Achieving Near-term, Aircraft-like Reusable Space Access[*]

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Abstract

Before the United States can practically expand its human space operations, the ability to transport passengers and cargo to low Earth orbit with aircraft-like safety and operability must be established. Contrary to popular belief, the critical technologies and system engineering principles and practices necessary to develop and deploy near-term, fully-reusable space access systems exist today. This paper describes how the design and operational heritage of aircraft, particularly military aircraft, can be used to develop the systems integrity processes that will guide the development and operation of reusable space access systems intended for the safe, routine, and frequent transport of passengers and cargo. This paper continues with a general description of special considerations that should be explored in defining the conceptual design of a near-term, aircraft-like, reusable space access system. The paper concludes with a brief introduction to the conceptual design of a near-term reusable space access system responsive to the system integrity considerations addressed in this paper.

Questions Addressed in this Paper

A critical and necessary advance in American spacefaring capabilities is the establishment of safe and routine transport of passengers and cargo to and from low Earth orbit (LEO). This paper addresses questions central to determining how best to proceed with establishing safe and routine space access. These questions are:

Section 1: What terms of reference are appropriate for describing the safety, operability, and effectiveness of an “aircraft-like” space access system?

Section 2: What constitutes an acceptable level of safety for the routine transport of passengers to and from LEO? Specifically, are levels of safety commensurate with the transport of astronauts sufficient or are greater levels of safety required for “aircraft-like” operations?

Section 3: Should the design and operational heritage of aircraft or expendable/ partially-reusable space access systems be used to achieve “aircraft-like” safety and operability in space access systems intended for routinely

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[*] Distribution A: Approved for public release; distribution unlimited by AFMC 06-291 and AFRL 06-0074.

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transporting passengers and cargo? Must these new space access systems be fully reusable or can they be expendable or incorporate expendable components?

Section 4: What constitutes a “near-term” system solution?

Section 5: What are the design options for near-term, fully-reusable space access systems?

Section 6: How can an aircraft-style systems integrity process be applied to reusable space access systems to achieve operational safety, suitability, and effectiveness?

Section 7: What are the general steps for achieving adequate system integrity and airworthiness during the conceptual design of near-term, fully-reusable space access systems?

Section 8: Can closed conceptual designs of near-term, fully-reusable space access systems be defined?

Introduction

In the 1930s and 1940s, the public came to believe in the existence of a natural barrier to aircraft flying faster than the speed of sound. It started with a 1935 newspaper report on high speed aeronautics wind tunnel testing.

> The myth of the sound barrier had its beginning in 1935, when the British aerodynamicist W. F. Hilton was explaining to a newsman about some of the high-speed experiments he was conducting at the National Physical Laboratory. Pointing to a plot of airfoil drag, Hilton said, "See how the resistance of a wing shoots up like a barrier against higher speed as we approach the speed of sound.” The next morning, the leading British newspapers were misrepresenting Hilton's comment by referring to "the sound barrier.” The idea of a physical barrier to flight—that airplanes could never fly faster than the speed of sound—became widespread among the public. Furthermore, even though most engineers knew differently, they still had uncertainty in just how much the drag would increase in the transonic regime, and given the low thrust levels of airplane powerplants at that time, the speed of sound certainly loomed as a tremendous mountain to climb. [1]
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> The plausibility of a sound barrier was reinforced during the early 1940s when fighter aircraft started to experience the effects of localized transonic airflow leading to flutter and loss of control. During World War II, fighter pilots encountered a new and terrifying phenomenon. Rolling over into steep dives, they accelerated to speeds of 500 mph and into the unknown region of transonic flight (0.7-1.3 Mach) where the effects of compressibility--loss of control and structurally devastating aerodynamic loads--began to take over with often deadly consequences.[2]

Despite the emergence of this transonic phenomenon during flight, many aerodynamicists recognized that no true sound barrier existed. Bullets and some artillery shells traveled at supersonic speeds. The German V-2 ballistic missile reentered the atmosphere at supersonic speeds and survived until it impacted the ground. Yet, the public's perception of the existence of a sound barrier made Chuck Yeager's first supersonic flight in the Bell XS-1 an instant historic event when it was announced.

Barriers are often more perception than reality. Just as the inadequate explanation of technical issues and events created an impression of an impassable sound barrier, comparable developments have created the impression of a barrier to safe and routine space access. The purpose of this paper is to discuss how good design, engineering, and planning can overcome this perceived space access barrier by providing near-term, fully-reusable space access systems capable of transporting passengers and cargo to LEO with aircraft-like safety and operability. Such a transformation in space access is critical to the United States becoming a true spacefaring nation.

Section 1: Terms of Reference

The focus of this paper on achieving aircraft-like safety and operability inherently uses common words and phrases, such as safety, in a way that requires the reader to have a clear understanding of their intended usage. The following definitions and discussions provide this understanding.

General Definitions

From the Oxford University Press web site:

Safe—without physical danger; not likely to lead to any physical harm or danger as in a safe and effective remedy for coughs and colds or the street is not safe for children to play in.

Safety—the state of not being dangerous, as in I'm worried about the safety of the treatment and the airline has an excellent safety record.

Routine—the normal order and way in which you regularly do things.

Acceptable—agreed or approved of by most people in society.

Integrity—the state of being whole or unified; soundness of construction.

Air Force Definitions Related to Aircraft Safety

More specific definitions of these terms, relevant to the discussions in this paper, are contained in Air Force publications:

Damage—any crack, flaw, corrosion, disbond, delamination, and/or other feature that degrades, or has the potential to degrade, the performance of the affected component.[3]

Damage Tolerance—the attribute of a structure that permits it to retain its required residual strength for a period of unrepaired usage after the structure has sustained specific levels of fatigue, corrosion, accidental, and/or discrete source damage.[4]

Design Service Life—the period of time (e.g., years, flight cycles, hours, landings, etc.) established at design, during which the structure is expected to maintain its structural integrity when flown to the design loads/environment spectrum.[5]

Durability—the ability of the aircraft structure to resist cracking, corrosion, thermal degradation, delamination, wear, and the effects of foreign object damage for a prescribed period of time.[6]

Fail-safe—a design feature that ensures that the system remains safe or in the event of a failure will cause the system to revert to a state which will not cause a mishap.[7]

Fail-safe Structure—a structure that retains its required residual strength for a period of unrepaired usage after the failure or partial failure of safety-of-flight structure.[8]

Operational Safety—the condition of having acceptable risk to life, health, property, and environment caused by a system or end-item when employing that system or end-item in an operational environment. This requires the identification of hazards, assessment of risk, determination of mitigating measures, and acceptance of residual risk.[9]

Operational Effectiveness—the overall degree of mission accomplishment of a system or end-item used by representative personnel in the environment planned or expected (e.g., natural, electronic, threat, etc.) for operational employment of the system or end-item considering organization, doctrine, tactics, information assurance, force protection, survivability, vulnerability, and threat.[10]

Operational Suitability—the degree to which a system or end-item can be placed satisfactorily in field use, with consideration given to availability, compatibility, transportability, interoperability, reliability, wartime use rates, maintainability, full-dimension protection, operational safety, human factors, architectural and infrastructure compliance, manpower supportability, logistics supportability, natural environmental effects and impacts, and documentation and training requirements.[11]

Safety—freedom from those conditions that can cause death, injury, occupational illness, or damage to or loss of property, or damage to the environment.[12]

Safety Critical—a term applied to a condition, event, operation, process or item of whose proper recognition, control, performance, or tolerance is essential to safe system operation or use.[13]

Structural Integrity—the condition which exists when a structure is sound and unimpaired in providing the desired level of structural safety, performance, durability, and supportability.[14]

System Safety—the application of engineering and management principles, criteria, and techniques to achieve acceptable mishap risk, within the constraints of operational effectiveness and suitability, time, and cost, throughout all phases of the system life cycle.[15]

This paper addresses the need to develop aircraft-like space access capabilities. While widely used, this term “aircraft-like” also needs to be defined in the context of its use in this paper. Some may interpret “aircraft-like” as relating to a general configuration of a flight system with a fuselage, wings, and ailerons or to a manner of operation as in a horizontal takeoff from a runway. **In this paper, the use of "aircraft-like" refers to achieving levels of operational safety, suitability, and effectiveness consistent with military or commercial aircraft.**

Airworthiness and Related Definitions

The Federal Aviation Administration (FAA) addresses the definition of airworthy in the following:

> The term "airworthy" is not defined in Title 49, United States Code (49 U.S.C.), or in 14 CFR; however, a clear understanding of its meaning is essential for use in the agency's airworthiness certification program. Below is a summary of the conditions necessary for the issuance of an airworthiness certificate. A review of case law relating to airworthiness reveals two conditions that must be met for an aircraft to be considered "airworthy." 49 U.S.C. § 44704(c) and 14 CFR § 21.183(a), (b), and (c) state that the two conditions necessary for issuance of an airworthiness certificate:
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> a. The aircraft must conform to its [type certificate] TC. Conformity to type design is considered attained when the aircraft configuration and the components installed are consistent with the drawings, specifications, and other data that are part of the TC, which includes any supplemental type certificate (STC) and field approved alterations incorporated into the aircraft.
>
> b. The aircraft must be in a condition for safe operation. This refers to the condition of the aircraft relative to wear and deterioration, for example, skin corrosion, window delamination/crazing, fluid leaks, and tire wear.
>
> NOTE: If one or both of these conditions are not met, the aircraft would be considered unairworthy. Aircraft that have not been issued a TC must meet the requirements of paragraph 9b above.[16]

Note that there is no mention of suitability or effectiveness in this definition of airworthiness. This is because the FAA's responsibility focuses on protecting public safety and not on assessing whether an aircraft's design will provide useful, affordable, and cost-effective operation. Hence, commercial airworthiness of a flight system only addresses one of the three important aircraft-like characteristics of safety, suitability, and effectiveness.

The requirement to be airworthy applies to military as well as civilian aircraft. "Aircraft owned and operated by the Air Force fall under the Federal Aviation Regulation definition of public aircraft and thus the Air Force is the responsible agent for certification of airworthiness."[17] The Department of Defense has an integrated set of policy directives, instructions, specifications, and standards that are used to implement and verify that the airworthiness, as well as the suitability and effectiveness, is established and maintained for Air Force aircraft. The primary requirements for airworthiness of air systems are defined in the Department of Defense Handbook on

Airworthiness Certification Criteria.[18] The following definitions are taken from this handbook.

Air System—an air vehicle plus the training and support systems for the air vehicle, and any weapons to be employed on the air vehicle.

Airworthiness—the property of a particular air system configuration to safely attain, sustain, and terminate flight in accordance with the approved usage and limits.

Airworthiness Certification—a repeatable process implemented to verify that a specific air vehicle system can be, or has been, safely maintained and operated within its described flight envelope. The two necessary conditions for issuance and maintenance of an airworthiness certificate are 1) the aircraft must conform to its type design as documented on its type certificate, and 2) the aircraft must be in a condition for safe operation.

Integrity—refers to the essential characteristics of a system, subsystem, or equipment that allows specific performance, reliability, safety, and supportability to be achieved under specified operational and environmental conditions over a specific service life.

Passenger—any person on board an air vehicle who is not mission trained regarding the passenger safety/emergency capabilities of that particular air vehicle and mission. For a specific flight, this includes any person who does not have active crewmember duties and is not essential for accomplishing mission tasks. NOTE: Mission training constitutes specialized air vehicle training beyond preflight safety briefings.

Safety Critical—a term applied to any condition, event, operation, process, or item whose proper recognition, control, performance, or tolerance is essential to safe system operation.

Safety-of-Flight (SOF)—the property of a particular air system configuration to safely attain, sustain, and terminate flight within prescribed and accepted limits for injury/death to personnel and damage to equipment, property, and/or environment. The intent of safety-of-flight clearance is to show that appropriate risk management has been completed and the level of risk (hazards to system, personnel, property, equipment, and environment) has been appropriately identified and accepted by the managing activity prior to flight of the air system.

System Safety—the application of engineering and management principles, criteria, and techniques to achieve acceptable mishap risk, within the constraints of operational effectiveness and suitability, time, and cost, throughout all phases of the system life cycle.

Air Force Definitions Related to Space Systems

The Air Force space community is developing engineering and management processes to guide the development and operation of military space systems to achieve operational safety, suitability, and effectiveness. While the definitions of operational safety, suitability, and effectiveness applied to spacecraft are the same as for aircraft, one area of difference is in the concept of airworthiness or space flight worthiness for space systems. The following definition of space flight worthiness has been developed by the Air Force:

Space Flight Worthiness—measures the degree to which a spacecraft, launch vehicle, or critical ground system as constituted has the capability to perform its mission and measures the associated risks.[19]

Note the difference in definition of what constitutes airworthiness and space flight worthiness. The former focuses on safety while the latter focuses on mission execution and risk assessment. While the selection of the terminology "space flight worthiness" appears to be a takeoff on "airworthiness," its definition does not directly address safety. Also, note that the definition is not explicit in what is or is not space flight worthy. Space flight worthiness only assesses the "degree to which" desired mission capabilities will be achieved. In contrast, an airworthy aircraft is one that is explicitly in "a condition of safe operation."

Department of Defense Directive Related to Safety

The Department of Defense (DoD) directive on space policy includes the following:

> Spaceflight Safety. All DoD activities to, in, through, or from space, or aimed above the horizon with the potential to inadvertently and adversely affect satellites or humans in space, shall be conducted in a safe and responsible manner that protects space systems, their mission effectiveness, and humans in space, consistent with national security requirements.

National Aeronautics and Space Administration (NASA) Human-Rated Definitions

Since the beginning of human space travel, NASA has used the term "man-rated" or, more recently, "human-rated" to establish an airworthy-like descriptor for its human transport systems. The following definitions are from a recent NASA procedural requirement for the human-rating of space systems:[20]

Crew—any human on board the space system while in flight that has been trained to interact with the space system; same as flight crew.

Passenger—any human on board the space system while in flight that has **no** functional responsibility to perform any mission task for that system (emphasis added).

Certification—documentation that validates that the requirements were correct, the system will perform its mission in the expected environment, and verifies that the requirements were met.

Human-Rated Space System—a space system that incorporates those design features, operational procedures, and requirements necessary to accommodate human participants such that:

a. Risks have been evaluated and either eliminated or reduced to acceptable levels;

b. Human performance and health management and care have been appropriately addressed such that the system has been certified to safely support human activities; and

c. The capability to safely conduct human-tended operations has been provided, including safe recovery from any credible emergency situation.

Human-Rating Certification—human-rating certification is the documented authorization granted by the Associate Administrator for Space Operations that validates that the system will perform its mission in the expected environment, and verifies with objective quality evidence that the requirements were met allowing the program manager to operate the space system within its prescribed parameters for its defined reference missions. Human-rating certification is obtained prior to the first crewed flight (for flight vehicles) or operational use (for other systems).

