Case Study of the Benefits of Collaboration Between Aircraft and Space

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Only 100 years ago, taking a flight across the ocean was as unattainable to much of the world as traveling to space seems today. However, the airline industry underwent a commercial revolution that made air travel a staple in the global economy. That growth was remarkably similar to the rapid change that the space industry is seeing today. As a supplier to both commercial aircraft and space platforms, Collins Aerospace, an RTX business, has taken advantage of its broad expertise and performed cross-discipline collaboration to bring commercial aircraft and space lessons learned together for use in the commercialization of space. This paper discusses the findings from work completed by Collins Aerospace Space Systems and Interiors that looked at one area where these business units directly overlap - the commode. The work aimed to determine what differences exist between the space systems and aircraft approaches to the commode and how these differences could be leveraged to optimize the design and execution of the commode for the space market. The key outputs to be discussed include findings from the exercise and the implementation of the findings on a new commode architecture.

Nomenclature

AES	=	Advanced Exploration Systems
DFMR	=	Design for Minimum Risk
FAA	=	Federal Aviation Administration
FMEA	=	Failure Mode and Effects Analysis
ISS	=	International Space Station
JSC	=	Johnson Space Center
LEO	=	Low Earth Orbit
NASA	=	National Aeronautics and Space Administration
RTCA	=	Radio Technical Commission for Aeronautics
RTX	=	Raytheon Technologies Corporation
TDP	=	Technology Development Plan
TRL	=	Technology Readiness Review
UWMS	=	Universal Waste Management System

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I. Introduction

THE commercialization of space drives the need for alternate technical and programmatic approaches. To ease this transition, the space industry can look to existing commercial industries for insight, one possible industry being commercial aircraft. Collins Aerospace, an RTX business, has a strong presence in both space and commercial aircraft, and has completed a case study to assess the benefits of collaboration between these industries. This case study was completed on the commode, an area where Collins Aerospace has over 30+ years of legacy Space toilet and 30+ Million Flight Hours of aircraft toilet experience. Through this study, it was determined that cross-industry collaboration enables advancements in technology, increases in efficiency, architecture improvements, and an increase in safety for the benefit of both sectors.

This study occurred in three phases, beginning with preparation work to define the study's scope and the current state of both industries. The scope of the study was to capture the differences between the space and aircraft commode and document how those differences could be leveraged to make improvements to the current state of space. A secondary goal was to develop a new space commode design that could be used in a pilot program to implement the learnings from the case study. With respect to this secondary goal, the boundaries of the design space were opened, and the team worked towards creating a simplified waste management system to collect, contain, store, and enable reclamation of water from human waste. After the scope was set, the space and aircraft groups independently gathered information on their respective products, including both technical and programmatic insights such as use case, requirements, design definition, and program execution behaviors. This step was critical to ensure a common understanding of the challenges and opportunities for the team to consider.

Once all relevant data was collected, the team entered the collaboration phase. In this phase, the team explored technical and programmatic approaches to product development, delivery, and sustainment. While comparing the current state of both industries, the team challenged traditional space assumptions to generate a revised list of most important requirements. Using these requirements, the team then explored possible component and system level design improvements. This resulted in several new architectures for a waste management system that are able to meet a range of mission requirements, such as short versus long duration habitation. With respect to programmatic opportunities, topics such as manufacturing, supply chain, and aftermarket were discussed.

The last phase of the collaboration was to bring the lessons learned from the case study to fruition. Collins Aerospace has created a Technology Development Plan (TDP) for the new commode architectures and has begun early stage development research and testing to rapidly advance the technology readiness level (TRL) of the concept. The programmatic lessons will inform the program and product support plan as they are developed.

This report will provide a summary of the prework, findings from collaboration, and a high-level overview of the development work completed on the alternate commode architecture.

II. Background on the Space and Aircraft Markets and Commode Solutions

The aircraft and space markets share similar goals of carrying passengers and cargo to their destination. Every day, the commercial airline industry flies an average of 2.9 million passengers.[1] In contrast, less than 1000 people have ever been to space. However, this large volume production and operation has not always been the case for commercial aircraft, and the road to commercial viability was not simple. The transition from hundreds of units to thousands of units was driven by government demand as a part of World War I. After the war, even with increased production reducing costs and driving innovative improvements, aircraft manufactures and commercial airlines struggled to exist. To support the industry, governments provided direct funding and funding in the form of contracts to deliver the mail. Through government support, increased demand, and cost reduction, commercial aviation and the associated aircraft manufacturing industry were eventually able to become sustained markets.

The reduction in aircraft costs as a part of commercialization is a fascinating aspect of the industry's history, reflecting both technological advancements and strategic business developments. One of the major ways the aircraft market achieved cost reduction was through economies of scale and optimized cost of ownership. Technological innovations such as the transition from piston-engine aircraft to jet-powered planes in the mid-20th century oftentimes enabled these improvements. The jet-powered engine significantly reduced travel times and increased fuel efficiency, leading to lower operating costs per mile flown. The late 20th and early 21st centuries witnessed continued advancements in aircraft technology, enabling airlines to carry more passengers over longer distances at lower cost. Today, the aviation industry continues to evolve and commercialize, driven by advancements in technology, evolving consumer needs, and environmental concerns. Overall, the history of aircraft commercialization is a story of innovation and efficiency, enabled by government support. This has resulted in the continuous reduction of costs making air travel more affordable, and therefore accessible, to the public.[2]

Space is in the early stages of a similar transformation. Traditionally, NASA and other government divisions have supported and controlled the American space market. Under a traditional model, NASA defines a need, oversees development, and selects a commercial aerospace contractor to build the system. This is changing through programs such as NASA's Commercial Crew Program, the Next-Gen Space Suit, and Commercial Destinations in Low Earth Orbit where NASA is identifying a need and buying a service, rather than owning the hardware and infrastructure required to provide a function.[*] Additionally, private demand and development in space is further pushing what is required of space technologies.[†]

In an effort to take advantage of the experience and capabilities of an already commercialized market, Collins Aerospace Space Systems is completing collaboration work with the Commercial Aircraft division of the business and seeing great opportunity, with the commode being a successful case study of this.

