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Can We Fly it? Yes We Can: A Comparative Study of Military Airworthiness and Flight Operations

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The objective of this paper is to highlight the similarities and differences between the MIL standard way to certify and operate aircraft and the civilian FAA based 14 CFR system in the United States. Like commercial transport regulation, military aircraft regulation has ensured safety, reliability, and progress within the field. Understanding how regulatory action operates for military aircraft further shows that the many documents that are created serve a great purpose for organization and safety. In this work, we survey the historical evolution of certifying rules in structures, flight sciences, instrument calibration and pilot operating rules. Key differences among military and civilian regulations are illuminated in these areas by us. We discuss, as case studies, the Bell X-1, the North American X-15, and the Boeing KC-46. Whether for Military or Civilian operation, it is imperative to correctly and accurately construct an airworthy vehicle for safety measures.

I. Introduction

IN FISCAL 2022, the United States Federal government budgeted the Air Force to spend $156.3 billion.[1] This 2.3% increase over 2021 is partially due to the Russo-Ukrainian War; it expedites the development of a new generation of munitions, fighters, and other high-performance aircraft.[1] With the renewed push to develop next-generation military aircraft, we became curious as to the distinctions in basic aircraft design and operations between civilian and military use. Clearly, military aircraft may contain weapons, systems, and subsystems (like missile countermeasures) that civilian aircraft lack. But, beyond this, we were curious as to document the distinctions in basic design standards for airworthiness and flight operations between United States civilian and military aircraft.

In this work we seek to understand how military or other governmental aircraft fit into the legal framework of 14 CFR, which broadly regulates aeronautics and space within the United States.[2] We muse over what regulations were considered when we first went to the moon? What rules must Air Force airmen follow when conducting a flyby over a football game?

In this work, we discuss the legal boundaries, rules, and regulations of US military aircraft and space operations. What follows will highlight groundbreaking events in military aviation/space exploration history along with interesting aspects of operations – routine and special. We also will rely heavily on the United States Code of Federal Regulations (CFR), as well as military standards and handbooks to further our discussion.

When analyzing any given aircraft, the authors tend to use civilian transport-category standards (14 CFR § 25) and flight operations rules (14 CFR § 91 and 14 CFR § 121) as a common benchmark.[3][4][5] Commercial transport aircraft share similar design qualities with general aviation and military aircraft; transport category aircraft make up the highest volume of daily air transport. We tend to view 14 CFR § 23, airworthiness standards for general aviation aircraft as a modification of basic transport category rules.[6] Similarly, the 14 CFR § 121 and 14 CFR § 135 airline flight operations rules that place additional burdens upon "common carriers" – generally enhancing safety margins – all build upon the foundation of basic 14 CFR §91 flight rules.[7][8]

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Civilian aircraft designers may have some passing familiarity with aspects of military aircraft design. For example, 14 CFR § 25.603 states that "the suitability and durability of materials used for parts, the failure of which could adversely affect safety, must … conform to approved specifications (such as … military specifications …) that ensure their having the strength and other properties assumed in the design data."[9] Thus, most civilian aircraft designers are familiar with MIL-HDBK-5 for materials properties of traditional steel, aluminum and high-temperature alloys.[10] Many other civilian aircraft designers work under a systems engineering architecture (SRR, PDR, CDR, FRR) standard derived from MIL-HDBK-881 ("Work Breakdown Structures") and MIL-HDBK-245 ("Statements of Work").[11][12] Those of us who work in flying qualities may find the flight dynamics standards found in 14 CFR § 25 (and especially in 14 CFR § 23) excessively vague; and turn to MIL-STD-8785C and/or MIL-STD-1797A for solace to assist determining the configuration that produces superior stability and control characteristics.[3][6][13][14]

Beyond these few examples, civilian aircraft designers (either transport or general aviation) may not be aware of the largely parallel body of MIL-STD and MIL-HDBKs which govern the "law" of military aircraft design. We thus see that familiarity with general aviation law may not be the same for military aircraft regulation. Some aspects of military aviation are completely outside of the FAA's jurisdiction, whereas the FAA has complete jurisdiction over general aviation. Aircraft with different purposes will differ in how they are regulated for flight and the key, substantial differences that military aircraft have are important for this paper.

In addition, there are a number of aircraft extant that blur the line between civilian and military design.