Safety—the freedom from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment.

Section Conclusion

An "aircraft-like" space access system will be one that achieves acceptable levels of operational suitability, effectiveness, and safety. In military aircraft these characteristics are achieved by establishing and verifying the integrity of the flight system which, in turn, leads to establishing the system's airworthiness. While NASA and the DoD both base their respective certification processes on the same definition of safety, there is a historical difference in what constitutes acceptable safety. This difference is explored in the next section.

Section 2: Safety Goals

The appropriate starting point for this discussion of how to establish aircraft-like space access is to address the question: what constitutes an acceptable level of safety for the routine transport of passengers to and from LEO? This section addresses:

- the level of space access system safety that may be required to support the routine transport of humans to a space hotel;
- a summary of the historical safety records of expendable launch systems and aircraft; and,
- a summary of the historical safety record associated with the expendable launch systems used for astronaut transport, including the proposed new Crew Exploration Vehicle.

Space Hotel Example

Assume that a targeted level of safety for passenger transport to LEO is a level of safety comparable to the Space Shuttle. From the Shuttle safety record, discussed later, the loss rate would be about one in sixty missions. [Note: The strong public expressions of loss and the extraordinary measures undertaken by the government to investigate the causes of the loss of the Challenger and Columbia are clear signs that this level of safety is not acceptable.] Now assume that the first space hotel—as an example of a future commercial space operation requiring increased and frequent passenger transport—has a capacity of ten guests per night. The travel adventure package to the hotel is for a seven-day stay. Adding the need to transport hotel operating crew and staff, the hotel would be expected to require approximately 75 passenger space access missions per year at ten passengers per mission. With a loss rate of one in sixty, at least one passenger flight would be expected to be lost every year. Over the course of a 20 year life of the hotel, an average of 25 space transportation systems carrying passengers would be lost—about one every eight months. Would an argument that this is an "acceptable" level of safety be reasonable?

In most commercial transportation operations, the loss rate of vehicles and any accompanying loss of life negatively impact the public's acceptance of the transportation system and, as a direct consequence, the commercial viability of the operating company. This loss rate is usually expressed in terms of missions flown successfully per loss. This influences insurance rates, the degree of government oversight, and public confidence in the transportation system. Large commercial transports, for instance, have historically experienced a fatal accident about every 4,500,000 departures. The uncontested operation of these systems provides one measure of what the public, government safety regulators, and insurance companies consider acceptable transportation safety, not only as it relates to passengers but also regarding the risk to the public in general. This level of safety may be thought of "acceptable" for routine air travel.

It would be reasonable to expect that the future space hotel owners, as an example of future commercial space users, would establish a requirement for no transportation system losses during the 20 year hotel life. Anything less may constitute an unacceptable level of risk from direct legal liability as well as loss of customer confidence. In this example, this would require a total of 20 x 75 (or 1,500 missions) without a loss. Doubling this number of missions to transport expendables, such as food, air, etc., the total number of required missions to be performed would be about 3,000. Hence, a loss rate of less than one per 3,000 could reasonably be expected to be established as a maximum acceptable accident rate. If the hotel were to grow to perhaps 50 people per night, with staff and supplies, this would require approximately 300-400 passenger and cargo missions per year. Over 20 years, approximately 6,000-8,000 missions would be needed. The objective loss rate would need to be less than one flight vehicle loss per 8,000 missions. This translates into a minimum successful mission rate of 99.99 percent. If the space hotel is successful and the hotel is expanded or competing hotels are established, then the objective would climb to less than one flight vehicle lost per 100,000 missions. This translates into a minimum successful mission rate of 99.999 percent.

Historical Safety Records

The Space Shuttle used for U.S. human transport missions uses expendable elements. Russian and Chinese human transport missions are conducted using expendable launch systems. NASA now plans, after the retirement of the Space Shuttle, to deploy a new expendable launch system for astronaut transport. In contrast, all human passenger flight missions use fully-reusable aircraft.

Expendable/partially-reusable space launch systems and aircraft reflect two significantly different system design, development, production, and operational cultures. It is important to understand how each of these two cultures would or would not meet future space access needs for providing acceptably safe and routine passenger transport to and from orbit. The starting point in gaining this understanding is reviewing the historical safety records for expendable launch systems, aircraft, and NASA past and future astronaut transport systems.

— Expendable Historical Launch Success Rates

For the purpose of this discussion, an abbreviated assessment of the launch success rates of a selected group of U.S. and foreign ballistic missile and space launch systems was performed. The systems included the Atlas, Minute Man, Polaris, Titan, and Trident ballistic missiles as well as the Ariane, Atlas, Delta, Saturn, Space Shuttle, Soyuz, Titan, Vostok, and Zenit launch systems.* From 1958 through 2005, the total number of launches included in this assessment was 4,122, of which 316 were launch failures. The success mission rate was 92.3 percent and the failure rate was 7.7 percent.

Recognizing that the state-of-the-art of the design of expendable launch systems has improved over the last five decades, the 1958-2005 period was divided into decade intervals assessing the launch success rate for all systems of the same type launched for the first time in each decade. For instance, the Atlas D, with 135 launches, was flown from 1959 through 1967. All of its launches were included in the decade of the 1950s. The Atlas E, with 58 flights from 1960 through 1995, was included in the decade of the 1960s. This approach, in a limited manner, does not penalize the launch success rate of later decades for the expected lower reliability of the early designs. From this data analysis method, the following launch and failure rates were determined:

1950s – 728 launches; 123 failures; 17 percent failure rate

1960s – 1,677 launches; 125 failures; 7.4 percent failure rate

1970s – 1,015 launches; 35 failures; 3.4 percent failure rate

1980s – 402 launches; 21 failures; 5.2 percent failure rate

1990s – 262 launches; 12 failures; 4.6 percent failure rate

2000s – 38 launches; 1 failure; 2.6 percent failure rate

[Note: The totals for the 2000s represent a low total number of launches and do not cover an entire decade.]

Edgar Zapata, of the NASA Kennedy Space Center, has compiled flight success/failure histories of the primary launch systems. Data for 1960 through 1999 for the Ariane, Atlas, Delta, and Titan 4 launch systems shows that a total of 579 launches experienced 44 failures for a failure rate of 7.6 percent. Summarized by decades, the record is:

1960s – 94 launches; 11 failures; 11.7 percent failure rate

1970s – 121 launches; 9 failures; 7.4 percent failure rate

1980s – 116 launches; 9 failures; 7.8 percent failure rate

1990s – 248 launches; 15 failures; 6.0 percent failure rate

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* This information was compiled from information found at www.astronautix.com.

For 2000-2005, excluding the loss of the Space Shuttle and the failure of the Falcon 1 on its first flight, there have been 22 successful U.S.-manufactured medium/large payload class expendable launch system missions with no complete failures and one partial failure due to an upper stage malfunction. During this same period there have been 17 sea-launched Zenit missions with one failure for a 5.9 percent failure rate. There have also been eight smaller payload class missions with two failures for a 25 percent failure rate.[21]

— Aircraft Historical Failure Rates

The Air Transport Association web site provides commercial air transport accident statistics for the period 1927 to 2005 for U.S. air carriers.[22] For this entire period, historical data is provided identifying the accidents per million flight miles for piloted aircraft. From 1948 to the present, data is also provided for accidents per million departures. [Note: Accidents include significant damage to the aircraft whether or not fatalities resulted.]

For the last ten years (1996-2005), an annual average of 6.8 billion miles were flown with an annual average of 10.3 million departures and 660 miles per flight. The average annual number of accidents was 38.6. Of these, there was an annual average of 2.3 fatal accidents with an annual average of 103.5 fatalities per accident. Statistically, the average number of accidents was 0.0056 per million miles and 3.7 per million departures, or one accident per 267,000 departures. This corresponds to a successful flight rate of 99.9996 percent per departure. During this same period, the number of fatal accidents was 0.0034 per million miles or 0.22 per million departures.

For the first ten years of recorded data (1927-1937), at the very beginning of commercial aviation, an annual average of 42 million miles were flown with an average of 88.6 total accidents per year. Of these, there was an average of 11.7 fatal accidents per year with an average of three fatalities per accident. Statistically, the average number of accidents per million flight miles was 2.1. Assuming the average flight was 150 miles (compared with 210 miles in 1948, the first year the number of departures was recorded), the estimated average number of departures per year was 280,000. This corresponds to an average of 316 accidents per million departures. Another way of stating this is that there was the likelihood that one flight in approximately 3,200 would experience an accident. This corresponds to a successful flight rate of approximately 99.97 percent or a failure rate of approximately 0.03 percent. During this same period, the number of fatal accidents was 0.28 per million miles or 41.8 per million departures.

In comparing the first and last decade of accident statistics, the accident rate had decreased by a factor of 375 per mile and 85 per departure. The mission success rate climbed from approximately 99.97 percent to the current average of approximately 99.9996 percent per departure.

Another way to assess aircraft flight safety is to examine the loss rate for first flights. Boeing Commercial Airplanes published a Statistical Summary of Commercial Jet Airplane Accidents: Worldwide Operations 1959-2004—a period of nearly 50 years involving the history of over 20,000 commercial jet aircraft.[23] The Boeing report shows that they have delivered over 12,000 commercial jet aircraft since 1959. An informal inquiry with Boeing found that it had not lost any commercial aircraft during the acceptance flight tests of each new production aircraft. Noting that the first aircraft acceptance flight is equivalent to the first (and only) flight of an expendable launch system, the successful first flight history of commercial jet transports demonstrates the potential to design and produce complex flight systems capable of successful first flights with very low failure rates.

— Astronaut Transport

A human-rated space system, as defined by NASA, is where the safety "risks have been evaluated and either eliminated or reduced to acceptable levels." Acceptable levels of safety for astronaut transport have historically been significantly higher than levels associated with air passenger transport. During the early days of the manned space program, when the term the "right stuff" was coined, the approximate mission failure rates, for expendable launch systems *prior to their first manned mission use* in Project Mercury and Project Gemini, were:*

Project Mercury suborbital flight on the Redstone: 34 missions flown with 23 failures for a 68 percent failure rate.

Project Mercury orbital on the Atlas D: 54 missions flown with 16 failures for a 30 percent failure rate. [Note: This only reflects the Atlas D flights and not earlier Atlas models.]

Project Gemini on the Titan 2: 35 missions flown with seven failures for a 20 percent failure rate. [Note: This only reflects the Titan 2 and not the Titan 1 model.]

For the Apollo program, two launchers were used—the Saturn 1B and the Saturn V. The Saturn 1B was used for the initial unmanned tests of the Apollo capsule, the first manned flight of the Apollo system, the Apollo flights for Skylab, and the Apollo flight for the Apollo-Soyuz mission. Four unmanned missions were completed without any failures prior to the first manned mission, Apollo 7. All manned missions were completed successfully. The Apollo 8 mission, the first to leave Earth orbit, was launched on the Saturn V. Two unmanned Saturn V missions were flown prior to Apollo 8. While both achieved orbit, one did not meet mission success criteria due to key subsystems failures and problems. During the execution of the Apollo lunar program for Missions 8-17, as well as the launch of the Skylab space station, eleven missions were undertaken. The combined mission failure rate was 7.7 percent.

The Space Shuttle has experienced two catastrophic accidents leading to loss of life. Of 118 launches to date, the first accident was during boost and the second was during reentry. In the first case, Challenger, the cause of the failure was due to the system being launched when the temperature was below conditions for which the O-ring seals in the refurbishable Solid Rocket Booster were designed. In the second case, Columbia, foam insulation on the exterior of the expendable External Tank separated during boost and struck the orbiter's wing leading edge thermal protection system causing damage that, during reentry, propagated to cause structural failure. The probability of loss of mission and loss of crew are both one in 59 for a failure rate of 1.7 percent.

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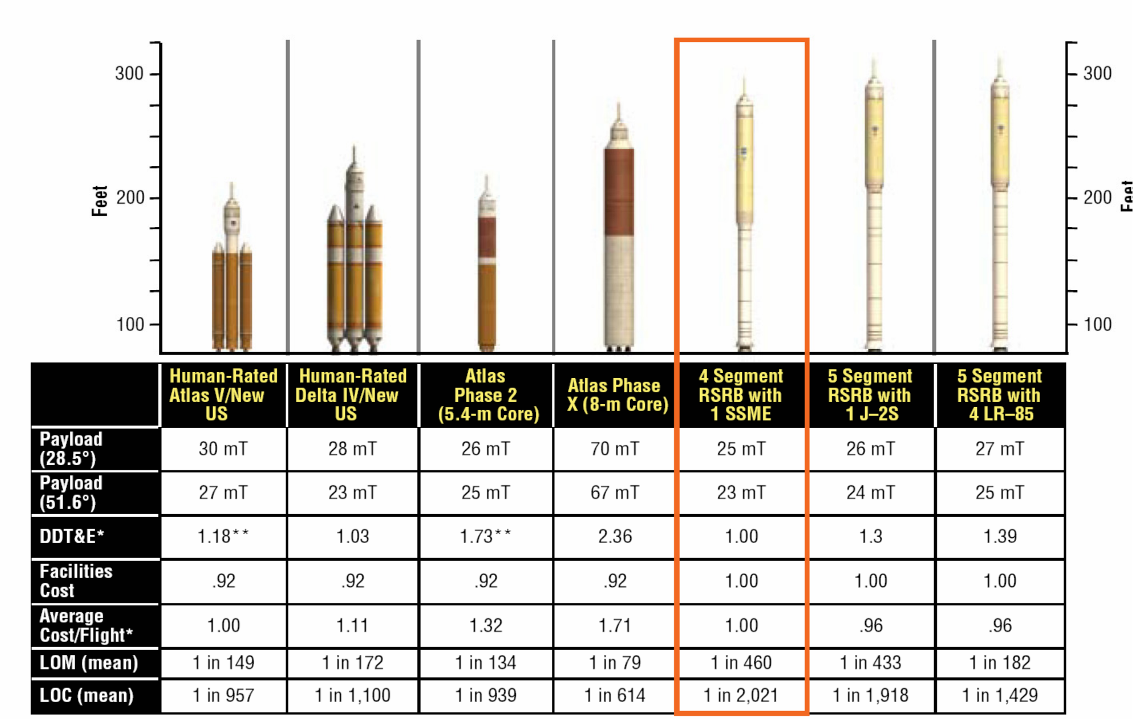
[*] This information was compiled from mission descriptions found at www.astronautix.com.

A key part of NASA's human-rating strategy during the 1960s was the inclusion of an escape system. While never operated on a manned mission, its presence—comparable to ejection seats in some military combat aircraft—provided a last measure of protection against loss of life during the earlier boost phase. This approach was abandoned with the Space Shuttle, but is apparently being reinstated with the next astronaut space transportation system.

