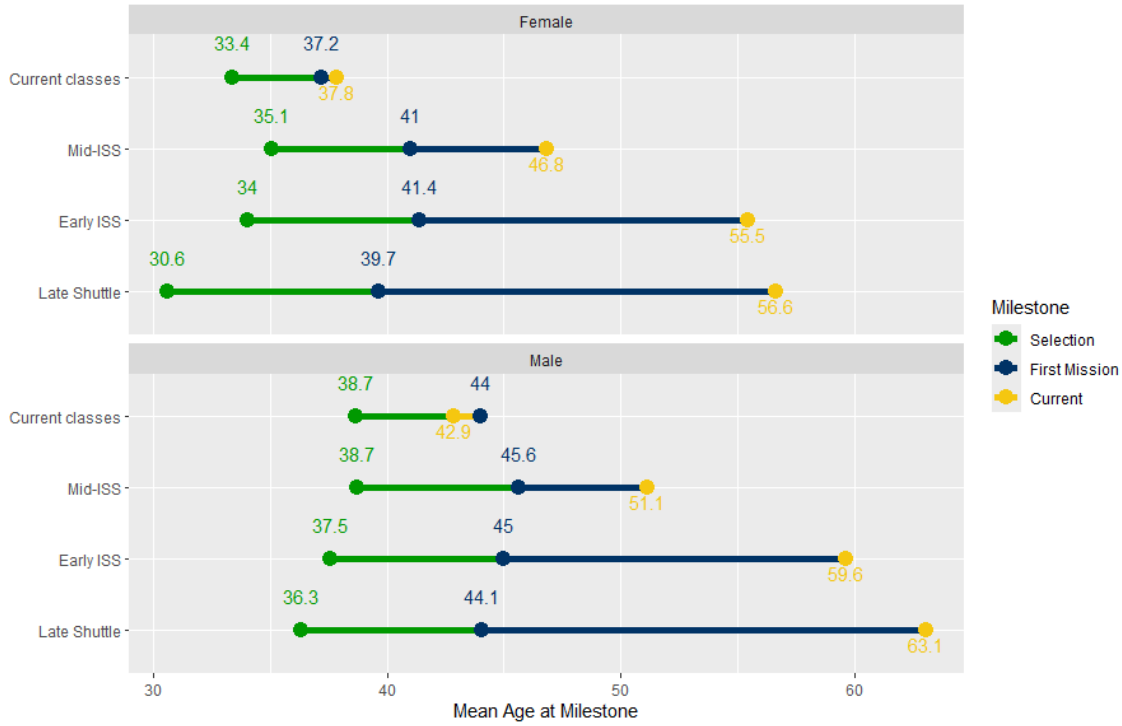

Figure 4. Age at career milestones by sex and selection epoch for active crew

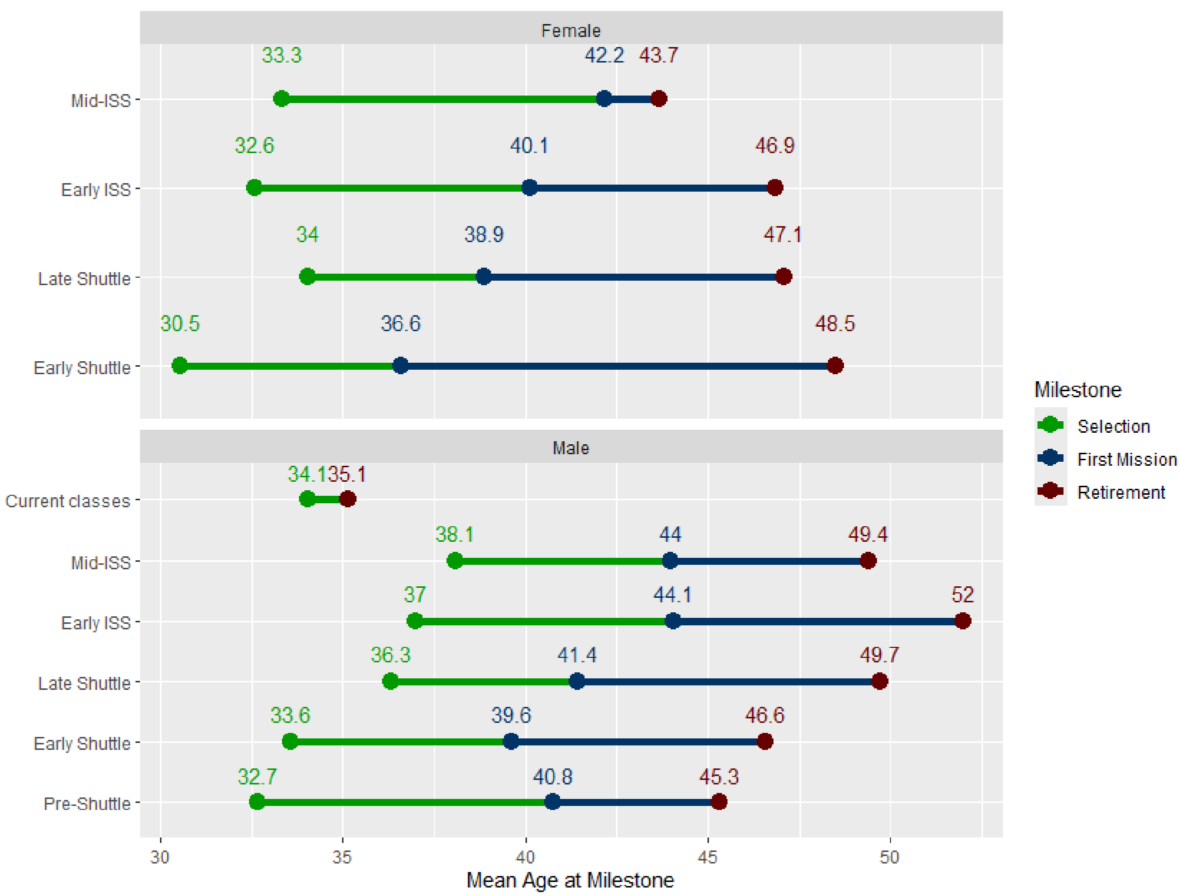

Figure 5. Age at career milestones