For a minimum change aircraft, the basic airframe is shared between civilian and military versions while flight manuals and other operational documents may vary. Two examples of this include the Lockheed LM-100, a civilian certified (minimum-changes) derivative of the C-130 military transport; see Fig. 1. We may also consider the Beechcraft C-12, a military derivative (minimum-changes) of the Beechcraft Super King Air 14 CFR § 23 general aviation transport; see Fig. 2.[15][16]

Fig. 1 Lockheed LM-100J(C-130J derivative) Commercial Freighter.[15]


Fig. 2 Beechcraft C-12 (B200 Super King Air Derivative) military transport.[16]


Fig. 3 McDonnell-Douglas KC-10 Extender (DC-10 Derivative) tanker.[17]


Fig. 4 Boeing KC-46A Pegasus (B767 derivative) tanker.[20]

Other aircraft have substantial changes, but with differing certification basis.

Consider the McDonnell-Douglas KC-10 tanker, a major change to the DC-10 airliner; see Fig. 3. We understand, per FAA Type Certificate Data Sheet A22WE that the KC-10 is a DC-10-30F Transport Aircraft originally built as a civilian conforming airframe, with FAA operational limits adjusted to consider the installation of the in-flight refueling boom. To quote the TCDS, "KC-10A airplanes are tanker/cargo versions of the Model DC-10-30F."[18] The FAA recognizes that "the maintenance, overhaul and modifications records of each aircraft must be reviewed for changes made by the military services that may affect the [civilian] airworthiness of the aircraft."[18] "Modifications, changes of equipment and repairs, which affect the safety or performance of the aircraft, must be approved by the FAA."[18] The FAA also notes that deviations from the FAA approved type design must be filed on "FAA Form 8130-2, "Conformity Certificate - Military Aircraft".[18] The KC-10A is flown to a special military standard flight manual, which includes adjustment factors (Drag Index) for external stores, military-style runway conditions (RCR), elevated takeoff and touchdown speeds, and takeoff critical field length taking credit for reverse thrust; none of these procedures are covered in a standard FAA approved manual.[19]

Also consider the Boeing KC-46A Pegasus, a derivative of the B767 airliner; see Fig. 4. Boeing states that the "KC-46A design uses a modified Boeing 767-200ER commercial airframe with numerous military and technological upgrades, such as the fly-by-wire refueling boom, the remote air refueling operator's station, 787 cockpit displays, additional fuel tanks in the body, and defensive systems."[21] The KC-46A combines "the 767-200ER's fuselage, with the 767-300F's wing, gear, cargo door and floor, with the 767-400ER digital flightdeck and flaps".[21] As we will see later in this paper, the USAF has gone out of its way to retain full FAA certification of the KC-46A.

II. Some Distinctions Between "Common Carrier", "General Aviation" and Military Aviation

Commercial air transport differs from private or military aviation through thousands of years of legal precedent regarding paid carriage. If a fare-paying passenger of the general public boards an aircraft and is hurt because of careless operation or substandard condition, who pays the injured party? Tradition holds that the operator was held liable for damages unless extenuating circumstances were proven.[22] For example, the 13th Century Rules of Oléron holds "…if by the master's orders and commands any of the ship's company be in the service of the ship, and thereby happen to be wounded or otherwise hurt, in that case they shall be cured and provided for at the costs and charges of the said ship."[23] Thus, tradition requires those offering paid carriage to provide a heightened duty of care, beyond any basic contract.

A Common Carrier is any commercial transportation service that holds itself to the public as being in the direct business of carrying passengers or cargo. They are "legally bound to carry all passengers or freight as long as there is enough space, the fee is paid, and no reasonable grounds to refuse to do so exist."[8] Common Carriers, like Airlines, are especially liable for equipment safety and reliability. The law demands that a Common Carrier design, maintain and operate their vehicles in a safe manner, avoiding negligence at every turn. Thus, we will see that the typical transport aircraft, designed to 14 CFR §25 engineering standards and flown under 14 CFR §121 or 14 CFR §135 rules, will typically offer additional safety margin compared to civilian private or military aircraft.[3][5]

III. Civilian vs Military Airworthiness Certification - Structures

An example where the FAA is "hands off" is in purely military aircraft airworthiness certification.

Aircraft airworthiness certification is official documentation and approval that an aircraft design can be produced and used for its purpose. For all branches of the military the guidelines for aircraft airworthiness certification are the MIL-HDBK-516C.[24] The Department of Defense handbook outlines all design regulations for fully military operational use aircraft, including sections on systems engineering, structures, propulsion, and passenger safety. In 2014 it was updated from and supersedes MIL-HDBK-516B. Each section is organized similarly to 14 CFR § 25, which governs the airworthiness of transport aircraft. An aircraft like a Lockheed F-22 has no civilian certification; it was designed purely to military airworthiness standards; see Fig. 5.