NASA has recently developed a strategy for implementing President Bush's vision for a return of humans to the Moon. As a replacement for the Space Shuttle for transporting crew/passengers to and from LEO, NASA has selected a refurbishable Crew Exploration Vehicle (CEV). Being an Apollo-style capsule, the CEV will be launched on an expendable launch vehicle. [Note: At the time of the writing of this paper, the specifics of the design of the CEV were changing as the design evolved.] As part of the Exploration Systems Architecture Study, a cost and risk assessment was performed by NASA. Figure 1 reproduces a chart from this study that summarizes these results.[24] The preferred launch configuration incorporates a modified Solid Rocket Booster from the Space Shuttle and a new expendable, liquid-fueled upper stage. This configuration has a predicted mean probability of loss of crew of one in 2,021 or approximately 0.05 percent per mission. The mean probability of a mission failure—referred to as "loss of mission" or LOM—is one in 460 or 0.2 percent per mission. Assuming 50 missions over a 20 year period of operations, the cumulative mean probability of LOM is 10.9 percent and the probability of loss of crew, LOC, is 2.5 percent. [Note: These are listed as mean or 50 percent probability values.]

In the space hotel example of 50 guests staying for one week, approximately 2,600



	Human-Rated Atlas V/New US	Human-Rated Delta IV/New US	Atlas Phase 2 (5.4-m Core)	Atlas Phase X (8-m Core)	4 Segment RSRB with 1 SSME	5 Segment RSRB with 1 J–2S	5 Segment RSRB with 4 LR–85
Payload (28.5°)	30 mT	28 mT	26 mT	70 mT	25 mT	26 mT	27 mT
Payload (51.6°)	27 mT	23 mT	25 mT	67 mT	23 mT	24 mT	25 mT
DDT&E*	1.18**	1.03	1.73**	2.36	1.00	1.3	1.39
Facilities Cost	.92	.92	.92	.92	1.00	1.00	1.00
Average Cost/Flight*	1.00	1.11	1.32	1.71	1.00	.96	.96
LOM (mean)	1 in 149	1 in 172	1 in 134	1 in 79	1 in 460	1 in 433	1 in 182
LOC (mean)	1 in 957	1 in 1,100	1 in 939	1 in 614	1 in 2,021	1 in 1,918	1 in 1,429

Figure 1. Comparison of crew LEO launch vehicle alternatives.

passengers would be transported each year. Over 20 years, this totals, when the space hotel's operating personnel are included, approximately 60,000 passengers. The CEV holds six crew and passengers. Assuming one crew member and five passengers per trip, a total of 12,000 transport missions (600 per year) would be undertaken. With the predicted mean loss rates for the CEV transport system, 26 missions would fail with approximately six mission failures resulting in the loss of the crew and passengers. One general passenger transport mission failure would occur on average every nine months and one mission with loss of crew and passengers would occur on average a little over every three years.

Section Conclusion

On average, U.S. residents have a one in 2.2 million chance of dying from a transport-related accident each day.[25] For the aforementioned commercial aircraft accident rate, the odds of being in a fatal aircraft accident are about one in 4.5 million. In comparison, the new NASA *astronaut* space transportation system is projected to have a *mean* probability of loss of crew of one in 2,021. Hence, for establishing future space transportation capabilities routinely used to transport *passengers*, achieving levels of operational safety more typical of aircraft will be necessary to establish routine and frequent human space access.

Section 3: Selecting a Design and Operational Heritage to Achieve Aircraft-like Operational Safety, Suitability, and Effectiveness

All engineered systems reflect a heritage of the technical and operational knowledge and experience drawn from the systems that have preceded it. A new space access system intended to provide routine transport of passengers and cargo to and from LEO with aircraft-like safety will also reflect the design heritage of the systems that have preceded it. Even with a so-called "clean-sheet" design, knowledge of what worked and did not work with previous projects influences the selection of the overall design approach, choice of design and mission requirements, selection of component hardware and subsystem manufacturing methods, selection of test and evaluation approaches, and selection of the processes used to design and sustain the system in routine operation.

To successfully develop a space access system with aircraft-like levels of operational safety, a suitable design heritage path must be selected. Will such a system build upon the expendable launch system heritage or will it be built primarily upon the aircraft system heritage? This section addresses this question with:

- a summary of early United States developments in space access systems;
- a discussion of the reasons why expendable launch systems came to be used for launching humans into space during the 1960s;
- a discussion of the technical and political decisions that led to the selection of the Space Shuttle configuration as a partially-reusable design;
- a summary of the early design development of aircraft;

- a summary of the role United States military aircraft development in advancing the application of new technologies and flight safety after World War II;
- an overview of the aircraft integrity processes in use today that provide the basis for establishing military aircraft safety, suitability, and effectiveness;
- a summary of the system safety and integrity process lessons-learned from the National Aerospace Plane program's attempt to develop a fully-reusable space access system;
- a discussion of the safety similarities of new expendable and reusable space access systems;
- a discussion of the key difference between an expendable and reusable space access system and why this places an expendable or partially-reusable system at a significant disadvantage in terms of providing aircraft-like safe transport of humans to space;
- a discussion of the economics of space access as they relate to the comparison on an expendable, partially-reusable, and reusable space access system; and,
- a summary of the key conclusions regarding the selection of the appropriate design heritage for achieving operational safety and affordability in an aircraft-like space access system.

Expendable Launch System Heritage

The fundamental nature of human self-transport—walking—is reusable. Sandals and boats, probably the first forms of successful artificial transport systems, are reusable in the sense that they are reused for multiple transport missions with little repair and maintenance. This concept of reusable transportation has been used throughout human history to establish increasingly more capable transportation networks. Today, it is difficult to identify any examples of human transportation systems or primary safety-critical subsystems intended for routine use that are not fully reusable, with the exception of space access and in-space mobility. Cars, boats, trains, airplanes, elevators, bicycles, roads, bridges, parachutes, skateboards, amusement park rides, climbing ropes, trapezes, and even the cannons used to hurl human cannon balls in circuses are all reusable. Against this millennia-long trend of reusable transportation emerged a world-wide total reliance on fully- or partially-expendable launch systems for transporting humans and cargo to LEO. Understanding how this happened—the interplay of politics, national security, and technology—is important to understanding the potential utility of expendable launch systems in providing future aircraft-like space access.

The 1950s "cold war" environment placed particular emphasis on national leadership in space and space technologies. The technologies and expertise of German scientists and engineers from the 1940s were exploited by both sides to transform the V-2 ballistic missile into more powerful theater and intercontinental ballistic missiles capable of carrying nuclear warheads. As the 1950s began, serious national discussions were started about the emerging possibility of human spaceflight. Wernher von Braun helped

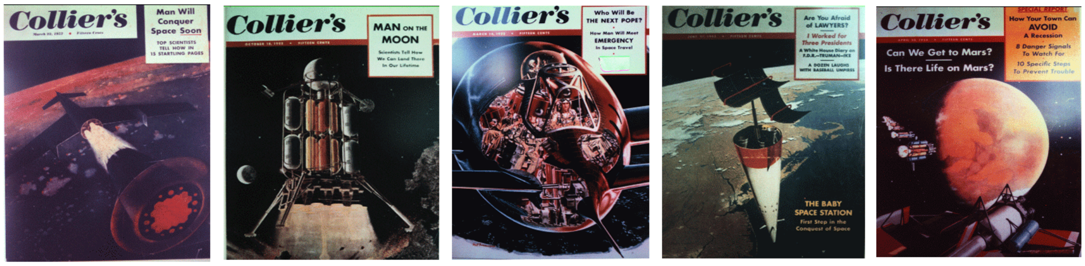


Figure 2. Collier's Magazine covers (1952-1954) depicting Wernher von Braun's ideas for human spaceflight (Source: NASA).

to initiate these discussions in 1952 with public presentations on manned lunar and Mars exploration programs using reusable space transportation systems (see Figure 2).

At about the same time, Air Force contractors began to investigate the potential to utilize ballistic missile technology to expand upon earlier Austrian-German concepts for rocket-boosted reusable spaceplanes to provide global military strike and reconnaissance capabilities from LEO. As the 1950s progressed, the nation’s principle path to initial human spaceflight was expected to be a reusable spaceplane launched on a modified intercontinental ballistic missile (ICBM), as a starting point, with a migration to a fully-reusable space access system as the enabling technology was developed. The military, being the nation’s only developer of new spaceflight systems, had the lead in these efforts with the support of the National Advisory Committee on Aeronautics (NACA–the predecessor to NASA) and similar technical institutions. While Wernher von Braun pursued the development of expendable launch systems for the Army, the Air Force evolved its rocket-boosted reusable spaceplane conceptual design efforts into the formal DynaSoar system development program. The intent was to field a series of progressively more capable reusable spaceplanes, launched on expendable boosters, which would provide global reconnaissance and strike capabilities, as well as some limited on-orbit satellite maintenance support. The program was intended to start with the initial suborbital developmental flights in the mid-1960s and progress to operational capabilities in the late 1960s and early 1970s. At the same time, the Air Force also began a significant investigation into the conceptual designs and enabling technologies for fully-reusable space access systems as part of the original Aerospaceplane program.

The fielding of the initial land- and sea-based ICBMs in the late 1950s and early 1960s coupled with the nation’s political response to the Sputnik “surprise” in 1957, the creation of NASA, and the start of the development of the first orbiting U.S. reconnaissance satellite, all contributed to policy and funding decisions that shifted the principal American human space efforts from the military to the new civilian NASA. Part of this shift reflected the impact of new military capabilities coming into operation. Strategic nuclear strike needs were being met with unmanned ICBMs and manned bombers (e.g., the new B-52) while orbiting unmanned satellites and manned reconnaissance aircraft (e.g., the Mach 3 SR-71) were providing intelligence capabilities. The more limited DynaSoar was not needed. But, perhaps more importantly, the shift reflected a decision by President Eisenhower that space should be used for peaceful purposes. In executing its national security responsibilities of the early 1960s, the military did not identify a reasonable need for military personnel in space executing military operations—a fundamental decision that persists to the present.

NASA, formed in response to the very public new space race with the Soviet Union, set about executing the mission of sending Americans into space. The military's development of ablative thermal protection materials for nuclear bomb reentry vehicles, and the associated theoretical and experimental research into blunt-body hypersonic reentry aerodynamics, enabled a small manned space capsule concept, utilizing an ablative thermal shield, to be rapidly developed and flight tested. As a result, when Yuri Gagarin first orbited the Earth on April 12, 1961, the U.S. was prepared to enable Alan Sheppard to use the Mercury space capsule and the Redstone rocket to follow into space within weeks on May 5, 1961, although only on a suborbital flight. Had the expendable space capsule option not been pursued, the first manned American space flights would probably not have taken place until the mid-1960s, at the earliest, using the DynaSoar. Further, President Kennedy's decision, *only three weeks after Sheppard's flight* on May 25, 1961, to establish a national goal to land a man on the Moon by the end of the decade could only be achieved using the path of expendable launch vehicles and expendable space capsules using ablative thermal shields.

It is difficult, nearly a half century later, to place President Kennedy's actions within the context of politics and national security issues of the time. Gagarin's and Sheppard's flights all transpired within four months of Kennedy being sworn into office after narrowly defeating Richard Nixon in the 1960 presidential election. The infamous "Bay of Pigs" operation, where U.S. Central Intelligence Agency-trained Cuban exiles attempted to invade Cuba, happened on April 17, 1961, between Gagarin's and Sheppard's flights. National security tensions with the Soviet Union were already running quite high with Gary Powers having been shot down while flying a U-2 spy plane over the Soviet Union less than a year earlier. Kennedy helped to raise concerns about the security threat posed by the Soviet Union with statements supporting the existence of a ballistic "missile gap" during the 1960 presidential election—a gap that did not in fact exist. War between North Atlantic Treaty Organization and the Warsaw Pact came close to starting in the following months over West Berlin (summer-fall of 1961) and Cuba (October, 1962).[26]

For whatever reasons, President Kennedy's dramatic decision, announced to a special session of Congress, permanently altered the course of human transport to LEO. The 1950s-era general plan to first establish reusable or partially reusable human and cargo transport to LEO, then to build LEO space bases to serve as orbiting logistics support bases, and then to use these orbiting bases to assemble reusable spacecraft to transport humans and cargo to the lunar surface—the essence of von Braun's 1952 plan—was abandoned in favor of expendable transportation systems. Development efforts for the reusable DynaSoar spaceplane—and the accompanying generation of successful engineering principles and practices for this reusable system—were stopped in 1963. Instead, the American aerospace industry focused on rapidly developing a series of new expendable transportation systems—the Saturn 1B, Saturn V, the Apollo system, the lunar lander, and the lunar ascent vehicle—all in about seven years.

While the manned lunar landing program that NASA defined and successfully implemented to achieve Kennedy's goal is certainly worthy of substantial praise, a fundamental reason for the ability to proceed with the 1960's human spaceflight program was the willingness of the astronauts to become passengers on the expendable launch vehicles. While good piloting skills were required for many critical aspects of the execution of the lunar exploration program—rendezvous and docking in Earth and lunar orbit and landing on the moon, as examples—and human presence was required for conducting the scientific exploration aspects of the program, the astronauts were simply passengers during the ride to LEO. Their willingness to participate established an "acceptable" level of safety that, as discussed earlier, "human-rated" the expendable launch systems and, as a direct consequence, enabled the Apollo program to be undertaken.

In looking back, these actions by the original astronauts are now viewed, appropriately, as being exceptionally brave. However, it is also apparent that human volunteers were placing themselves in exceptional danger in comparable activities. Test pilots were, at the beginning of the 1960s, still involved with advancing human flight with the Mach 6 X-15 program, the then classified Mach 3 SR-71, the DynaSoar/X-20, and the Mach 3 B-70 aircraft, as examples. As the Gary Powers' incident showed, pilots were also involved in very risky national security-related photographic aerial reconnaissance missions. In other areas, such as submarine warfare and undersea human operations, human volunteers were directly involved in establishing new and important operational capabilities in dangerous operational environments. Perhaps from the point of view of the astronauts—all active duty or former military officers—they did not view their actions as out of step with the risks being undertaken by their associates.

As the Apollo flights were starting in 1968, NASA and the Air Force were already looking forward to post-Saturn V launch systems for human spaceflight. Three design options were pursued: an updated DynaSoar concept using an existing expendable booster and a reusable spaceplane; a reusable launch system with a drop tank holding the propellants; and, a fully-reusable two-stage configuration. In February, 1969, President Nixon, less than a month after taking office, created a Vice-President-led Space Task Group to identify a course of action for the nation. On June 1, 1970, NASA published the following list of requirements for a new fully-reusable, two-stage space access system:[27]

- Two-stage-to-orbit, vertical takeoff, horizontal landing configuration.
- Initial operational capability by the end of 1977.
- 6,800 kg payload to a 500 km, 55 deg inclination orbit when launched from Cape Canaveral.
- 4.6 m x 18.3 m payload bay.
- Two orbiter alternates were to be proposed by the contractors: one with a 370 km cross-range (NASA requirement) and one with a 2784 km cross range (Air Force requirement). This implied a minimum lift-to-drag ration (L/D) for the high cross-range vehicle of 1.8, and a total heat load 5 to 7 times greater than the low cross-range alternative.
- Seven-day orbital mission capability.