by sex and selection epoch for non-active crew

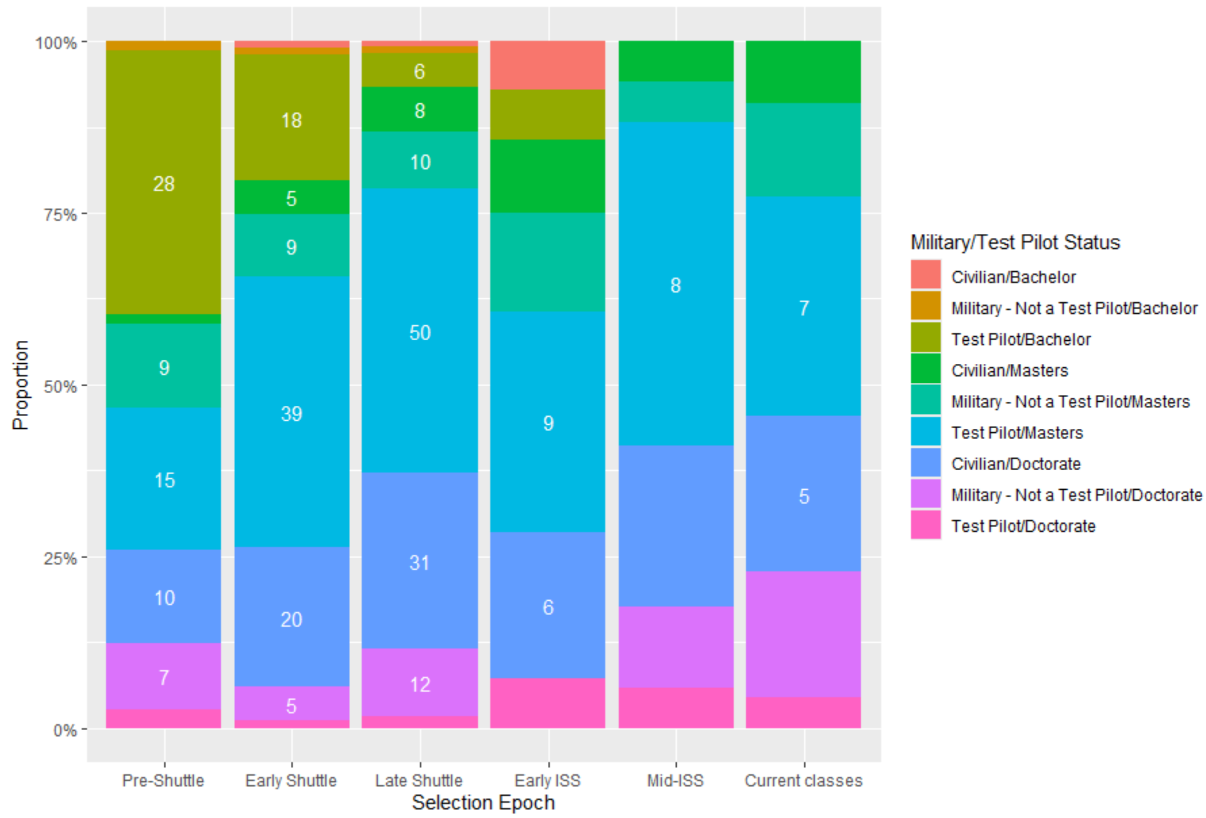

Figure 6. Highest achieved degree at selection by military, test pilot status, and selection epoch