A. Commode Solutions

The scope of the case study was consideration of a commode for use in a continuously inhabited station in Low Earth Orbit (LEO). Table 1 contains a summary of the use cases, functions, and environments for the space and aircraft applications. It can be noted that within aircraft, there are two primary sub-division: commercial airlines and business jet. The commercial airline division is the high quantity, mass accessibility segment of the market and business jet, or private jet, is the low quantity, luxury segment of the market. Although not the primary focus of the exercise, the team also captured insights that fell outside of this primary scope for consideration at a later date. This included considerations for other systems required in space, such as thermal control systems, as well as other space markets, such as lunar habitation.

Table 1. Primary Use Cases, Functions, and Environments for Space and Aircraft Toilet Systems.

	Use Cases	Functions	Environment Considerations
Space	- Human use on continuously inhabited station in LEO	- Collect human waste - Manage human waste through storage or direction/delivery - Condition human waste for reprocessing - Provide privacy/comfort - Noise, odor control, cleanliness, temperature, ease of use, general human factors considerations	- International Space Station (ISS)-like cabin environment - LEO Radiation - Microgravity - Hard mounted launch loads - Dormancy
Aircraft, Commercial Airlines	- High frequency usage	- Interface with non-Collins waste and water system - Noise, odor, cleanliness, general human factors considerations	- Flight profile up to 50,000 feet - Vibration - Shock and Acceleration - Temperature/Altitude - Fluid Susceptibility - Flammability - Electromagnetic Interference and Compatibility - External Environment • Humidity • Sand and dust • Icing • Explosive atmospheres
Aircraft, Business Jet	- Low frequency usage	- Full Waste and Water System integration - Water system may be third party supplied - Noise, odor, cleanliness, general human factors considerations	

In the commercial aircraft market, there are two primary commode designs: continuous and on-demand vacuum systems. Both systems contain the hardware necessary for waste deposition by a user and waste storage for the duration

* For further information, see NASA's webpage "Commercial Destinations in Low Earth Orbit" at https://www.nasa.gov/humans-in-space/commercial-space/low-earth-orbit-economy/commercial-destinations-in-low-earth-orbit/

† For further information, see Harvard Business Review's story "The Commercial Space Age is Here" at https://hbr.org/2021/02/the-commercial-space-age-is-here.

of the flight. For a continuous vacuum system, a use cycle begins with a user making a deposit into the system. When the deposit is complete, the user initiates a flush. This flush opens the vacuum valve, upon which the waste at the bottom of the bowl is exposed to the near vacuum pressure of the waste storage tank. This pressure differential pulls waste into the storage tank at high velocity. During this flush, the system then ejects a small amount of water into the bowl to complete a rinse and then closes the vacuum valve when the flush and rinse is complete. To reset, the system brings the waste tank assembly back to vacuum. This is accomplished using the vacuum pump if below 14,000 feet and cabin pressure differential to the external atmosphere if above 14,000 feet. Gravity is essential to waste direction into the system and phase separation in the waste tank assembly. When the flight is concluded, waste is drained from the waste tank and the tank is rinsed using water. Figure 1 contains a block diagram of the commercial aircraft commode system. The on-demand vacuum system functions similarly but generates vacuum in the holding tank only when the flush is activated, either by exposure to atmosphere or using the vacuum pump.

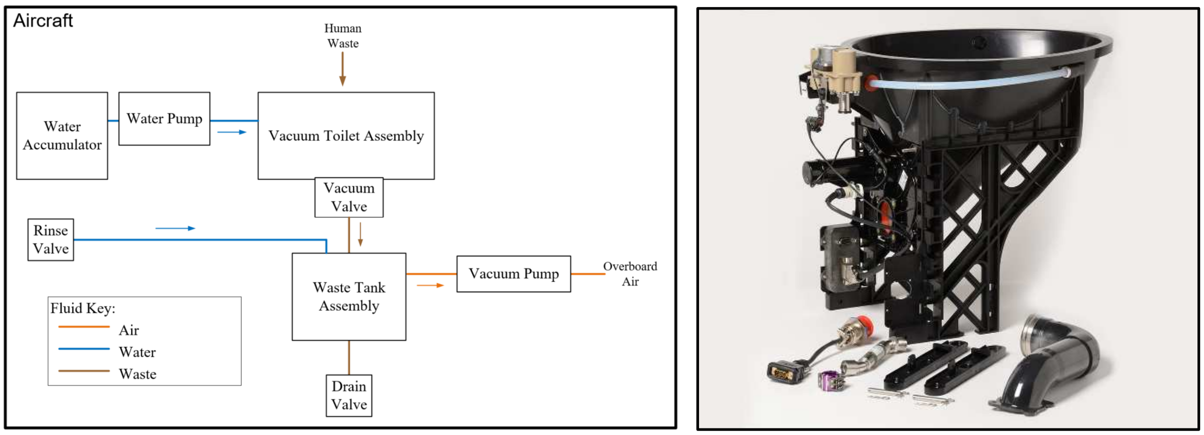

Figure 1. Block Diagram and Image of Commercial Aircraft Toilet Continuous Vacuum System.

The current Collins space commode, or Universal Waste Management System (UWMS), varies from this to account for the unique environmental factors of space, as is discussed in more detail in Section 3.1.1.2. A block diagram of the UWMS is shown in Figure 2.

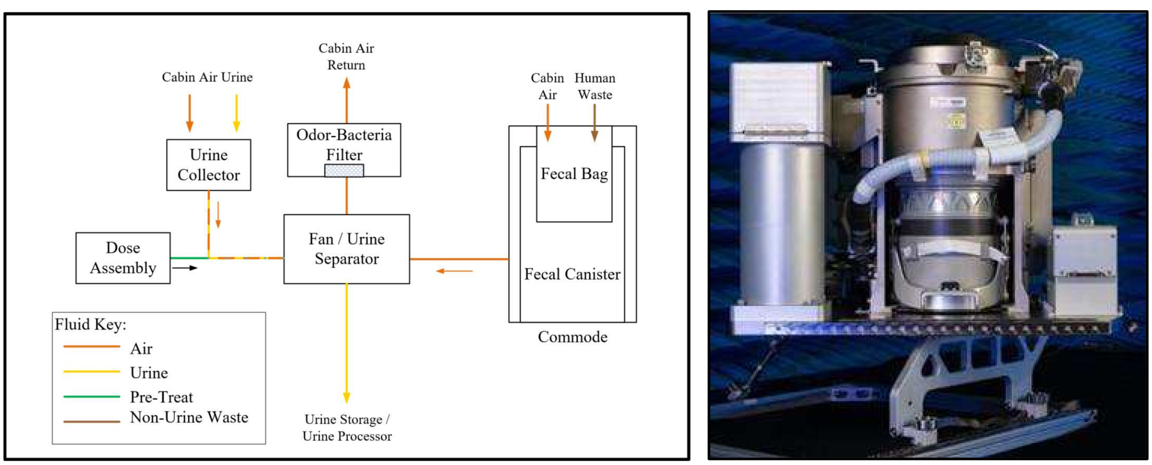

Figure 2. Block Diagram and Image of Universal Waste Management System (UWMS).