- Go-around capability on landing in case of a missed approach. This implied the use of airbreathing engines. Phase A studies showed that use of gaseous hydrogen from the orbiter's tanks as fuel for such engines drastically reduced the orbiter weight compared to use of conventional JP-4 jet fuel housed in separate tanks.
- Design to be capable of 25 to 70 launches a year, with a turnaround time of two weeks.
- G-forces limited to 3G on ascent.
- Two crew housed in a pressure cabin without spacesuits.
- 43-hour countdown time after assembly.
- Stage separation without the use of rocket devices.
- No in-flight refueling allowed.
- Capable of landing under FAA Category 2 conditions on a 3,000 m runway.
- All systems fail-operational - e.g. they would remain operational after any single component failure, and remain fail-safe for crew survival even after two subsystem failures.
- Quick safeing of vehicle systems after landing.
- No propellant cross-feed allowed between booster and orbiter.

Two problems emerged almost immediately with this set of requirements. The estimated cost of the development of the system exceeded the level of funding projected for NASA in the 1970s. The difference was on the order of $1 billion per year in then-year dollars. This shortfall led to the assessment and then adoption of the partially-reusable approach of the Space Shuttle system—reusable orbiter, refurbishable solid rocket boosters, and jettisoned liquid propellant tank.

The second issue was the need for Air Force support to gain Congressional approval. This required that the payload weight and size be increased and that the performance for polar missions launched from Vandenberg Air Force Base, California, be included. This dramatically increased the size of the system and probably made a fully-reusable. two-stage system impractical due to the demands this would place on the size of the first stage’s reusable rocket engines.

Several important conclusions arise from this turn of events. First, the Space Task Group initially decided in favor of a fully-reusable space access system over the alternatives of an expendable booster lifting a reusable spaceplane and a discardable propellant tank attached to a reusable spaceplane. With this decision, the nation was set to return to the original vision of a reusable system capable of comparatively high flight rates consistent with a desire for routine space access for passengers and cargo. Second, industry was able to define and propose fully-reusable space access concepts that were intended to satisfy the criteria outlined by the Space Task Group. Third, the decision to migrate to the partially-reusable design created significant unrecognized operational and safety issues that are still evident in the Space Shuttle system. Finally, and perhaps most important, once again, the aerospace industry was turned away from the opportunity to develop the technical experience and expertise that would move the nation forward towards routine, aircraft-like space access for passengers and cargo. While it gained significant and still beneficial experience with the Shuttle orbiter, it did not gain experience with designing, building, and operating fully-reusable first boosters and second stage orbiters with integral propellant tanks. Today, many interpret this decision to not build a fully-reusable system as an indication that this objective was not possible then and, by inference, is still not possible today.

One unrecognized facet of this shift from a fully-reusable system to a partially-reusable system was the impact on safety. It is not clear to what extent safety was a consideration in this change. Vigorous arguments were made within NASA and the Air Force that expendable boosters were more cost-effective than a fully-reusable space access system. But such an argument is only valid when differences in safety are not significant and when flight rates are low, as they are today. The human-rated safety strategy of the 1960s appears to have compensated for the comparatively high failure rates of expendable boosters by limiting the number of flights and incorporating a rocket escape system into the space capsules.

Recall that the Space Task Group's space shuttle system was intended to fly up to 70 missions per year. This rate—less than that required for a moderate space hotel—would equate to each year flying more than twice as many human space transport missions as the total of 31 U.S. human space missions undertaken in the 1960s and 1970s. The late 1960s-early 1970s advocacy of using expendable boosters for a new human space transportation system would appear to argue that improvements in safety were not needed. Yet, actual historical data for expendable boosters in the 1970s, 1980s, and 1990s shows that the failure rates remained unacceptably high indicating that there was no apparent technical reason in the late 1960s for an expectation of significant improvement. Hence, it may be concluded that safety was not the primary consideration in deciding to proceed with a partially-reusable Space Shuttle.

Consequences of this turn of events, nearly 35 years ago, are still evident with NASA's recent selection of CEV. It is apparent that economic circumstances, not unlike those at the time when the configuration of the Space Shuttle was being established, emphasized the need for a low program development cost. Consequently, they have chosen to maximize the utilization of existing government and industry technical expertise and manufacturing capabilities resulting, as was seen in Figure 1, in a decision to use expendable launch systems. It is interesting to note that one of the alternative system concepts considered has a mean probability of LOM of 1 in 79. Such a low value would indicate that no specific minimum numeric LOM and LOC criteria were established leading to a conclusion that "acceptable safety" has no specific minimum numeric threshold. It is also interesting to note that no fully-reusable alternatives were apparently included in the final assessment of alternatives.

Reusable Manned Flight Systems Heritage

The heritage of reusable manned flight systems stretches back to the first balloon flight in Europe in 1783. On January 9, 1793, Frenchman George Blanchard, on his 45th ascension, demonstrated free flight ballooning to George Washington when Blanchard departed from Philadelphia and landed in New Jersey. Almost one hundred years later,

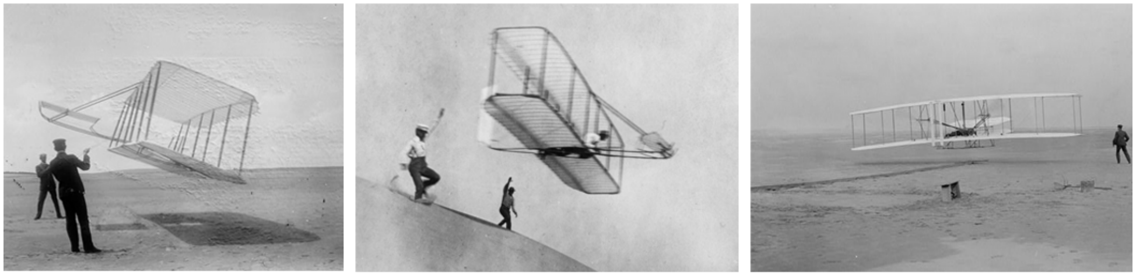


Figure 3. Wright Brothers' unmanned glider, manned glider, and first powered aircraft flight (Courtesy: Library of Congress).

on September 16, 1881, Samuel King attempted to cross the Atlantic starting in Minneapolis, Minnesota. It was his 480th ascension.[28]

The first successful flights of reusable, powered, controlled flight systems were made by Orville and Wilbur Wright at Kitty Hawk, North Carolina, and Dayton, Ohio, in the early years of the 20th century (see Figure 3). These flights were the culmination of a carefully-implemented program of inquiry, research, experimentation, analytical predictions, ground testing, and flight testing of the major design elements of lift, drag, weight and balance, stability, control, power, structures, and propulsion. These efforts included many hours of carefully conducted wind tunnel tests to establish airfoil section lift and drag characteristics and hundreds of unmanned and manned glider flights to validate the predicted aircraft performance and to learn how to pilot aircraft. As numerous historical reenactments have demonstrated, building these aircraft and successfully flying them, even with the foreknowledge of experienced aeronautical engineers and pilots, has proven to be very challenging.

Aeronautical technologies and aircraft designs advanced rapidly in the decades following the initial powered flights. In 1908-1909, technology leadership moved to Europe and, in particular, France, setting the stage for the rapid emergence of military aircraft in Europe during World War I. However, as the United States prepared to enter the war, interest in domestic-built military aircraft reemerged. One aircraft, the DH-4 bomber, was produced in large numbers (4,346) and served as the mainstay of American military and commercial aviation during and following the war.[29] In the post-war years, American aircraft technology designs continued to advance. This was accomplished through the efforts of early U.S. designers and aircraft companies, such as Bell, Boeing, Burnelli, Douglas, Hughes, Fairchild, Lockheed, Martin, McDonnell, and Northrop, through the advocacy of airpower by Brigadier General Billy Mitchell, and through formal and informal competition among aviators to establish new world records for speed, altitude, range, payload, and endurance.

As commercial aviation began to flourish in the 1920s, emphasis on aircraft safety emerged. Congress responded with the passage of the Air Commerce Act in 1926.[30] [Note: The formal recording of aircraft safety statistics started the following year.] A key part of the Air Commerce Act was the establishment of a new federal organization, the Aeronautics Branch, within the Department of Commerce to certify aircraft. The scope of federal involvement in air safety grew throughout the ensuing decades until in 1958, as the new era of commercial jet operations was about to begin, the Federal Aviation Administration was created to significantly expand the federal government's involvement in air safety. Improvements in the technologies associated with air safety were also a key responsibility of NASA, formed the same year.

—Increasing Influence of Military Aircraft Development

Within the United States, the 1930s saw a shift in the driving force for aeronautical technology advancement from civil aviation to military aviation as the threat of another world war emerged and commercial aviation sought to sell new aircraft to the War Department. Three hundred thousand military aircraft of all types would be produced by the time hostilities ended in 1945. In 1943, the U.S. aeronautical industry became the largest industry in the world employing 2.1 million workers. [31]

One important aspect of this increasing influence of the military was the expansion of the use of standards and specifications to ensure that military equipment was operationally safe, effective, and suitable and could be economically produced. A standard establishes uniform engineering or technical criteria, methods, processes and practices. A specification supports acquisition by describing the essential technical requirements for purchased materiel and the criteria for determining whether those requirements are met.[32] The establishment of these standards and specifications—usually undertaken by joint government-industry committees—and their contractual implementation broadly within the U.S. aerospace industry during and following World War II were critically important in capturing aeronautical engineering expertise and experience and transitioning this into the engineering principles and practices that formed the basis of rapid and continued growth in aeronautical capabilities during the late 1940s and 1950s. Over the years, many of these standards and specifications transitioned into general industrial standards and specifications used by industry as well as the government.

Government aeronautical standards covered all aspects of the flight system with the intent of providing best practices for their design, development, test, operation, and support. These standards were deterministic and prescriptive in the sense that they identified the approved methods that had worked and were to be used unless formal waivers were established. Throughout the 1940s and 1950s, this approach worked reasonably well as military aircraft transitioned from subsonic flight with piston-powered aircraft to supersonic flight with jet-powered aircraft. However, in the late 1950s limitations of the utility of this approach started to become evident. Two trends emerged. First, aircraft were becoming increasingly expensive to develop, produce, and operate. As a result, replacement intervals grew longer, and it became increasingly important to maintain the airframes in good operational condition over longer periods of time. The second trend was that new failure modes became evident. In particular, aircraft began to experience metal fatigue-related failures.

Metal fatigue, while poorly understood at the time, was not a new phenomenon. Steam boilers experienced this failure mode during the early years of steam engine designs often with catastrophic results when pressurized boilers exploded. In 1957, the Air Force began to experience usage-driven structural failures in the B-47 jet-powered bombers that were the backbone of the Strategic Air Command. The wings of aircraft in the fleet of over 2,000 bombers were experiencing fatigue cracking that resulted in the loss of several aircraft during flight. This led to a temporary emergency grounding of the aircraft to begin to resolve the problem.

The emergence of unforeseen structural failures that had not been identified through static and cyclic-load structural analyses raised concerns about the structural integrity of the fleet. Once it was understood that previous structural design methods were no longer sufficient to address newer military aircraft designs and usage, the Air Force initiated a formal Aircraft Structural Integrity Program (ASIP) to update the structural integrity process. From Military Handbook (MIL-HDBK) 1530C, the current objectives of the ASIP are to:

a. define the structural integrity requirements associated with meeting operational safety, suitability, and effectiveness requirements;

b. establish, evaluate, substantiate, and certify the structural integrity of aircraft structures;

c. acquire, evaluate, and apply usage and maintenance data to ensure the continued structural integrity of operational aircraft;

d. provide quantitative information for decisions on force structure planning, inspection, modification priorities, risk management, expected life cycle costs, and related operational and support issues; and,

e. provide a basis to improve structural criteria and methods of design, evaluation, and substantiation for future aircraft systems and modifications.[33]

Execution of an ASIP for a specific aircraft is undertaken through the following five, interrelated functional tasks:

a. Task I (Design Information). Task I is development of those criteria which must be applied during design to ensure the overall program goals will be met.

b. Task II (Design Analysis and Development Testing). Task II includes the characterization of the environment in which the aircraft must operate; the initial testing of materials, components, and assemblies; and, the analysis of the aircraft design.

c. Task III (Full-Scale Testing). Task III consists of flight and laboratory tests of the aircraft structure to assist in determining the structural adequacy of the analysis and design.

d. Task IV (Certification & Force Management Development). Task IV consists of the analyses that lead to certification of the aircraft structure, as well as the development of the processes and procedures that will be used to manage force operations (inspections, maintenance, modifications, damage assessments, risk analysis, etc.) when the aircraft enters the inventory.

e. Task V (Force Management Execution). Task V executes the processes and procedures developed under Task IV to ensure structural integrity throughout the life of each individual aircraft. This task may involve revisiting elements of earlier tasks, particularly if the service life requirement is extended or if the aircraft is modified.

Within the ASIP program, the ability of the airframe to resist the propagation of damage that could result in catastrophic loss of the aircraft is called damage tolerance. The intent of the ASIP plan for each aircraft is to ensure that all aircraft remain damage tolerant for a prescribed period of usage with the intention that loss of an aircraft in flight due to structural failure will be a rare occurrence. Also within the ASIP program, the ability of the aircraft to resist the propagation of damage that would become uneconomical to repair is called durability. Corrosion is a typical form of durability-related structural degradation. Ensuring good durability of the aircraft is critical to achieving cost of ownership and operational availability objectives for the fleet.

ASIP and the similar Engine Structural Integrity Program (ENSIP) and Mechanical Subsystem Integrity Program (MECSIP) are the primary means by which the Air Force establishes and maintains the operational safety and proper mechanical functioning of Air Force aircraft. The successful implementation of these programs provides confidence that the safety of Air Force personnel and the public are well protected as Air Force aircraft are operated routinely—in other words, that Air Force aircraft remain airworthy—and the Air Force's fleets are able to meet affordability and availability objectives.

A key attribute of the ASIP approach is that it is tailorable to address new technologies, new aircraft designs, and new operational flight envelopes. This represents a change from the military standard approach of the post World War II decades when aircraft were designed to a rigid set of aircraft standards. Today, each new aircraft program starts with the basic ASIP approach and then produces a tailored specification, derived from a government guide specification, that defines the specific design, manufacturing, verification, and integrity preservation approach that will be used to establish and sustain the aircraft's integrity. The tailored specification is prepared by the contractor and then reviewed and approved by the government as part of the proposal review and selection process. This yields aircraft that are airworthy *and* capable of meeting the Air Force's operational effectiveness and suitability objectives.