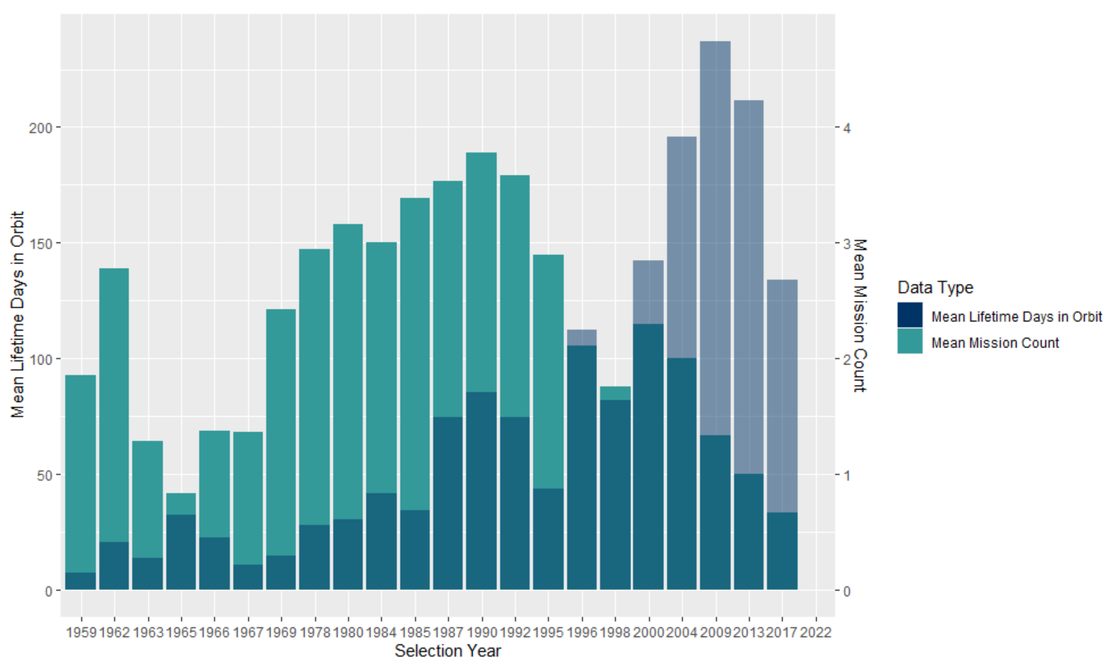

Figure 7. Lifetime mission count and cumulative days in orbit by selection class

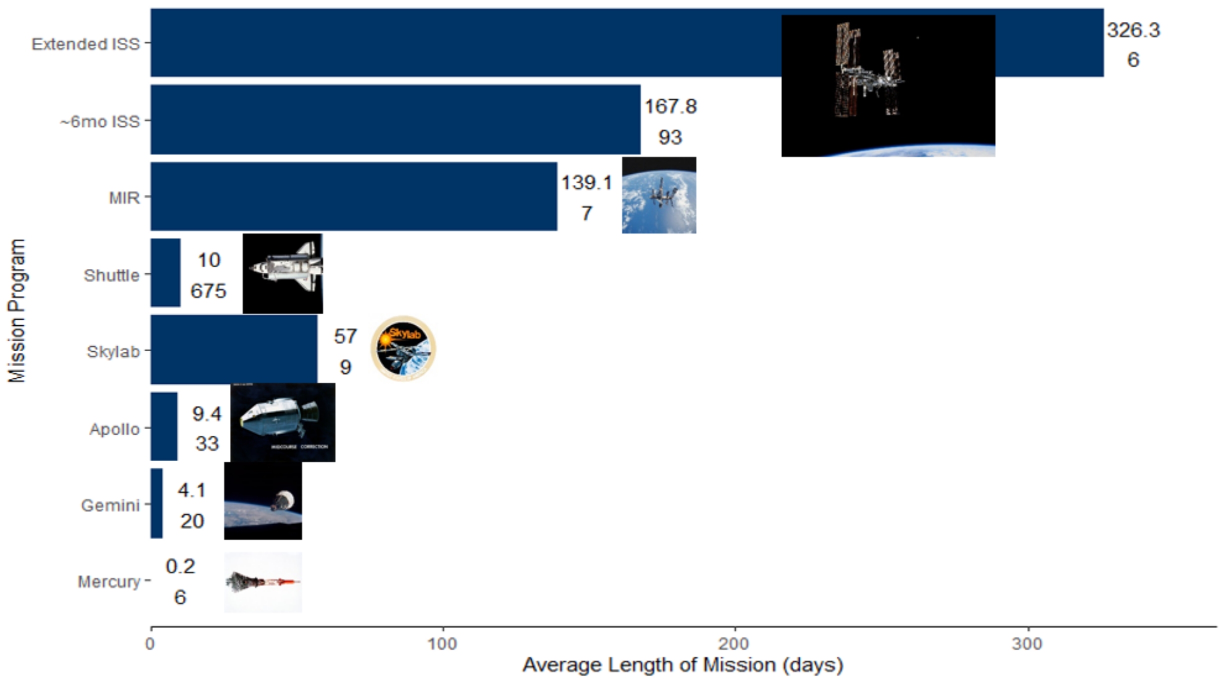

Figure 8. Average length of NASA spaceflight missions (days) and number of missions by program

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