The UWMS uses airflow from the fan/urine separator to entrain urine and non-urine wastes, which are collected simultaneously through separate air flow paths. Non-urine waste such as feces, vomit, and menses are entrained in airflow moving into the commode and collected by an air-permeable, single-use Fecal Bag. After each use, the Fecal Bag is sealed and stored in the Fecal Canister. The Fecal Canister is changed out by hand when full. Urine is also collected using airflow at the funnel/hose interface. From here, urine flows towards the Fan/Urine Separator assembly and the pretreat assembly injects pretreatment into the flow stream. At the Fan/Urine Separator, urine is separated from the air using a rotary separator. The urine is directed to either a urine storage tank or urine processing system, and air is returned to cabin. Return air is filtered and conditioned as it passes through a replaceable Odor-Bacteria Filter. Although not shown in the block diagram, power conditioning, control, failure detection & notification, and data processing are performed by a single controller. The controller provides an RS-422 serial interface which transmits UWMS health and status data. An existing ICES paper, ICES-2020-278, discusses the development of the UWMS as a NASA Advanced Exploration Systems (AES) Technology Demonstration Payload and its applicability to long term operation on the ISS as well as shorter duration Orion and Artemis missions.[3]

III. Comparison of Aircraft and Space Commode Approaches

At the beginning of the exercise, both the space systems and commercial aircraft teams shared information on their current state product offerings to provide all participants the context required for critical assessment of challenges and identification of opportunities. The prepared current state information included details over the life of a program, from idea conception through system delivery and finally system deactivation. The information and the associated findings tended to fall into three major categories: requirements, technical solution, and program execution.

A. Requirements

Requirements levied by regulating agencies define the high-level boundaries of a program. For aircraft and space systems in the United States, the primary regulating agency of flight is the Federal Aviation Administration (FAA). Within space, the FAA and NASA partner to define the requirements applied to the space market as a part of the NASA's Commercial Crew Program and the FAA's Commercial Space Licensing Process. Here, the FAA is responsible for public safety and NASA is responsible for crew safety.[4]

The scope of requirements for both commercial aircraft and space systems includes hundreds of requirements from multiple documents. However, the sources for these requirements can differ. One example of this is potable water. In space, potable water is defined by NASA-STD-3001, which cites JSC 63414, Section 6.3 of the Human Integration Design Handbook, NASA/SP-2010-3407, and the "United States Environmental Protection Agency Maximum Contaminant Levels."[5] In contrast, the aircraft industry is held to the requirements of the Code of Federal Regulations Citations 40 CFR Part 141 that is used for aircraft, public water systems, and other general applications. This regulation is the result of the Safe Drinking Water Act and the National Primary Drinking Water Regulations as developed by the Environmental Protection Agency and regulated by the Environmental Protection Agency, the Food and Drug Administration, and the Federal Aviation Administration. As opposed to space, this requirement for the aircraft industry has only one source but has multiple regulating bodies. These industries also differ in the content of the requirements. The aircraft industry traditionally receives requirements that define the end goal rather than the method by which to reach the end goal. An example of this is the lack of a mechanism requirement in commercial aircraft that exists for many space programs, as defined by NASA-STD-5017B. At a lower level than scope, the key requirements and verification approaches in commercial aircraft and space have many similarities and difference, both of which provide opportunities for space as it becomes more commercial.

1. Key Requirements and Considerations

Within program requirements, the top five design driving factors for the commode in Space and Commercial Aviation applications are shown in Table 2, roughly ordered by importance. It can be seen that the driving factors for Commercial Aviation and Space are more similar than different. In both cases, the primary consideration was safety.

Table 2. Primary Drivers for Space and Aircraft Products.

Space Systems	Commercial Aircraft
- Safety - Environment Challenges - Cost (considering low production volume) - Mass - Unique use cases: long term waste storage and processing, water reclamation	- Safety - Cost (considering high production volume) - Mass - No maintenance over the life (20-40 years) - Unique use cases: user behavior outside of typical use

a. Safety

Both the space systems and commercial aircraft business units at Collins hold safety as the top design consideration. In space systems, safety is typically defined through design direction provided by the regulating body, NASA, and supplemented by internal best practices. NASA provides requirements and guidance to primes and suppliers through documents such as SSP51721.[6] These documents contain a range of safety related requirements covering fault tolerance, hazard controls, and specific design requirements that promote safety, among other topic areas. For aircraft, overarching safety requirements are provided by the FAA according to 14 CFR 25.1309.[7] Although not written as requirements documents, sources such as Advisory Circular 25.1309-1A[8] and ARP4761[9] provide additional guidance.

In space, safety is often defined according to fault tolerance. Fault tolerance is dictated by the nature of the potential hazard driven by Failure Modes and Effects Analysis (FMEA), with specific attention given to failure modes that could result in Catastrophic Hazards and Critical Hazards. A Catastrophic Hazard is defined as any condition that "can result in a disabling or fatal personnel injury or illness, and/or one of the following: loss of ISS, loss of a crew-carrying vehicle, or loss of a major ground facility."[6] A Critical Hazard is defined as any condition that "can result in a non-disabling personnel injury or illness, loss of a major ISS end item, loss of redundancy for on-orbit life sustaining function (i.e., with only a single hazard control remaining), and/or loss of use of systems needed for essential logistics".[6] In the aircraft industry, safety requirements by completing a Functional Hazard Assessment to "identity and classify hazardous failure conditions."[8] From this, failure conditions are identified and classified based on the severity of the consequence of failure. As is the case in space, the most extreme failure creates a Catastrophic Failure Condition, defined as a "failure conditions which would prevent continued safe flight and landing."[8] Below this is a Major Failure Condition, which "would reduce the capability …to cope with adverse operating conditions." Some of these adverse operating conditions could result in a significant reduction in safety margins or functions, degraded conditions for the crew, or discomfort to the occupants. In more extreme cases, a major failure condition may result in more extreme variants of these conditions up to the point of being classified a Catastrophic Failure Condition. Finally, the lowest severity failure while still having some effect on the vehicle is a Minor Failure Condition upon which the failure "would not significantly reduce airplane safety."[8]