—National Aerospace Plane Lessons-Learned

The National Aerospace Plane (NASP) program was the first attempt since the late 1960s to develop a fully reusable space access system. A single-stage, airbreathing design with horizontal take off and landing was baselined as the primary program objective (Figure 4). Recognizing the challenges inherent in developing such an advanced flight system, NASP started with a robust conceptual design and critical technology development phase. If successful, the detailed design, fabrication, and flight test of the experimental X-30 aircraft would then be undertaken. If the experimental aircraft was successful in demonstrating needed performance and sufficient technology maturity, the development of an operational system would then be undertaken. However, in the early 1990s after six years of investigation, it was determined that further basic technology advancements in materials, structures, aerothermodynamic optimization, stability and control, and propulsion were required to achieve this specific form of single-stage reusable space access.

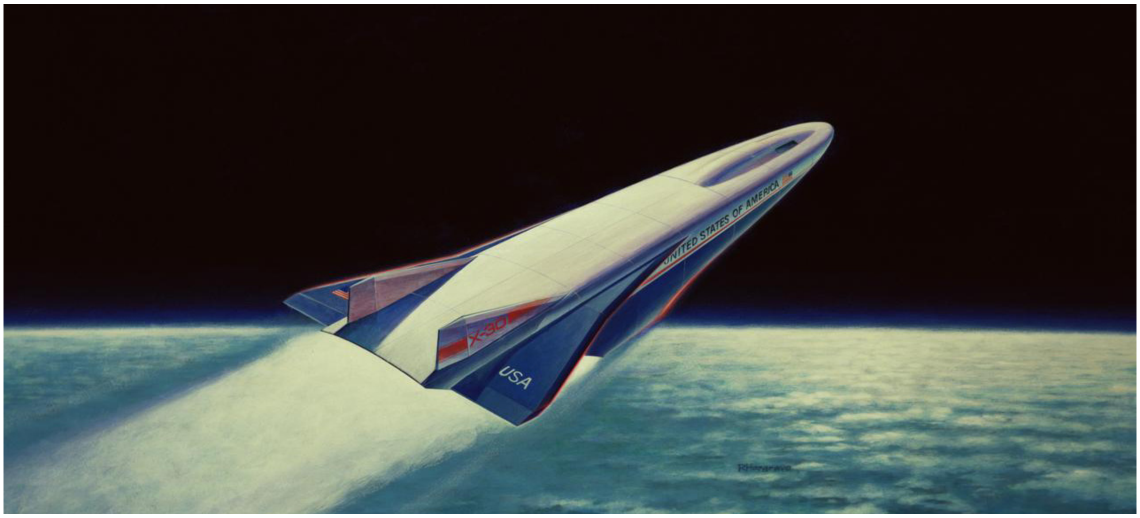


Figure 4. Artist illustration of the National Aerospace Plane (Courtesy of NASA)

Drawing from the experience with the early conceptual design and technology development of the X-30, an assessment of the application of the ASIP, ENSIP, and MECSIP processes to reusable space access systems leads to the following conclusions.

a. Applicability. Achieving aircraft-like operational safety, suitability, and effectiveness in a reusable space access system will not just happen by fortunate circumstance. As with any aircraft of a new design, this requires the consistent and thoughtful application of integrated integrity processes, throughout the life of the flight system, to develop a product that is safe, operable, and affordable. ASIP, ENSIP, and MECSIP have been demonstrated to be successful in guiding the development of advanced military aircraft employing leading-edge technologies. There is no apparent reason why these programs should not provide guidance in successfully developing and operating a fully-reusable space access system (or reusable in-space transportation systems).

b. Design selection. The five interrelated tasks of the integrity programs provide boundaries within which a successful aircraft design must be executed. The same will be true for a successful fully-reusable space access system. If these tasks cannot be practically or affordably implemented for a particular reusable space access system design, then that design will most likely not achieve airworthiness certification and will not enter routine operational use. Consideration of how the requirements of the integrity processes will be fulfilled must begin coincidently with the earliest conceptual vehicle design studies. Quite often this will need to occur during research and development when decisions on particular science and technology development proposals are being made. The failure to consider integrity requirements during science and technology development or early system conceptual design is a common oversight.

c. Damage tolerance. The consequences of damage and the mechanisms of damage propagation are less well understood for reusable space access systems because of the lack of experience with designing operational systems. Yet, the consequences of damage without good damage tolerant designs, particularly in areas related to propellant storage and transfer and exterior thermal protection, may potentially be catastrophic. Experience with aircraft shows that it may be relatively straight-forward and inexpensive, in terms of cost and weight, to identify and address damage tolerance requirements early in the design process compared with attempting to resolve these issues during the detailed design, production, or operational phases. The Space Shuttle experience associated with addressing the damage resulting from external tank insulating foam striking the orbiter's thermal protection tiles is a relevant example. Damage tolerance design considerations must become an integral part of the reusable space access conceptual design process just as accurate trajectory optimization, propulsion performance estimation, and conceptual design weight estimation are important elements of a quality design capability.

Similarities of Expendable and Reusable Space Access Systems

There are two similarities between expendable and reusable launch systems that will impact safety and operability. The first is that both systems store fuel and oxidizer on the vehicle. This close proximity of large quantities of both fuel and oxidizer presents an additional safety risk that appears to be unavoidable with most near-term concepts. Hence, these systems will require specific ground and flight safety requirements and processes once propellants are loaded. Fortunately, historical experience with rocket-powered, reusable aircraft, such as the X-1 and X-15, indicate that appropriate ground and flight safety requirements and processes can be identified and successfully implemented.

The second similarity is that, at least for the near-term, fully-reusable space access systems will employ some form of an emergency separation and recovery capability where the human passengers could be safely recovered in the case of a detectable failure that could lead to catastrophic loss of the vehicle. For the new NASA CEV, conceptual depictions of the system show that a one-use emergency separation and recovery capability will be included. For a small spaceplane expected to be used as the passenger transport system for a near-term, fully-reusable space access system, the emergency separation and recovery capability is expected to be accomplished using the vehicle's propulsion and flight control subsystems. This important safety capability would be demonstrated as part of the development and acceptance testing of these reusable passenger vehicles prior to these vehicles entering service—an important distinction discussed in the following.

Key Disadvantage of Using Expendable Space Access Systems for Human Transport

There is one fundamental difference between expendable and reusable space access systems that forms the basis for the expectation that reusable space access systems should be preferred and would better encourage the growth of routine human space operations. This is the fact that each expendable production article's first and only full system usage is the operational mission. As a direct consequence, production expendable systems are operated *without* explicit knowledge that each production expendable element fully and safely functions as intended. This has clear implications for the safety of humans riding on an expendable launch.

Take the example of providing routine transport of passengers to an orbiting space hotel. The use of space access systems with expendable elements would constitute a significant change in safety-assurance protocols in that non-test pilot humans would be riding on the expendable system during its first flight. The standard protocol for aircraft transporting humans is that flight test pilots and flight test engineers are the first to ride in a new or significantly modified aircraft. Specially trained, well-experienced, and integrally-involved with the development of the new flight system and preparation of the test aircraft for flight, they use their experience and expertise to balance safety and risk to make the final determination if a new flight system is acceptably safe to fly prior to airworthiness being fully demonstrated. This approach is used to ensure that those asked to first fly on a new system are able to make an informed decision—a judgment—as to whether the aircraft is acceptably safe to fly. They make this judgment based on their technical knowledge of the system and their professional relationships with the senior people responsible for designing, building, and operating the system.

This approach extends into operation. For a certified aircraft, a pilot new to the aircraft is fully trained in the operation and functioning of the system and demonstrates piloting competence in ground simulators and during pilot familiarization and checkout flights prior to flying with passengers. The pilot's presence in command of the aircraft then provides assurance to the passengers that the aircraft is acceptably safe to fly through a chain of successful activities starting with the earliest conceptual design meetings continuing up to the pilot's walk-around inspection of the aircraft before the passengers are permitted to board. At the point of push-back from the boarding gate, all elements of *that* aircraft have been through all required safety inspections, including acceptance flight tests, and all flight-critical subsystems are operating as intended.

A fully reusable space access system, developed and demonstrated to be airworthy using aircraft-style systems engineering principles and practices, would enter operational service *with explicit knowledge* that the correct system functioning and safety of each production system, including recoverable emergency aborts, have been demonstrated. Development and acceptance tests requiring human involvement would be undertaken by test pilots and test engineers carefully trained in the design, operation, and possible failure modes of the system. It is only after acceptance testing of each production system has been successfully completed would that system be placed into service for routine passenger transport.

Expendable (or partially-reusable) space access systems, in contrast, *cannot* achieve aircraft-like safety. As mentioned, *no explicit knowledge* of the correct functioning of all safety-critical subsystems is possible to achieve. Lacking this information, there is no way to provide comparable levels of assurance of safety to passengers. Nor is there any way to provide sufficient knowledge and understanding to the passengers for them to make an informed decision as to the increased level of risk to their safety—a significant increase, based on historical data—to which they would be exposed.

Affordability of Space Access Systems

In the space hotel example, ten guests are staying for seven nights. Using a CEV-like expendable space access system capable of transporting five passengers, the space hotel creates a demand for two CEV flights per week or approximately 100 flights per year. Assuming 50 percent additional flights are required for operating crew, spares, and replenishables, the total number of flights required is about 150 per year. Over the course

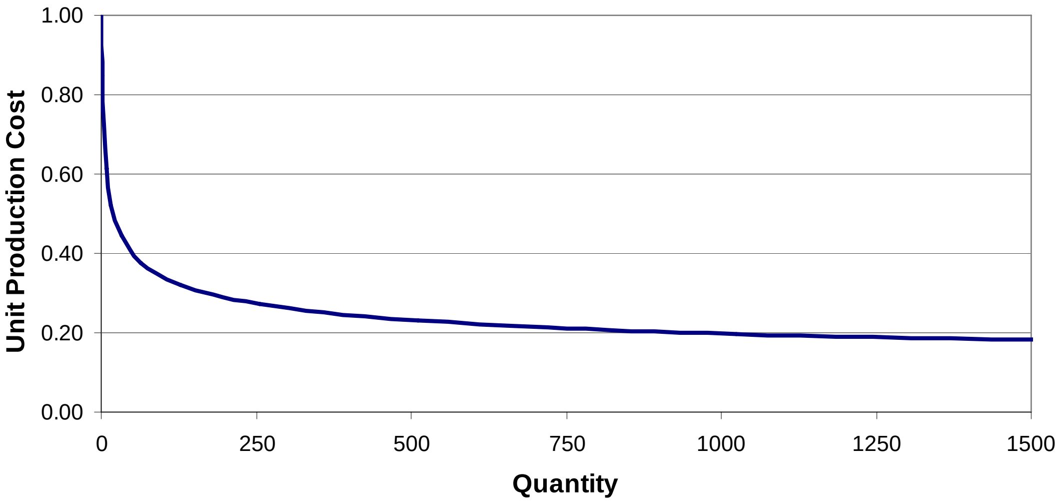


Figure 5. Reduction in unit cost as a function of an 85 percent learning curve.

of 20 years, this totals 3,000 launches. If assured space access is dictated, then at least two different types of launch system would need to developed and used. Thus, in this example, each type of system would fly 1,500 missions over 20 years requiring, obviously, at least 1,500 CEV-like systems to be produced.

The unit production cost for identical or nearly identical units decreases as a function of the "learning curve." First defined in 1936 by T. P. Wright at Wright-Patterson Air Force Base, the learning curve relates the cost of production of a unit when the number of units produced has doubled. A learning curve of 80 percent means that the second unit costs 80 percent of the first unit, the fourth unit costs 80 percent of the second unit, etc. Traditional aerospace systems have learning curves of 85 percent (see Figure 5).[34]

Using the average aerospace learning curve value of 85 percent, a rough order of magnitude estimate of the *per passenger cost* of using CEV-like expendable

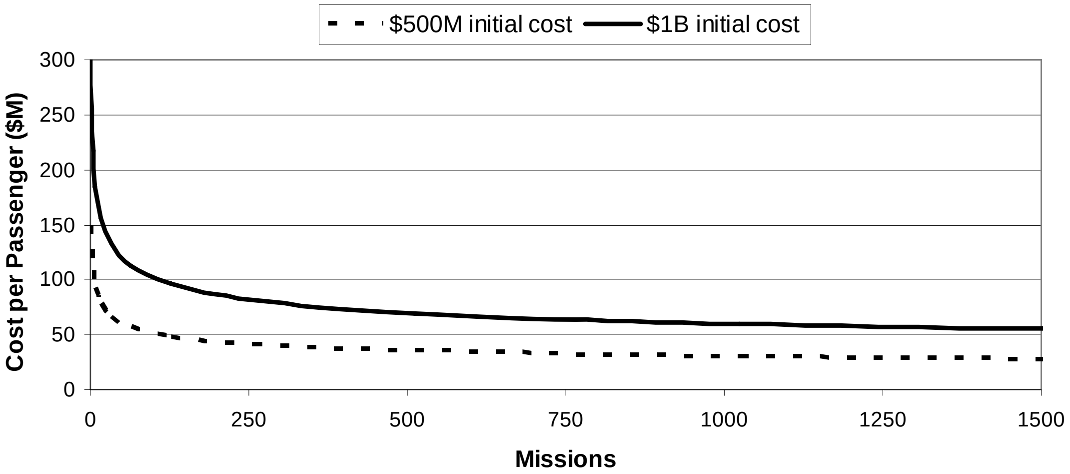


Figure 6. Rough order of magnitude estimate of the per passenger cost for an expendable space access system with initial mission costs of $500M and $1B.

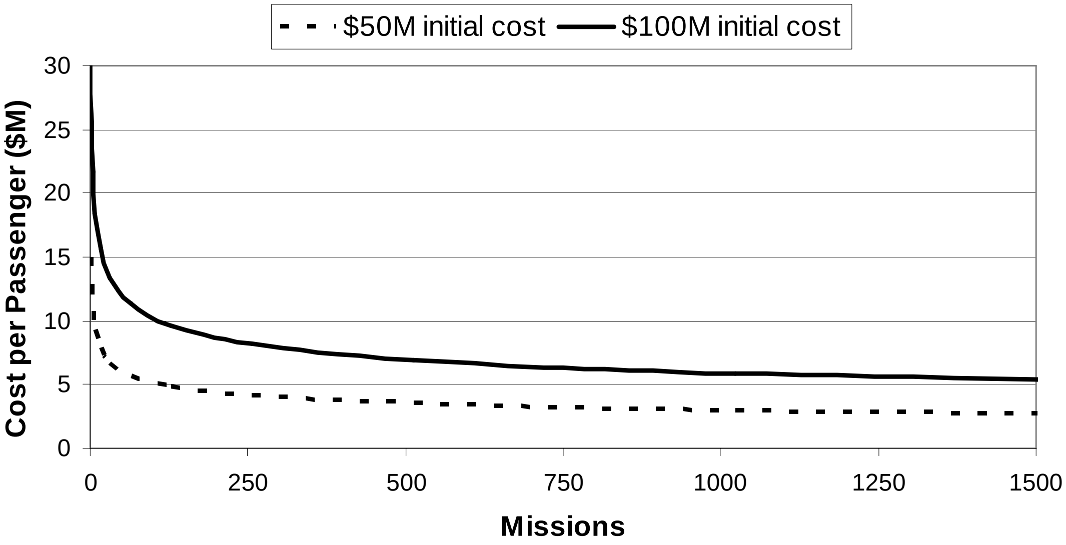


Figure 7. Rough order of magnitude estimate of the per passenger cost for an expendable space access system with initial mission costs of $50M and $100M.

transportation is shown in Figure 6. In this estimate, an initial upper-bound total mission cost of $1.0B and a lower-bound total mission cost of $0.5B are assumed. Assuming five passengers per flight, the per passenger cost ranges from $150-300M for the initial mission to $27-54M for the 1500th mission.