How these hazards or conditions are avoided vary in space and aircraft. In space, Catastrophic Hazards require fault tolerance against any combination of two failures, two operator errors, or one of each or meet Design for Minimum Risk (DFMR) criteria as hazard controls, and Critical Hazards require tolerance against any single failure or single operator error or meet DFMR criteria as hazard controls. For some systems or products, zero fault tolerance to function is acceptable. Hazards are generally addressed in a phased approach with Program Safety Review Boards, typically 4 Phases: 0, 1, 2 and 3. Hazards, their causes, applicable safety requirements, and safety critical systems and operations are identified and discussed at Phase 0. Hazard Controls are presented and approved at Phase 1. The Hazard Controls Verification Plan is presented and approved at Phase 2. The Objective Hazard Controls Verification Evidence is presented and approved at Phase 3. These reviews can take from hours to multiple days depending on the complexity of the system at hand. To ensure the intent of safety is met, SSP51721 also provides a plethora of specific design, controls, and verification requirements to promote safety.[6] In contrast to the approach typically taken by space systems, safety on aircraft is often verified based on a probability assessment father than a fault tolerance. The classifications of the failure conditions result in some acceptable probability of occurrence, which is then decomposed onto subsystems and components. ARP4761 defines the various methods for assessing safety and demonstrating compliance.[9] Advisory Circular 25.1309-1A also provides a list of qualitative design principles that can be used in combination to promote fail-safe designs, including but not limited to redundancy, proven reliability, and margins or factors of safety.[8]

b. Environment Challenges

Holding the spot of second importance for space systems is environment challenges. When comparing the environments of the two markets, it was found that there are instances of stark differences and areas with higher than anticipated levels of similarity.

Environmental considerations such as radiation, microgravity, and existence in a closed environment are not factors that must be considered by commercial aircraft. Aircraft designers are not required to consider the environmental radiation experienced by space systems. Therefore, opportunities for electronic hardware reuse have a large gap to close through testing, product modification, redundancy, or other means. Microgravity can also have a significant impact on the system. In the case of the commode, the current state in space uses airflow to direct waste away from the user and into the system. In contrast, commercial aircraft commodes are dependent on gravity to direct waste into the system and accomplish phase separation when storing waste. Collins is continuing to investigate solutions and approaches used in defense applications, where -1 g could be encountered.[10] Finally, systems designed for use in space long duration missions must consider functioning in a closed environment. This consideration requires platforms to maintain strict cabin air quality and minimize the loss of consumables to space. Control of microbial growth and material off gassing have significant effects on the design and operation of existing space commodes. While these factors are also considered by commercial aircraft, the regular supply of external air allows for less extreme limits and simpler or nonexistent mitigation approaches. The refresh of cabin air also enables the use of materials typically not used in space due to their potential for off gassing, such as plastics. Additionally, an aircraft's use of the external environment as a source of vacuum could drive an undesirable loss of cabin air in a space application. Regarding acoustics, the aircraft commode is required to maintain noise levels less than 85 dB, and the duration is between 1 and 3 seconds. In contrast, the UWMS has a target of 68 dB at the point of user detection and occurs for 40-100 seconds. Using A-weighting, a method of accounting for the relative loudness perceived by the human ear, this 20% reduction relative to the aircraft requirement translates to an acoustic load that is approximately 3.2 times louder at the point of user detection.[3] This shows that there is a significantly stricter acoustics requirement for the space commode than the commercial aircraft commode. Although these factors drove differences in the designs between the commercial aircraft commode and current LEO commode solution, it is important to note that all space missions may not face these same constraints. Upon the establishment of habitats on the moon or Mars, there may be an opportunity for system simplification leveraging the partial gravity.

Not all environmental differences were more extreme for the space commode than the aircraft commode. Comparison of thermal loads demonstrates an example of increased robustness of the aircraft system compared to space. The primary thermal use case difference is the need for space toilets to undergo planned non-operational dormancy durations and survive prolonged periods of inactivity that usually coincide with more extreme thermal environments. While the UWMS is tested and analyzed at comfortable cabin temperatures of about 58°F to 90°F, aircraft toilets are able to nominally function at the more extreme operable range of 34°F to 165°F, and in short term cases even up to 185°F. Aircraft toilets are also able to function in a degraded state (without water) below freezing temperatures down to -40°F. The UWMS is tested to survive dormancy temperature ranges of 35°F to 115° without the need for additional preparation, which are benign in comparison to the rated operational and degraded state range of the aircraft toilet. Another example where aircraft hardware was held to more extreme environmental requirements was tolerance to dust and sand. Although not a current concern for hardware on ISS, components and systems designed for Lunar or Martian missions may look to aircraft for insight on sand tolerance.

The primary areas of interest where aircraft and space systems are held to similar requirements with respect to the commode were shock, vibration, and acceleration. If soft stowed, the shock and vibration loads experienced during space launch are the same order of magnitude of those that must be tolerated by a commode on a commercial aircraft. This is because a commercial aircraft is required to design the commode to withstand crash loads without becoming a projectile. The exact loads a component or system is qualified to depends on the platform and location on an aircraft, but Radio Technical Commission for Aeronautics (RTCA) DO-160G defines the "Environment Conditions and Test Procedures for Airborne Equipment," and was used for this general assessment.[11] Components can often withstand higher loads than qualified to and may be directly applicable to use in space applications.

c. Cost

Third in importance for space and second in importance for commercial aircraft are cost considerations. Cost is composed of many subcategories, and the importance of those categories vary between commercial aircraft and space programs. Total cost can include labor and material costs associated with non-recurring engineering/hardware, recurring engineering/hardware, and operating costs. In commercial aircraft, the recurring and operating costs are the primary concern. With a high production volume, the aircraft industry is able to benefit from the dilution of nonrecurring engineering effort over hundreds or thousands of units and from economies of scale. A majority of the space market is still in the state where quantities are low. Space must continue to look for opportunities to overcome the entry barrier for market existence and must, for now, continue to place a higher level of importance on the non-recurring cost of a system.

There are instances where aircraft does complete small quantity programs, such as interior retrofits with a Collins product. In these cases, as much of a commodity design is reused as possible. For example, the aircraft toilet bowl is largely standardized across programs, but the tank, driven to a unique design by each opportunity due to mounting points and size constraints, is custom. Even when custom designs are required, the development process for a new tank design is standardized.

d. Mass

Fourth in importance for space and third in importance for commercial aircraft is mass minimization. For commercial aircraft, strict mass requirements are imposed to minimize fuel usage. Although a small mass increase may not make a significant impact during a single flight, over 20 years of operation and an entire fleet of airplanes a small mass increase can have large operational cost impacts. An additional pound can cost an airline approximately $30 in annual fuel costs per plane.[‡] With fleet sizes near 1000, this means a large commercial airline companies could incur up to $30,000 worth of cost per pound per year.[§] This is similar to space, where an additional kilogram of mass being launched to ISS costs thousands to tens of thousands of dollars.[12] The importance of mass minimization in both applications is a similarity that promotes reuse of components and design approaches.

e. Low Maintenance Burden

Minimizing the maintenance burden is the fourth most important design driver for commercial aircraft. Although it was not listed in the top five considerations for space in this exercise, it is also an important metric for space systems. The commode for a commercial aircraft is designed to require no maintenance over the life of the aircraft, which can range from 20 to 40 years. Protecting for the case that maintenance is required, there is significant focus placed on designing to promote ease of maintenance. The aircraft commode design is completely modular and allows for piece-level disassembly in seconds. Additionally, all component replacement maintenance can be completed using only one tool – a 25 cent coin. In comparison, the space system can take up to 15 minutes and a custom toolkit to access some regular maintenance components, adding additional burdens to the already time-constrained crew. The design effort to enable aircraft's high level of ease is not insignificant. Some strategies employed include requiring minimal tools, ease of access and intuitive design, which are very similar to those in space.[13] For space systems, there are additional factors such as 0g operations that must be considered. As discussed, a trade must be made between nonrecurring engineering costs to design for ease or minimization of maintenance and the cost of completing difficult maintenance. With astronaut time valued at around $130,000 per hour[¶] and future commercial crews having less expertise and training than traditional NASA astronauts, designing for ease of maintenance can be beneficial. Implementing strategies developed in space and aircraft can enable this.

f. Unique Use Cases

The fifth listed driver for both aircraft and space systems are unique use cases. In the case of commercial aircraft, the unique use cases are driven by users interacting with a system in a way that is not intended, with or without malicious intent. For example, the commode on a commercial aircraft must be designed to be capable of flushing a wide range of items, including lighters, hygiene products, and cellphones, among other oddities. It also must be designed to prevent smuggling or other tampering by the user that may cause a security concern. Currently, this is not the case in space, as astronauts are trained in how to interact with systems on a space station. However, as space becomes increasingly commercial, it may be necessary to account for some of the undesirable behaviors commercial aircraft are currently required to consider.

Unique use cases that space must consider that the aircraft market does not include waste processing and long-term storage. Space must minimize loss of any materials to vacuum/external environment due to the high cost of resupply. Therefore, processing waste in preparation for potable water reclamation systems is oftentimes an interface requirement. Current waste reclamation technologies on station include the Urine Processor[14] and Brine Processor[15]. The Urine Processor requires that only urine be sent to the system and that the urine is pretreated, which drives separate collection of urine from other forms of waste. The pretreatment chemically stabilizes the urine deposit using hazardous chemicals, strong oxidants and acids, to achieve four objectives that assist in reclamation: 1) control microbial growth, 2) limit urea hydrolysis, 3) convert ammonia gas into the water-soluble ammonium ion, and 4) minimize solids precipitation in both wastewater storage tanks and water recovery systems. This drives the inclusion of hardware such as pumps to add pretreat to the urine and operational controls to safely process hazardous materials.

Commercial aircraft are not required to store waste over long durations because waste tanks are emptied and rinsed at a cadence of at least every few days. Because of this, waste is not treated for microbial or bacterial growth and does not undergo processing to allow for direct potable water reclamation. An interesting note is that the empty and rinse activity performed by aircraft is completed with only water but still prevents detrimental bacterial growth. In contrast

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‡ For further information, see National Geographic's "The Hidden Costs of Flying" at https://www.nationalgeographic.com/environment/article/urban-expeditions-graphic-V21

§ For further information, see Wikipedia's "Largest Airlines in the World" at https://en.wikipedia.org/wiki/Largest_airlines_in_the_world

¶ For further information, see Medium's "How Much is an Astronaut's Time Worth?" at rld/how-much-is-an-astronauts-time-worth-e0e21491af72#:~:text=On%20their%20list%20of%20ISS,or%20%2436%20for%20every%20second to this, space applications are required to store waste in a manner that does not allow for contamination of the station, either through off-gassing or bacterial growth, for months while the station waits for a disposal or return to Earth vehicle to leave the station. The previously discussed urine pretreat and odor/bacteria filters on air outlets and fecal canisters during long term storage manage this. These actions add hazardous chemicals and increased consumables to the space application. Although these measures are likely still necessary for near term space missions, if alternate management methods are investigated, the data from aircraft flight hours could help enable a change in approach.

2. *Verification Approaches*

The stances of the responsible regulatory agencies for commercial aircraft and space systems, the FAA and NASA, respectively, are very similar with respect to requirement verification. In some cases, Collins is responsible for independent system certification while in others, Collins plays a supporting role to a prime integrator.

When completing verification, both space systems and commercial aircraft follow traditional qualification programs that sacrifice a flight hardware unit to testing, but this is more common in the commercial aircraft market. Because of the oftentimes low quantity of units produced for space, space has leveraged proto-flight or proto-qual approaches when hardware cost or schedule is prohibitive to executing a full flight qualification program. With both approaches, the flight hardware undergoes a testing that proves the required performance over the intended usable mission life but prevents extracting the majority of the hardware life. Oftentimes this means testing to reduced thermal ranges and fewer cycles during thermal/thermal vacuum cycle testing, lesser random vibration profiles and/or shorter durations at each vibration test axis, fewer pyrotechnic shocks, and no cyclic pressurization tests. Commercial aircraft also use a tailored qualification process approach, called Safety of Flight testing, to reduce schedule. Here, hardware is permitted to fly, but only to the reduced life that it was certified to until full qualification has been performed. The higher quantity of aircraft systems also allows for opportunities in statistics–based verifications, such as sampling, to reduce the time and cost required for verification. These strategies are not possible with the low quantities more common in space systems. However, this approach could be considered for high quantity consumable items or components used in many locations within a platform. As demand for commercial space increases, it is expected that many of the verification efficiencies used by commercial aircraft will become more feasible in commercial space applications.