One argument made in favor of the use of expendable launch systems is that by taking advantage of the opportunity for a "clean sheet" design, substantial production cost reductions could be achieved. Figure 7 shows the approximate impact of a 10X reduction from the costs used in the above estimate. Using the same assumptions for the learning curve but with initial mission costs of $50M and $100M (including the cost of the CEV-like capsule), the per passenger cost ranges from $15-30M for the initial mission to approximately $4-8M by the 250th mission.

From the Figure 1 illustration of possible CEV configurations, it is seen that the size of an expendable launch systems required to transport six crew members to space is substantial. To establish a successful routine space access capability requires that the system be affordable. This requires good flight rates made possible by a sustainable market demand which, in turn, requires attractive prices. These rough estimates of the per passenger cost for an expendable launch system would indicate that a system design of the size of the Delta IV heavy launch system needs to be developed from scratch and achieve at least a factor of 10 reduction in unit production cost to *start* to bring costs into the right order of magnitude. This, of course, assumes that acceptable flight safety suitable for passenger transport can be achieved.

Aircraft intended for routine and frequent operation achieve affordable pricing not through low production costs, but through operational safety and operability enabling sustained and frequent operation. Fundamental to achieving acceptable operational safety and operability are good damage tolerance and durability, introduced above and discussed in more detail in the following section. Damage tolerance, which includes certain flight-critical subsystem redundancy, enables the flight system to be operated with high confidence that should damage occur the flight system can continue to operate safely until the system lands or until an in-service inspection detects the failure and corrective actions are implemented. Durability is also important because a durable flight system can be operated with acceptable recurring costs for repair or replacement of parts that degrade with use. Together, damage tolerance and durability limit the cost of operations by minimizing pre- and post-flight inspections, by providing reasonable periods of in-service operations before scheduled inspections are required, and by limiting the cost of performing the in-service inspections and any associated repairs and refurbishment. Application of this strategy to achieve operational safety *and* affordability of fully-reusable space access systems is discussed below.

Section Conclusions

Over the course of a century of technology and design development, aircraft have evolved into highly complex systems capable of providing safe, routine, and affordable transportation of the public. Well-defined systems engineering principles and practices have been developed and tested that enable increasingly complex and capable aircraft to be designed, developed, produced, tested, and brought into operation with high confidence. In the 1950s, routine space access was expected to use reusable flight systems capable of routine and frequent space access with aircraft-like safety. The United States twice tried to pursue this approach, first in the late 1950s with the partially-reusable DynaSoar and then in the late 1960s with a fully-reusable space shuttle. However, political, national security, and economic circumstances combined to, instead, choose the path of expendable and then partially-reusable space access systems. While the aircraft design heritage has produced increasingly capable and safe public and government air transportation, the expendable and partially-reusable design heritage has not yet been able to, and seems unlikely to, produce an integrated set of engineering principles and practices that will yield future public space transportation systems with acceptable safety and affordability. Given that there are no fundamental design or process restrictions on the application of aircraft engineering principles and practices to fully-reusable space access systems, *the conclusion is reached that using the aircraft design heritage, while taking advantage of appropriate lessons learned and useful practices from expendable launch systems, provides the preferred approach for achieving aircraft-like operational safety and affordability.*

Section 4: Defining a "Near-Term" System Design

A near-term system design is one that can enter full-scale system development without first requiring significant further enabling technology maturation. Within the aerospace community, one method commonly used to assess the maturity of a proposed system design is to evaluate the maturity of the enabling technologies. For this purpose, NASA has developed a Technology Readiness Level (TRL) scale on which any technology—from the initial raw observations to the final operational application—can be ranked (see Figure 8). To be considered a mature technology sufficient to support a decision to proceed with full-scale system development, all enabling technologies need to have achieved at least a TRL of 6—"system/subsystem model or prototype demonstration

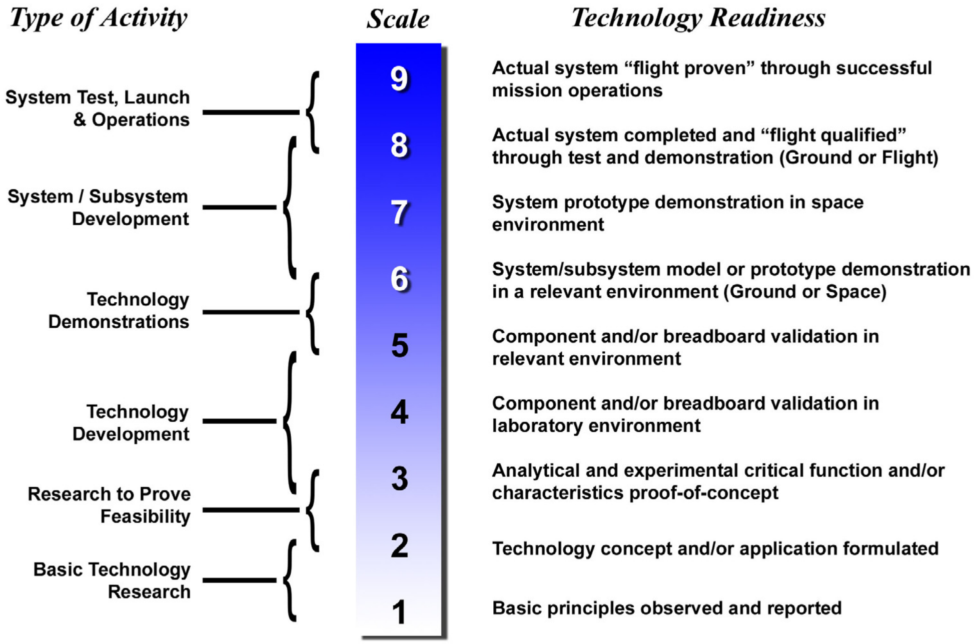


Figure 8. Technology readiness level scale (courtesy of NASA).

in a relevant environment (ground or space)"—if the program's development is to proceed with low risks.

With this level of maturity, a normal pace of system development will produce a production design in 3-4 years and a first production article in 5-7 years. A relevant benchmark is the Space Shuttle that started development in 1972 and was ready for first flight in 1980—about 8 years. However, many critical technologies, such as the thermal protection tiles and reusable rocket engines were only TRL 3-4 at the beginning of the system's development. This helped to extend the development period by 1-3 years. Another relevant benchmark was the early 1990s Delta Clipper Experimental single-stage rocket technology demonstrator. This 40,000 lb subscale, low-speed demonstrator of a single-stage reusable space access system used TRL 8-9 technologies and went from the preliminary design review to the first flight in about 18 months. The advantages of using mature technologies was demonstrated with this program.

Section 5: Near-Term Options for Fully-Reusable Space Access

The design of fully-reusable space access systems can take many forms. They can be single-stage or multiple-stage systems using rocket or a combination of airbreathing and rocket propulsion. They can carry all of the propellants at takeoff, consume oxygen from the atmosphere during part of the ascent, or "manufacture" and store oxidizer in flight using some form of oxygen extraction and collection system. They can takeoff horizontally on a runway, launch vertically, lift off a powered sled or ramp, or be shot from a gun. They can land vertically or horizontally under power, glide to an unpowered horizontal landing, or land using a parachute or another form of aerodynamic deceleration. Finally, they can climb a space cable as in the proposed space elevator concepts. Regardless of the design, what they must have in common is sufficient

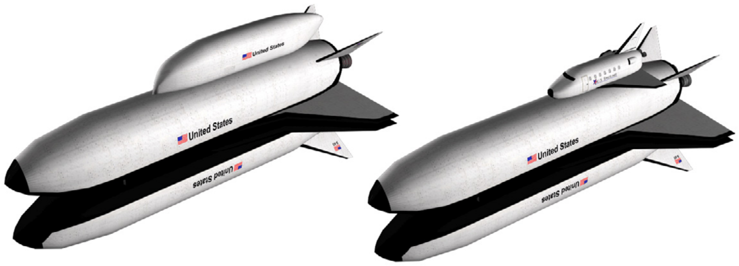


Figure 9. Generic two-stage, fully-reusable space access system with cargo container (left) and passenger transport spaceplane (right).

performance to achieve orbit and the system integrity that provides for safe and routine "aircraft-like" space access for passengers and cargo.

Of the alternative design approaches listed, only a two-stage system using primarily rocket propulsion is considered a near-term design with TRL 6-9 enabling technologies. Conceptual design studies conducted for the Air Force Research Laboratory by the Air Force Materiel Command's Aeronautical Systems Center indicate that any conventional single-stage system requires advanced technologies that are currently less than TRL 6. The same can be concluded for any reusable space access concept that, in flight, separates and stores oxygen for later use with the rocket engines, uses a powered sled or ramp for takeoff assistance, is shot from a gun, or uses advanced airbreathing propulsion. And, certainly, any space elevator concept does not yet have a mature set of enabling technologies. Hence, absent a remarkable new design innovation for a single-stage system, the only expected near-term solution is a fully-reusable, two-stage system shown generically in Figure 9. [Note: This illustration is intended to only depict the arrangement of the elements of the system and does not represent a sized concept design as is shown later.]

Near-term Reusable Space Access System Concept

This two-stage concept is rocket powered, launches vertically, and lands horizontally on a runway. For cargo transport, the cargo is carried in a container mounted externally on the second stage. For passenger transport, the passengers and flight crew are transported in a small spaceplane carried in place of the cargo container. The first stage is primarily an advanced metallic and/or composite primary structure (including propellant tanks) with limited additional passive thermal protection on areas of the nose, wing leading edge, and lower forebody that exceed the permissible temperature of the primary structure. The second stage is similar to the first except that the passive thermal protection system covers most of the external surface. Both stages have four primary engines.

In operation, the first stage engines power the system to a separation velocity of 7,000-12,000 ft/sec. Following separation, the first stage typically aerodynamically decelerates to subsonic speeds, turns, and uses airbreathing jet engines to cruise back to the spaceport for a powered landing. The second stage, after separation, ignites its engines, accelerates, and climbs into a low Earth orbit. After deployment of the cargo or release of the passenger spaceplane, the second stage reenters the atmosphere and uses aerodynamic deceleration and unpowered maneuvering to position the vehicle for an unpowered landing at the spaceport.

Section 6: Applying an Aircraft-Style Systems Integrity Process to the Development of a Reusable Space Access System

Since the introduction of the first jet-powered military and commercial aircraft in the 1940s, aircraft performance, safety, suitability, and effectiveness have all advanced significantly. When the first Pan American Boeing 707 entered service in 1958, the cost of a one-way coach ticket from New York to London was about $270.[35] Taking consumer price inflation into account, that cost would be approximately $1,800 today. Yet, airfares in the range of $400 one way for coach are widely advertised today indicating that per seat cost reductions of about 80 percent have been realized through the successful introduction of improved technologies and designs. There are three reasons for this success that will be critical in developing successful near-term reusable space access systems: the influence of military aircraft development, the use of a government-industry partnership to lead the engineering development and application of new safety-critical technologies, and the use of a design philosophy of incremental technology advancement.

Going into World War II, in part due to the economic depression of the 1930s, the U.S. government had not emphasized military fighter aircraft technology development—the leading edge of aircraft performance technology advancement. As a result, at the outset of the war, U.S. fighters were operationally inferior and lacked sufficient range to fully perform their missions of establishing air superiority to protect U.S. military forces. While this situation was rectified by 1943 for piston-powered aircraft, in many areas, such as jet-powered fighters and rockets, Germany still maintained a significant technological lead that was not overcome by the end of the war. Recognizing the critical importance of technological superiority to deter and, if necessary, defeat aggression, the U.S. military became more directly involved in advocating and developing advanced military aeronautical technologies as the military transitioned from a wartime to a peacetime status and then to a "cold war" status.

As in any technological endeavor, establishing and maintaining world leadership requires assuming additional risk because the pathfinder is the first to discover and the first to resolve unforeseen difficulties. To counter-balance the inherent higher program risk of developing new technologies and utilizing new designs, the military, starting in the mid-1970s, strongly emphasized the development and implementation of system integrity processes to enable these more advanced military aircraft to achieve the targeted level of safety, suitability, and effectiveness as well as performance. To develop and implement these integrity processes, the military has developed an integrated series of directives, policies, instructions, specifications, guidance documents, and training programs, as described earlier. These provide government and contractor engineers and program managers with a well-documented understanding of past lessons learned and guidance on how to define, tailor, and implement successful integrity programs that, in most cases, lead to successful new aircraft.

The second reason for success is the government's intentional dependency on private industry to develop and produce new military aircraft. Occasionally, organic government design bureaus have designed a new flight system and then contracted with industry to have it built. This process did not recognize the inherent iterative nature of the interplay of design, analysis, developmental test, and production—especially as new technologies, design approaches, and missions are being addressed—that makes segregation of the development and production processes unlikely to be successful. Hence, the government has adopted a general philosophy of being a smart customer identifying good requirements for performance and capabilities, relating past lessons learned, and then providing management and technical oversight of the contractor as the system development is executed. With this relationship, industry develops the detailed expertise, experience, and industrial capabilities to develop and produce new military aircraft. As successful experience is achieved with military aircraft, the engineers, scientists, and managers at the prime contractors, vendors, and suppliers can transition these new technologies and designs to commercial aircraft while drawing on their success in demonstrating the military aircraft's airworthiness to help substantiate airworthiness of the new commercial aircraft.