B. Technical Approach

As discussed in Section II, the current state technical approach in commercial aircraft and space systems for commodes vary at both the system and component level. This is driven by the factors discussed above as well as the evolutionary paths of each system. However, there are opportunities to leverage commercial aircraft approaches and components in commercial space applications to realize system improvements.

1. *Component Level*

Commercial space is looking to alternate, high volume industries for off-the-shelf components that can be used in space systems for a reduced cost and development effort. These industries include the defense, automotive, and aircraft industries, among others. This case study was limited in scope to collaboration with commercial aircraft, but Collins has found similar lessons from collaborating with other industries. Generally, it was found that there are both benefits and pitfalls associated with the use of an aircraft component in a space system.

Cost reduction, reduced development time, and lower lead times are some of the most prominent benefits discussed when considering the re-use of alternate industry components in space systems. In addition to these benefits, commodity hardware oftentimes has a higher availability of performance, life, and reliability data. In contrast to space life support systems, where one system may be developed and implemented, commercial aircraft have thousands of flight hours on thousands of units, allowing for the collection of a robust data set that enables statistically sound performance analyses and predictions. This can benefit the initial design by enabling a reduction of the required safety factors, the logistics planning by enabling increased accuracy of life predictions, and logistics execution through reduced lead time for spare hardware. In addition to the increased availability of data, a commodity supplier is mass producing components, which can result in more consistent product. This consistency can be in the form of performance or availability. A custom component made at a low quantity and low rate is susceptible to variations in quality due to lack of expertise, employee changeover, tooling/vendor limitations, and deviations arising from non-standard work. Additionally, if a large amount of time has elapsed between purchase orders, a supplier may no longer having the tooling or expertise to create the component, resulting in a large amount of rework and or inconsistencies between builds. In contrast, when purchasing from a commodity supplier, the supplier's production is largely independent of purchases from an individual customer, mitigating the aforementioned concerns. This also results in a reduction in the risk of a supplier going out of business or being bought between purchase orders. Finally, a benefit of using technology from alternate and large industries can result in the ability for advanced technologies to be incorporated without requiring the space supplier, prime, or NASA developing the technology. For example, the aircraft industry is developing specialized coatings to increase cleanliness of commode systems. By collaborating with the aircraft industry, Collins Space Systems can benefit from that development work without having to fund or complete the work within the Space Systems group.

It is clear that there are significant potential benefits to the use of commercially available components in space systems. However, there are also potential pitfalls that must be considered before the implementation of a commercial component. The most prominent is the lack of visibility into and control of the product. When using a commodity component, there is a risk of the supplier altering the product performance, quality, or manufacturing process without consulting customers. This can force redesign and requalification if the previous component becomes obsolete. This lack of visibility can also result in challenges surrounding traceability and quality assurance. However, the selection of components used in the commercial aircraft industry can reduce this risk, as this industry is also held to strict quality requirements.

When considering the value of implementing a commercially available component, one must trade the time, cost, and risk associated with making the component compatible for use in space. Modifications can negate many of the benefits of using commercial hardware, such as reducing the cost benefit and removing the credibility of performance data. Additionally, even for commercial aircraft, if a component is modified or used on a new platform, it must be requalified. It is unlikely that a component qualified for use in a commercial aircraft application will not be required to undergo qualification for use in space. The cost and time associated with this must be considered when a commercial component is compared against a traditional, custom space design. The environmental radiation and unique electrical interfaces are examples of requirements that can drive modifications to a commercial component to make it compatible with use in space. Table 3 contains a list of typical electrical, data, and communications interfaces used in the space and commercial aircraft industry. This shows that there is potential for reuse of electrical components from commercial aircraft with minimal modifications. This is oftentimes not the case for hardware outside of the aerospace industry.

Table 3. Typical Power and Data Interface in Space and Aircraft.

	Space	**Aircraft**
Power	28 VDC (+/- 5 V) 120 VDC (+16/-24 V)	28 VDC (+4 /-6V)
Connectors	MIL-DTL-38999 (typically hermetic) MIL-DTL-24308	D38999 Series III (Customer Interfaces) D38999 and SJS (Internal component)
Data / Communications	RS-422 MIL_STD-1553 Spacewire RS-485	ARINC 429 RS232

There are actions that can be taken to minimize the risk and impact of the potential pitfalls. Because Collins space systems would be working directly with the Collins commercial aircraft team within a single business, there is a unique ability to minimize the risk and impact of the potential pitfalls discussed. One example of this is leveraging the large buying power of the commercial aircraft portion of the business to reduce the probability of supplier driven design changes, among other strategies. Another opportunity is reuse of the qualification plans, facilities, or expert personnel when completing qualification of aircraft components for use in space systems.

In summary, the decision to implement a commodity component must be considered on a case-by-case basis. Table 4 contains a list of the points discussed when executing such a trade. ICES-2024-172 discusses the development of a trade study method that considers cost, mass, and other technical factors over the life of a component to assist in these decisions.[16]

Table 4. Summary of Benefits and Potential Pitfalls for Commercial Aircraft Component Reuse in Space.

Benefits	Potential Pitfalls
- Lower non-recurring and recurring engineering cost - Lower lead time - Increased availability of performance, reliability data - Potential for more consistent supply of components at a known quality level - Supplier security - Incorporation of new technologies not yet developed for space	- Inability to verify or meet requirements: • Performance requirements, special attention to unique required performance such as off-gassing • Interface requirements • Environmental requirements - Potential for suppliers to change a component for their production without consulting space systems, resulting in obsolescence - Lack of visibility into process, traceability, etc. - Added cost of any necessary modifications and qualifications

2. System Level

One of the great benefits of collaboration across separate markets but on adjacent technologies is the introduction of people with a high degree of knowledge on core technical details without the experience and biases that may come from working in a specific industry. During this exercise, the space systems team was challenged to reconsider traditional assumptions and found opportunities for possible system level improvements. While some of the questioned assumptions were warranted, others existed as an artifact of historical limitations or best practices that are no longer valid.

One assumption challenged was the general usage and operation of space commodes, and what maintenance, cleaning, or operator actions can be expected of the user. Some standard practices of space systems, such as designing for minimal cleaning burden on the crew or auto-start sensors to ease crew interaction, were challenged by the commercial aircraft team. Historical space commodes put a large emphasis on the design of the waste capture mechanism to limit cleaning required by the crew. However, the current state commode design requires manual sealing of a fecal bag and fecal bag compaction after each use, which would not be acceptable on a commercial aircraft. In contrast, commercial aircraft assume some regular cleaning of the commode's bowl that space includes consumables to avoid. The primary takeaway from the discussion was that comfort and acceptable actions are oftentimes a relative measure that can and should be reassessed as designs evolve.

Another opportunity identified in this collaboration was the reuse of common components across programs and architectures. For example, the aircraft toilet bowl is largely standardized across programs, but the tank is custom for each platform, driven by mounting points and size constraints. This allows platform owners to utilize the same part number across all aircraft types, providing maximum fleet commonality and reducing complexity for airline inventories. A similar approach for commercial space customers was discussed, such as a common user interface and cabin footprint, with a custom waste processing assembly fit to best match the specific platform needs. Modular design with component reuse in mind could have major advantages that reduce cost and complexity in the developing commercial space industry.

A noticeable difference during the initial system comparison was the number of sensors and amount of data recorded by the systems. The simplicity of the aircraft design is intentional. Requiring fewer sensors for operation results in fewer failure modes and a reduction in required maintenance, replacement, and troubleshooting activities. The baseline continuous vacuum system collects data from three sources 1) pressure sensors monitor the cabin pressure differential to the external atmosphere and controls whether the system vacuum source will the vacuum generator or the external atmosphere 2) discrete level sensors monitor the fill status of the waste tank 3) overcurrent is monitored on the vacuum generator. The on-demand system includes additional sensors on the vacuum generator including over temp, locked rotor, overspeed monitoring due to the added capabilities required of this component in the on-demand design. There are no additional components required for fault indication that would drive increased integration effort, power, and maintenance. Optionally, customers can increase the number of sensors in the system based on their preference for serviceability. Denoting essential and optional components is one potential strategy to shape the simplicity and maintainability of future commercial space systems. However, altering system designs between opportunities will result in additional development and product costs.

The final system design difference of note was maintainability. As discussed in Section III, simplicity and ease of maintenance is a major factor in the aircraft system's continued success as it minimizes operating delays and costs for its customers. A similar, extreme emphasis on maintainability will become more warranted as space commercializes.

This change in the market is expected to alter the average crew skillset and increase the quantities of commodes on orbit. Because of these changes, the high value of crew time, and the desire for limited required tooling on stations, the additional effort to design to the high level of maintainability seen on aircraft could become a cost positive design activity.

C. Aftermarket

For the commercial aircraft industry, aftermarket and customer support is a large part of program success, with the customer and supplier playing active roles in ensuring successful operation over the life of the platform. Within the aircraft industry, operating costs are typically tracked according to block hours, or the time between the aircraft door closing for departure and opening upon arrival. For a narrow body passenger plane, such as a Boeing 737, the operating costs are approximately $4,250/block hour, with maintenance costs accounting for approximately $700/block hour of this.[17] At an average of approximately 3,900 hours of utilization per year, the maintenance costs total around $2.7M per aircraft.[18] With a purchase price of around $100M, this makes the yearly maintenance costs associated with a small body aircraft equal to around 3% of the acquisition cost.[#] Aftermarket is also an immense portion of manned space, with ISS annual operating costs being approximately $3 billion, of which operations and maintenance costs are "about $1.1 billion a year from fiscal year 2016 through 2020."[19] With an estimated cost of $150 billion, yearly maintenance costs equal around 1.5% of the acquisition cost. For commercial aircraft, aftermarket support begins as soon as the product is delivered with support during assembly, integration, and aircraft level testing. Following an aircraft being added to the fleet, aftermarket support can include monitoring system performance, anticipating spare hardware needs, manufacturing spares, storing spares, and providing field support. The exact contracting mechanisms used for aftermarket can vary. These can range from agreements on the cost of spares to fully inclusive aftermarket as a service contracts, such as the *Power by the Hour* model. In this type of model, the customer pays a service rate, charged based on hours of operation, and Collins provides aftermarket services and hardware as required.

There are many factors to consider in aftermarket and each platform can vary greatly, but they are all common in that the scope is defined at the signing of the initial contract. For this to occur, field support hours and rates, spares costs and lead times, anticipated spares required, ownership of risk, and many other variables must all be predefined and agreed to. A short list of some of the questions that need to be answered can be found below. Again, this occurs before signing the initial contract.

- When is customer support provided in the form of labor throughout entire program?
- How is this field support charged and at what rate?
- What is the scope of field support?
- Who stores spares?
- How much will spares cost?
- How long will it take to get a spare?
- What is the mechanism for getting more spares?
- What is the estimated number of spares?
- What happens if that number is way off?
- Who manages spares needs?
- Who monitors system performance?
- Is there any form of guarantee of performance?
- Who holds risk in the case of unexpected failures?
- Who is responsible for completing failure investigations?
- How will failed hardware be delivered to the group conducting the failure analysis?

The space industry will likely struggle to answer many of these questions due to a lack of data, the immaturity of the commercial market, and the small size of the commercial market. The lack of performance data will make accurately predicting program needs challenging. Additionally, the immaturity of the market will drive increased risk, as profits and on-going investment funding are uncertain. The small size of the market will make on-demand replenishment of consumed spares more challenging due to the inconsistent demand. This small size will also make the cost of monitoring performance and providing support per system more expensive. To combat this, commercial companies must look to both NASA and other commercial industries for data to create informed and accurate answers to the questions necessary for mutual success in aftermarket. Additionally, advanced technologies such as Leto™,

[#] For further information, see Simple Flying's "How Much Do Airbus Aircraft Cost?" at https://simpleflying.com/how-much-do-airbus-aircraft-cost/

discussed further in ICES-2024-210,[20] are looking to generate and process data in a way that reduces the human labor necessary for system sustainment and anticipates sustainment needs. Leto™ accomplishes this through the use of physics-based models and AI-powered algorithms to continuously monitor the performance of vehicle ECLSS.