The final reason for industry's success in developing ever more capable aircraft is the utilization of a design philosophy of selected technology and design advancement. From generation to generation, the detailed structural, mechanical, aerodynamic, stability and control, and propulsion designs of a new aircraft have been quite similar to the successful designs of previous aircraft. Only where necessary to improve operational suitability and effectiveness, achieve improved mission performance, reduce manufacturing and operational costs, or correct previously unrecognized performance and integrity problems, are new technology and design innovations introduced. The development of the Boeing 707-727-737-747-757-767-777 commercial aircraft represents such a design evolution.[*] Each new generation of aircraft was introduced only when changes in market demand or challenges from competitors could *not* be met through incremental improvements in existing products. The importance of this strategy is that it enables new designs with improved performance and capabilities to be introduced with a level of confidence in the success of the new product—confidence that the product will achieve cost, performance, and mission capability goals while remaining safe—sufficient to gain commercial financing of the new design's development and to earn pre-production customer orders.

These three critical elements of aircraft design heritage are directly applicable to the strategy for developing a successful near-term, aircraft-like reusable space access system. The system integrity documents, available on the Internet, will provide a proven starting point for defining an integrity program, as discussed below, suitable for achieving desired

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[*] The key to Boeing's long-term success was its willingness to take risk by investing corporate funds in building the prototype 387-80 that led to the Air Force's decision to build the new KC-135 tankers, which then led to the Boeing 707. The "-80" refers to the fact that the final prototype was the 80th design iteration, reflecting the fact that many design cycles were needed to successfully develop a jet-powered transport aircraft design attractive to customers on the basis of safety and operability. While not diminishing the fact that Boeing took significant corporate risk in undertaking the company-funded 387-80 project, it should be recalled that the jet-powered British De Havilland Comet 1 had flown in 1949; one of Boeing primary American competitors, Douglas, was also pursuing jet-powered transports; and, Boeing had developed the jet-powered B-47 in 1947 and was also developing the jet-powered B-52. The 387-80 was a successful step in applying the two bombers' swept-wing, jet-powered technologies to passenger transport aircraft.

levels of safety, suitability, and effectiveness in fully-reusable space access systems. The existing aircraft industry's experience and expertise with the application of these integrity processes, developed through the government-industry partnership for military aircraft development and the comparable elements of the commercial airworthiness certification process, will provide the foundation of knowledge to successfully tailor these integrity processes for utilization in developing aircraft-like, reusable space access systems. Finally, industry's experience with developing flight systems with similar structural, aerodynamic, stability and control, mechanical subsystems, developmental analyses and testing, production, and ground and flight operations, will enable a near-term design to be developed that incrementally builds on existing aircraft technologies and the design of the Space Shuttle's orbiter to produce two-stage, fully-reusable space access system designs with acceptable performance, costs, and program risks.

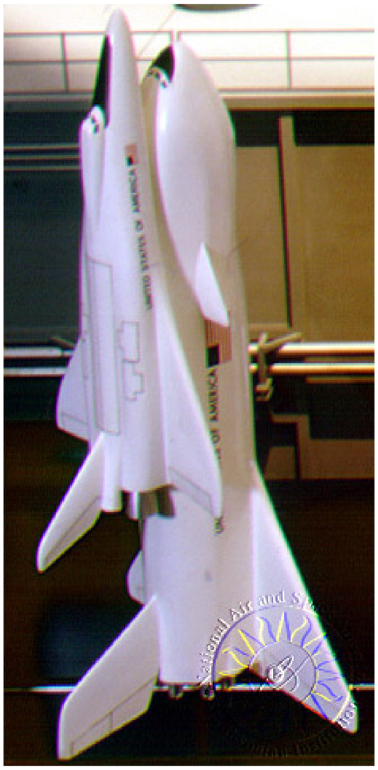

Figure 10. Model of late 1960's Rockwell two-stage fully-reusable space access system (courtesy of the National Air and Space Museum).

To enable this aircraft design heritage to be effectively used, the near-term solution, shown in Figure 9, represents a return to the two-stage system concept initially designed for the Space Shuttle in the late 1960s (see Figure 10). [Note: Figure 10 is one of the concepts developed in the late 1960s that led to the 1970 criteria for a fully-reusable space access system discussed earlier in this paper.] The Figure 9 solution, which represents the side-by-side mating of two aircraft-configured reusable flight systems, enables the first-stage booster and the second-stage orbiter to be designed using conventional aircraft structural, aerodynamic, and stability and control design and systems integrity assurance methodologies. Rocket propulsion, propellant storage and handling, thermal protection, and payload handling will be incorporated by drawing on industry's experience and expertise with the Space Shuttle's orbiter and by tailoring and applying the military aircraft system's integrity processes to these subsystems. As the preliminary design of this system is undertaken, mature and emerging TRL 6-7 technologies will be incorporated into the design. For example, the Air Force Research Laboratory is developing improved thermal protection system technologies that will increase the thermal protection system's durability compared with current operational capabilities.[36] There have also been proven advances in areas such as metallic and advanced composite propellant tank design and production, aircraft stability and control, electrical and hydraulic power subsystems, and vehicle health monitoring. The resulting modernized version of the 1970s design should provide a near-term solution with operational safety, suitability, and effectiveness approaching the current standards for aircraft.

Defining a System Integrity Process for Fully-Reusable Space Access Systems

United States military aircraft continually apply new technologies, incorporate new design features, and expand the operational flight envelope to provide needed operational capabilities. As was discussed above, success in these accomplishments has come from the tailored application of the system integrity assurance processes first developed for aircraft primary structures and then extended to the propulsion and mechanical subsystems. Following the integrity model used by the DoD and, in particular, the Air Force, the five primary tasks of a reusable space access system integrity process are:

- Task I (Design Information). Task I is development of those criteria that must be applied during design to ensure the overall program goals will be met. These goals include operational safety, suitability, and effectiveness as well as cost-related goals for development, production, and operations.

- Task II (Design Analysis and Development Testing). Task II includes the characterization of the environment in which the fully-reusable space access system must operate; the initial testing of materials, components, and assemblies; and, the analysis of the design of the structure, propulsion, mechanical, and avionics.

- Task III (Full-Scale Testing). Task III consists of flight and laboratory tests of the flight-critical subsystems to assist in determining the structural and mechanical adequacy of the analysis and design.

- Task IV (Certification & Fleet Management Development). Task IV consists of the analyses that lead to certification of the flight-critical subsystems, as well as the development of the processes and procedures that will be used to manage fleet operations (inspections, maintenance, modifications, damage assessments, risk analysis, etc.) when the space access system enters operation.

- Task V (Fleet Management Execution). Task V executes the processes and procedures developed under Task IV to ensure system integrity throughout the life of each individual space access system. This task may involve revisiting elements of earlier tasks, particularly if the service life requirement is extended or if the flight-critical subsystems are modified.

The Critical Role of Damage Tolerance and Durability in Achieving Aircraft-like Reusable Space Access

As with aircraft, damage tolerance and durability will form the core of an aircraft-like, reusable space access system's integrity process. These are essential to establishing acceptable flight safety and sustaining economical operations.

Recall that damage tolerance is defined by the Air Force as "the attribute of a structure that permits it to retain its required residual strength for a period of *unrepaired* usage after the structure has sustained specific levels of fatigue, corrosion, accidental, and/or discrete source damage." Essentially, this relates to the ability of the flight system to continue to operate safely in the presence of damage. This damage may be present but undetectable in an "as manufactured" part, may develop while the system is in use through chemical (e.g., corrosion) or time- and temperature-induced change (e.g., flaw growth and thermal creep), or it may be introduced after the system has been placed in service (e.g., space debris impact on the thermal protection system). While the concept of damage tolerance was initially developed and applied to the airframe, it is now applied to all flight-critical parts—even down to connecting wires and solder joints on circuit boards. This attribute will enable reusable space access systems to be flown frequently and routinely with confidence in a successful and safe mission outcome. This attribute will also enable the extensive and elaborate pre-flight inspections and go/no-go decision processes typical of current space launch operations to be substantially scaled back. Drawing an analogy to mountain climbing, the damage tolerance aspect of system integrity is like climbing with a partner and using safety ropes, whereas a system design without damage tolerance is like free climbing—less expensive, faster, but certainly with severe consequences from mistakes.

Durability is defined as "the ability of the aircraft structure to resist cracking, corrosion, thermal degradation, delamination, wear, and the effects of foreign object damage for a prescribed period of time." It relates to the economic cost of maintaining adequate integrity and acceptable mission functioning in the flight system. Almost all parts of a flight system degrade with time and usage due to cyclic loading of structural elements and environmental-induced physical and chemical changes. Eventually, if left unaddressed, mission-critical and flight-critical subsystems may fail to properly function, leading to degraded mission performance, mission aborts, and, possibly, loss of the flight-critical subsystem function. While damage tolerance focuses on localized failures that could lead to immediate and catastrophic system loss, durability focuses on generalized degradation that has a high cost of repair.

Modern aircraft design methods and materials, combined with the moderate level of usage expected for a near-term, reusable space access system, should enable the space access system to operate routinely for 20-25 years with minimal durability-related repair and maintenance requirements. For example, if the system were to fly every two weeks, over the course of 25 years it would undertake approximately 650 missions. This is approximately the number of missions flown by a commercial airliner, such as a Boeing 737, each year. Hence, traditional durability-related design issues associated with high levels of usage, such as generalized fatigue cracking, may not develop as a significant cost-of-ownership issue. However, non-traditional design aspects of a reusable space access system, such as thermal protection system, non-metallic cryogenic propellant tanks, and cryogenic tank insulation, will likely require durability-related attention during design, production, and operation.

Section 7: General Steps for Achieving Adequate System Integrity and Airworthiness during the Conceptual Design of Near-Term, Reusable Space Access Systems

A reusable space access system with acceptable integrity will have sufficient strength to resist static and dynamic loads resulting from permissible normal and emergency ground and flight operations; will be acceptably damage tolerant and durable; will incorporate appropriate flight-critical subsystem redundancies; and, will be under a specified system of inspection, maintenance, and repair that maintains the system's integrity throughout its operational life. In other words, the reusable space access system will be airworthy.

The identification of the conceptual design of near-term, fully-reusable space access systems that can be expected to have acceptable integrity can be undertaken using the following general steps:

A. Select mature technologies.

As has been emphasized in this paper, selection of mature, TRL 6-9 technologies is important for successfully developing a near-term solution. Besides reducing the development risk and cost, the use of mature technologies increases the likelihood that predictions of safety, weight, performance, operational cost, and operational capabilities will be achieved, thereby increasing confidence in the program and the ability to secure funding. The use of mature technologies also provides the advantage that the experience and expertise needed to successfully resolve problems can be quickly located and applied. Finally, the use of TRL 8-9 technologies brings with them embedded good engineering principles and practices that have previously produced airworthy components and subsystems.

B. Eliminate possible failure initiation causes.

The easiest way to eliminate operational failures is to select a design that eliminates possible failure initiation causes. Military Standard (MIL-STD) 882C states this good engineering practice as, “the priority for system safety is eliminating hazards by design.”[37] Experience with the Space Shuttle is relevant to this discussion. The Space Shuttle orbiter Challenger was lost due to the failure of seals in the Solid Rocket Boosters. This potential cause of failure can be eliminated by not using solid rocket boosters. The Space Shuttle orbiter Columbia was lost, it is believed, due to foam from the External Tank shedding and hitting the orbiter’s thermal protection system. This potential cause of failure can be eliminated by not incorporating expendable, foam-insulated external tanks in the design. Both of these failure initiation causes did not exist in the original fully-reusable Space Shuttle design, as seen in Figure 10. Unfortunately, they were created as the fully-reusable design evolved into a partially-reusable design responding to development cost constraints.

C. Set flight limits to increase operational safety and simplify the system design.

Figure 11 provides definitions for hazard probability levels from MIL-STD-882C. Only if a hazard is “improbable,” can it be excluded from consideration during the system’s design. Hence, if a hazard cannot be designed out of the system, the imposition of limits on the use of the system may make the failure initiation cause improbable and enable it to be excluded from consideration in the design of the system. The intentional exclusion of failure initiation causes increases operational safety while at the same time simplifies the design and verification of the system’s integrity.

Good examples of this relate to variations in the magnitude of weather conditions or excessive flight loads. Hazards caused by weather and flight conditions that would place excessive structural loads on the vehicles or make the vehicle uncontrollable can be made improbable by placing limitations on permissible weather flight conditions and selecting

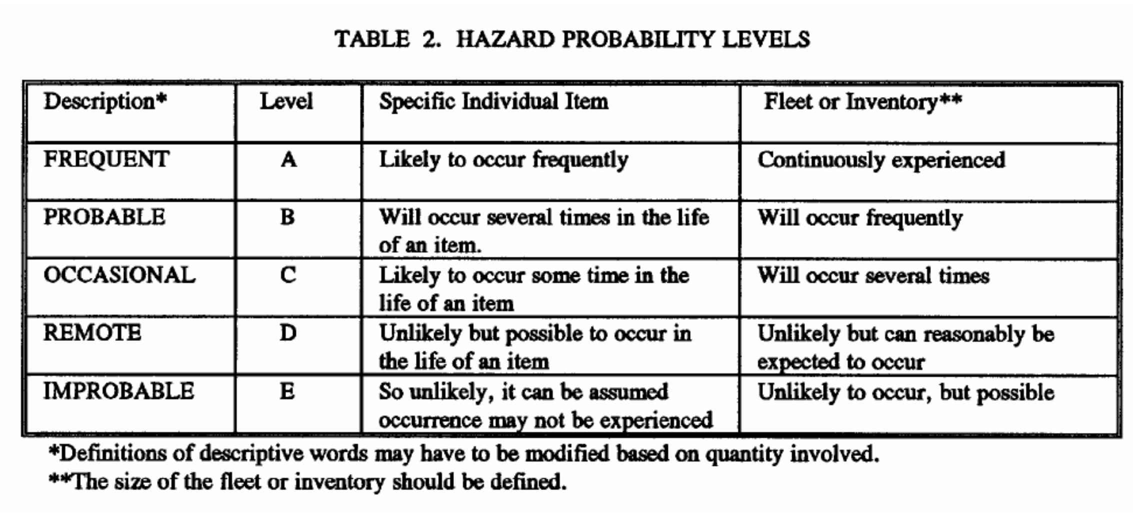

TABLE 2. HAZARD PROBABILITY LEVELS

Description*	Level	Specific Individual Item	Fleet or Inventory**
FREQUENT	A	Likely to occur frequently	Continuously experienced
PROBABLE	B	Will occur several times in the life of an item.	Will occur frequently
OCCASIONAL	C	Likely to occur some time in the life of an item	Will occur several times
REMOTE	D	Unlikely but possible to occur in the life of an item	Unlikely but can reasonably be expected to occur
IMPROBABLE	E	So unlikely, it can be assumed occurrence may not be experienced	Unlikely to occur, but possible

*Definitions of descriptive words may have to be modified based on quantity involved.
**The size of the fleet or inventory should be defined.

Figure 11. Definitions of hazard probability levels from MIL-STD-882C, page 11.

flight envelope restrictions. The temporary closing of an airport during thunderstorm and icing conditions is an example of imposing operational limitations that make the hazards of localized, but extreme, wind gusts or icing during takeoff and landing improbable. Placing limitations on the launch of space access systems when wind velocities at altitude exceed established limits is another example of using flight restrictions to make the hazard of severe wind shear improbable.

D. Set operational flight limits and modes that will keep critical design loads and operating conditions within predictable ranges.

Consistent with the use of mature technologies is developing a conceptual design that operates within established flight regimes such that the prediction of the critical design loads and operating conditions can be made with good confidence. Good confidence in the accuracy of external load prediction reduces the development effort, simplifies ground and flight verification of the system integrity, and reduces the weight typically added to the first flight articles to provide an increased safety margin to protect against failure due to higher than predicted external loads.

E. Establish an internal arrangement that is weight and volume efficient, readily manufacturable, and enables an operable and maintainable system.

Drawing on the experience of aircraft, reusable space access systems such as the Space Shuttle orbiter and X-15 (see Figure 12), and expendable launch vehicles, the conceptual design of the near-term, reusable space access system should strive to achieve an elegant internal arrangement. In developing this internal arrangement, attention should be given to defining weight-efficient, readily-predictable load paths with appropriate static and thermal redundancy for damage tolerance; thermal shielding of internal structure and equipment; propellant storage, transfer, and internal cavity venting; cargo handling; internal load transfer between stages; manufacturability; access for airworthiness inspection; internal load segregation to enable component and full-scale testing; access for instrumentation installation and maintenance; and, access for subsystem maintenance, repair, and component replacement.

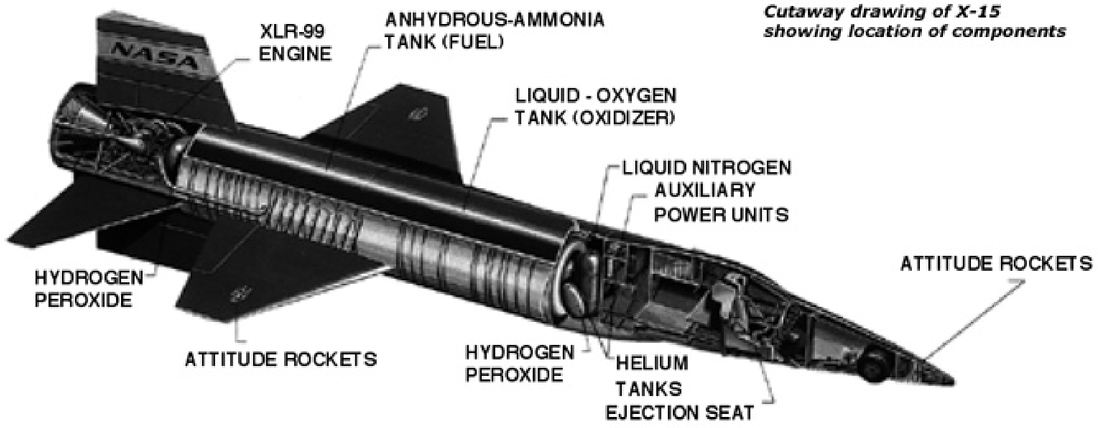

Figure 12. Cut-away view of the X-15 (courtesy of NASA).

F. Identify damage initiation causes.

The key to developing a damage resistant and durable system is having a good understanding of the damage initiation causes. While the design and operational heritage of aircraft and the Space Shuttle orbiter will provide a good experiential starting point in identifying damage initiation causes, care needs to be taken in translating this knowledge to the reusable space access system. Hence, prior to establishing the system integrity requirements to be used in the detailed design, analysis, and verification of airworthiness of the reusable space access system, a careful survey of the system's intended design and functioning and internal and external ground and operational environments should be undertaken to identify the nature and extent of non-improbable damage initiation causes. Once completed, the system conceptual design should be reevaluated to determine if different mature technologies, changes in the design, and additional flight limitations can be used to eliminate or reduce the severity or frequency of the damage initiation causes.

G. Produce a tailored set of system integrity requirements.

As discussed, DoD has an integrated series of documents, available on the Internet, that provide guidance on tailoring system integrity requirements to a particular flight system's design and intended operation. The resulting tailored system integrity plan and specific design and verification requirements form the core of the systems engineering process that has the goal of producing a new flight system with acceptable operational safety, suitability, and effectiveness. When completed, this tailored plan and accompanying design and verification requirements are used to prepare estimates of the funds, schedule, and resources necessary to transform the conceptual design into a fielded system and establish the maintenance activities that will maintain airworthiness and operability throughout the system's intended life.

In developing this plan and requirements, special attention should be paid to the following:

a. The need to add additional or adjust existing design and verification requirements to address design, ground, and flight conditions that are not bounded by previous design and operational experience. An example may be the use of liquid hydrogen as a propellant. Reusable, flight-weight liquid hydrogen propellant tanks have not been previously used in flight systems. As a result, specific new design criteria to address internal heat transfer, differential thermal expansion, internal cavity venting of hydrogen gas, etc., may be needed.

b. The availability of affordable ground and flight test methods to verify the airworthiness of the flight system. A fundamental precept of the system integrity approach is that the analytical prediction of the integrity of the proposed system design can be verified through affordable ground and flight testing. For example, if the thermal protection system is to use primary structure as part of the thermal protection system, as was used in the X-15, then the system integrity plan must identify how the primary structure's ability to resist the combination of time-dependent aerodynamic, thermal, inertia, and, perhaps, acoustic loads without failure, unacceptable deformation, or wear can be affordably tested within the development program's proposed budget and schedule.

c. The availability of test instrumentation suitable for measuring the external loads and internal strain/temperature environments of the reusable space access system during ground and flight testing. Advanced flight systems, particularly those operating in extreme thermal and acoustic environments, often encounter significant problems with locating, relocating, installing the wiring for, and maintaining the operation of ground and flight article instrumentation. For this reason, the design of the reusable space access system should be reviewed to ensure that the installation of the test instrumentation and access to the locations where critical loads need to be measured, to complete the test verification of the integrity of the design, can be implemented.

d. The ability to establish the proper functioning of replacement components after the flight system has been repaired or upgraded. Traditional engineering practices do not place safety-critical subsystems back into operation until the subsystem's proper functioning has been demonstrated. Replacement or repaired jet engines, for example, are tested on the ground, after their installation on the aircraft has been completed, prior to returning the aircraft to flight status. For a reusable space access system, provisions for ground testing the main and secondary propulsion systems, secondary power, active thermal protection systems, etc., should be addressed in the design of the system and the planning of its maintenance and repair capabilities. In some cases, such ground testing may establish critical design conditions for the subsystems as well as the full system.

Section 8: An Example Near-Term Reusable Space Access System

As part of the aforementioned Air Force studies of options for reusable space access systems, the conceptual designs of several near-term, fully-reusable systems were completed. Figure 13 illustrates one of these systems configured to operate unmanned carrying cargo in an external cargo container or transport passengers in a small 6-10 passenger spaceplane carried in place of the cargo container. With an estimated gross weight of approximately 2.7 million pounds, the estimated payload performance of this system is shown in Figure 14. A detailed description of the conceptual design of these systems is contained in Reference 38.

The fielding of two types of near-term, reusable space access systems—with three operational systems of each type for assured space access—would have a flight capacity of approximately 150 missions per year when each system flies once every two weeks. This would be sufficient to launch U.S. government and commercial satellites, transport astronauts and supplies to the International Space Station, and provide about 100 flights each year to support a commercial space hotel and expanded human space operations. This fielding of two design-independent types of reusable space access systems would provide an assured space access capability to both support critical U.S. government missions and to provide an assured capability to evacuate personnel from the International Space Station and similar on-orbit space habitats should an accident ground one of the two types of reusable space access systems.

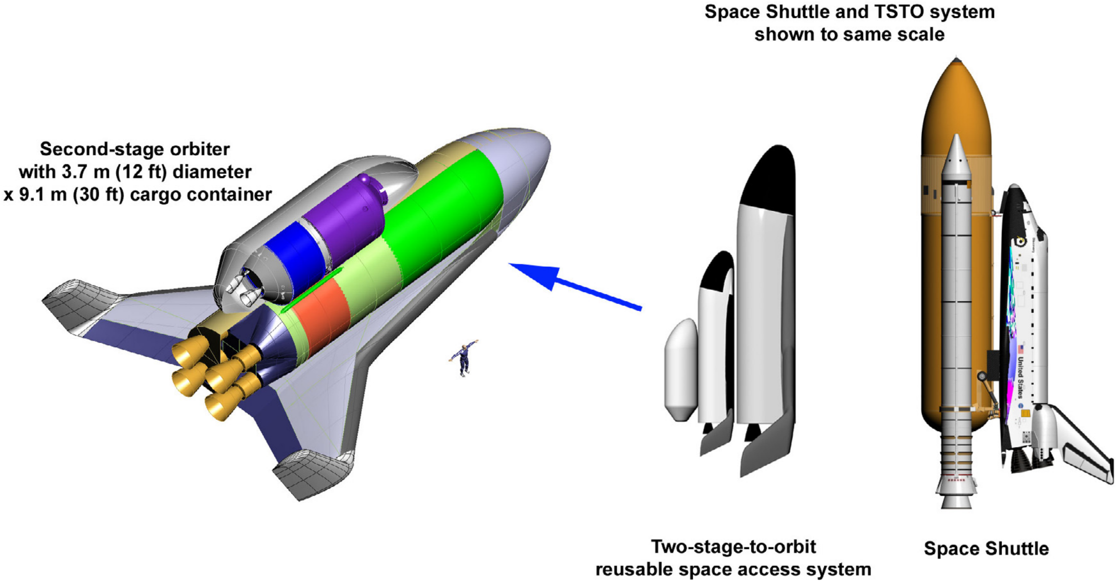

Figure 13. Comparison of the Space Shuttle to a near-term, fully-reusable, two-stage space access system (Courtesy: Air Force Aeronautical Systems Center).

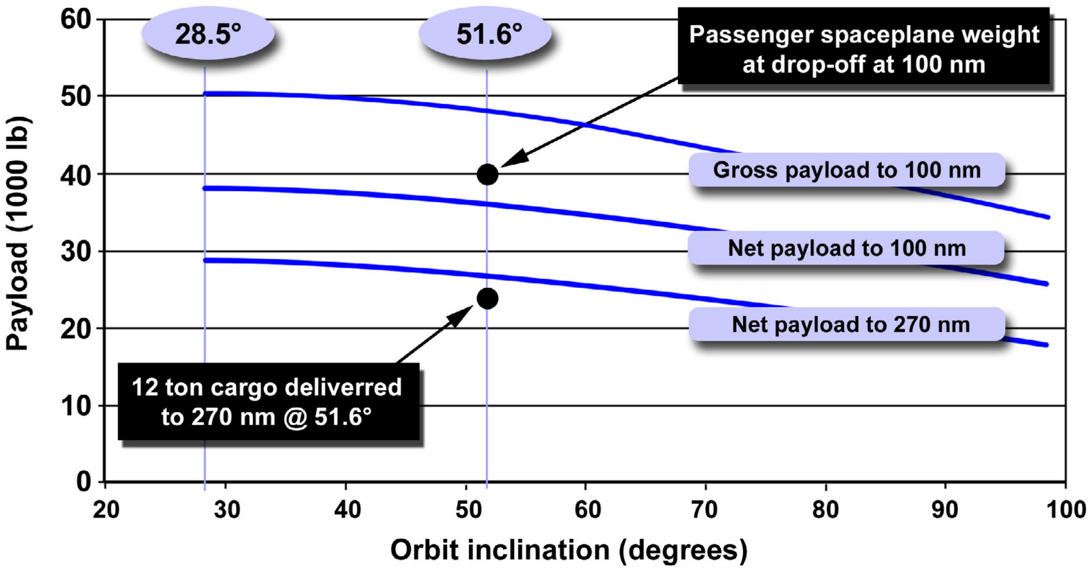

Figure 14. Estimated performance of the near-term, two-stage-to-orbit, fully-reusable space access system shown in Figure 13.

Section 9: Conclusion

The idea of developing reusable space access systems with aircraft-like safety and operability can be traced back to the early concepts of Austrian Eugene Sänger in the late 1920s. These efforts were matured in Germany in the 1930s and then brought to the U.S. in the 1950s. They formed the core of the projected U.S. manned space program in the late 1950s and were evident in the X-15, X-20 DynaSoar, and initial Aerospaceplane programs of the late 1950s and early 1960s. Unfortunately, political and national security circumstances of the late 1950s and early 1960s forced the U.S. prematurely into space using expendable launch systems. Yet, to become a true spacefaring nation, the capability for routine and safe access to and from space for passengers and cargo must be established. This paper has addressed three issues related to establishing this capability.

First, safe and routine space access for passengers can only be achieved using fully-reusable space access systems. Only fully-reusable space access systems can be placed into operational service with the explicit knowledge that each production system is airworthy.

Second, the design, production, verification, and operation of the fully-reusable space access systems should be undertaken using aircraft-style systems engineering principles and practices. Specifically, the current military aircraft systems integrity processes should be used to guide the identification of the reusable space access system's engineering principles and practices that will lead to airworthy space access systems. Any successful development of reusable space access systems must draw primarily upon the successful design heritage of military and commercial aircraft.

Finally, recent government conceptual design studies have identified closed designs of fully-reusable, two-stage, vertical takeoff and horizontal landing space access systems with performance suitable for passenger and cargo transportation. These conceptual designs were completed using TRL 6-9 technologies demonstrating that developing and fielding such a system is a near-term possibility.

In closing, it is worth reflecting back on the early days of the first-of-its-kind Space Shuttle program. Many of the safety, performance, and operational "promises" addressed in this paper for fully-reusable space access systems are similar to those discussed during the early days of the Shuttle program. Unfortunately, many budgetary and programmatic issues, as well as technical issues, emerged in the Shuttle program that impacted the ability to deliver on those earlier promises. Yet, to put things into perspective, this was a time before pocket calculators. Nearly forty years of further aerospace technology development—in particular the emergence and maturing of the aircraft damage tolerance and durability integrity criteria—have occurred. Also, we have the advantage of the substantial experience and expertise existing today that did not exist when the Shuttle program began. It is time to look ahead with our expectations and to act with confidence in what can now be accomplished. It is time to begin to develop the type of reusable space access systems necessary for the United States to start to become a true spacefaring nation.

Acknowledgements

The author wishes to acknowledge the critical work undertaken by the United States Air Force's Aeronautical System Center's Engineering Directorate. The conceptual design analysis capability developed by their Aerospace System Design & Analysis Group has been instrumental in being able to analyze current industry capabilities for developing near-term, fully-reusable space access systems. In particular, the efforts of John Livingston, Alicia Hartong, Brendan Rooney, and Barry Hellman to develop and validate the conceptual design and performance models for these reusable space access systems have been crucial in understanding near-term opportunities for improving space access.

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