IV. Opportunities Applied to the Space Commode

To put these collaboration inspired philosophies into action, the Collins product development team began a pilot project to investigate a new potential commode and water reclamation system that presents an ambitious step-change from the current space solution. The new product aims to emphasize the themes of architectural and component simplicity and modularity. When challenging the current state of space waste management, the team saw that the current architecture is the product of incremental improvement that would benefit from opening up the design space to incorporate some of the new and emerging technologies as well as learning from the aircraft industry. With this in mind, one of the major ways the team is simplifying the system is by designing the new commode to accomplish the functions of the traditional commode, urine processor, brine processor, and fecal processor in one system. The proposed solution also uses the existing aircraft commode design as the foundation, with modifications applied to enable use in space. Figure 3 contains two preliminary block diagrams of the concept, based on the mission constraints.

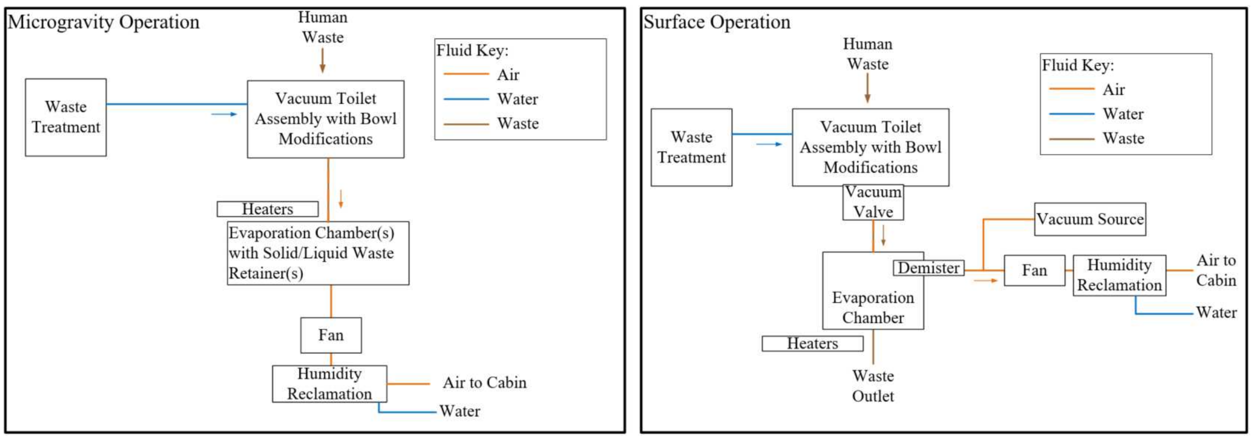

Figure 3. Two Example Block Diagrams of Advanced Commode Concept.

Several components that exist in the Collins aircraft toilet, upon initial review, showed the possibility for reuse in a space application. Trade studies are being applied to how the following components could be reused, assessing their suitability, and highlighting any gaps that would need to be addressed for use in space applications:

- Toilet bowl and structure
- Vacuum pump assembly
- Accumulator
- Vortex Separator
- Inline Heater
- Water Pump
- Sensors, Actuators, and Controller
- Low-maintenance surfaces and coatings

By leveraging components that have been proven in aircraft applications, more time can then be dedicated to the other parts of the system that must be uniquely developed for the space application based on the different gravity and radiation environment. In this instance, the core efforts left for development were the waste transport, containment, and water reclamation functions, as well as addressing the radiation susceptibility of electronic components. Table 5 highlights some of the development efforts in progress to address these key questions.

Table 5. Development Work Completed on New Commode Concept.

Effort	Finding
Waste Retention Material Investigation 	- ePTFE is promising as a material that is capable of the preliminary required airflow and phase separation. Pressure drop, evaporation rate, and phase separation testing with several variants of ePTFE has been completed. Investigation of the material's tolerance to lipids in fecal matter is in progress.
Water Reclamation Rate 	- ePTFE is capable of meeting the required water reclamation rate when alternating evaporation chamber concept is employed.
Size Weight and Power Comparison Over System Life to Current States	- System size and weight estimated to be less than current state (Commode, UPA, BPA combination). - Consumables size and weight estimated to be similar to or less than current state (Commode, UPA, BPA combination) - Power estimated to be higher than current state.
Human Interface Design	- Design and analysis in progress, testing to follow. Goal is to ensure solid and liquid waste capture at an air flow rate equal to or less than current state commode solution.
Behavior in Microgravity	- Analysis of fluid behavior in waste retention device in progress, team looking for test opportunities. - Analysis of waste behavior in flow paths of system in progress, team looking for test opportunities.

In working to reduce technical risk through development, the space and aircraft teams are continuing to collaborate to share technical expertise and capabilities. These include analysis or chemical expertise, test facilities, and business opportunities. Collins looks forward to using this investigation to continue to show the benefits of cross-industry collaboration, specifically with the aircraft industry. If the investigation does result in a high technology readiness product, the execution and aftermarket lessons learned from collaboration will also be implemented. However, these strategies are also planned for implementation in existing products. Future work for this system includes continuing development with the goal of end user collaboration.

V. Conclusion

In conclusion, it was determined that the knowledge, experience, and capabilities of the aircraft industry are beneficial to leverage in the commercialization of the space industry. Requirements imposed on aircraft have similarities to those imposed on space systems. Differences arise in the extreme environmental requirements and unique performance requirements of space missions, but there still are large opportunities for aircraft component reuse in space systems. After assessing opportunities for component reuse, it is recommended that each opportunity for commercial component use should be individually considered, as the benefits of commercial component use can be outweighed by required modifications or programmatic risks associated with the use of commodity hardware. In addition to component reuse, it was found that there are also potential benefits to working with system technical experts from an alternate market because this promoted challenging typical space industry assumptions and comparing best practices for system design. Finally, system and platform owners in the space industry can look to the aircraft industry for insight into successful strategies with respect to aftermarket and sustainment. To study the potential benefit of applying these lessons, Collins has begun development of a new commode design with continued engagement of experts in the commercial aircraft industry. Combining the technical expertise of commode engineers from within and outside of the space industry has resulted in an innovative design concept, and the team is continuing work with the intent of assessing the programmatic and aftermarket lessons learned as the program proceeds. Throughout the entire product lifecycle, commercialization will pose new challenges and opportunities for the space industry. To meet these challenges, space will benefit if it learns from the experience of adjacent industries.

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