Fig. 5 F-22 Raptor executing a 'Power Loop' maneuver. The aircraft experiences high structural stress and load factors during sharp maneuvers.

When comparing these regulations against each other, we see major discrepancies between commercial transport aircraft design practice in in the "STRUCTURES" section of the MIL-HDBK-516C.[24] One of these deals with subsection 5.1.7 "Analysis and testing of realistic flight loading conditions".[24] Statement 5.1.7(b) details that an aircraft's roll rate must be acceptable throughout an 80% symmetric nZ_{max} maneuver within the specified flight envelope, where symmetric nZ_{max} is the maximum load factor on the aircraft structure attained during a maneuver that is symmetric with respect to gravity. Statement 5.1.7(d) limits the asymmetric nZ_{max} to "80 percent (100 percent for rotorcraft)" for all asymmetric maneuvers. These are defined as "level flight rolls, elevated-g rolls, rolling pull-outs, aerial delivery rolls and takeoff/landing approach roll".[24] These criteria stand for all military aircraft. More specifically for different aircraft types, statement 5.1.7(c) requires at least a "50 degrees per second roll rate command for A (attack aircraft), F (fighter aircraft), TF (trainer/fighter aircraft), O (observer aircraft) and T (trainer aircraft) fixed-wing aircraft and 30 degrees per second for all other fixed-wing aircraft."[24] In contrast, for commercial transport aircraft, 14 CFR § 25.333 details the acceptable load factor range as a function of the aircraft's equivalent airspeed, which is the airspeed that takes into account the atmospheric pressure at a given altitude.[25]

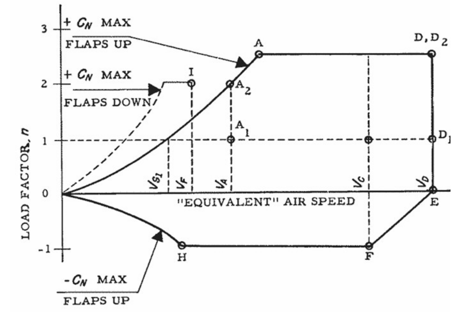

Fig. 6 Load factor diagram for certified commercial transport aircraft. The solid black lines represent the acceptable envelope according to airspeed.[25]

Fig. 7 AH-64 Apache helicopter inside a C-5 Galaxy. Different requirements drive different designs. Sometimes they are even transporting other aircraft.

This range is presented in a Load Factor Diagram, where V_{S_1} corresponds to the stall speed with flaps retracted, V_F is the design flap speed, V_A is the design maneuvering speed, V_C is the design cruise speed, and V_D corresponds to the design dive speed; see Fig. 6.[25] For commercial transport aircraft, rolling conditions, the regulations state that "conditions corresponding to steady rolling velocities must be investigated. In addition, conditions corresponding to maximum angular acceleration must be investigated [as well]". Furthermore, for V_A, V_C, and V_D speeds the aircraft must achieve a roll rate corresponding to a load factor of zero and a maneuvering load factor of two-thirds of the designed value.[26]

From this we see that the MIL-HDBK-516C is more relaxed than 14 CFR § 25 in defining acceptable structural load factors.[24][3] Because of this, it is important to note that military aircraft serve a much different purpose than transport aircraft. This is true across several types, as we saw above. As commercial transport aircraft are generally fixed, with slight changes in their overall design from year to year, it is easier to define structural safety limits more accurately for them. Many military aircraft are designed for specific, unique attributes. For example, the roll rates and maneuverability for military aircraft are more well-defined as these parameters are not as important in commercial transport.

Any aircraft design is driven by its requirements. Military aircraft design presents a wide range of these requirements, resulting in many designs. For example, velocity and maneuverability requirements for fighter aircraft control their design space. This leads to fighter jets and attack vehicles having a slender design and qualities that are engineered for specific missions. Stealth aircraft are designed in a similar way, but with the main requirement of having a low radar cross-section in the air. This makes them noticeably different in design. Military cargo and old bomber aircraft are designed most like commercial aircraft in comparison. This is because their requirement is to transport large payloads across far distances while being fuel efficient. Same requirement as commercial transport aircraft, except for the payload type. These aircraft can carry armaments and munitions; some are even designed to carry nuclear weapons; see Fig. 7.

In MIL-HDBK-516C, the regulations for the integration of armaments are a unique set of rules that only apply to military aircraft.[24] Section 17 of the handbook outlines these in four subsections titled "Gun/rocket integration and interface", "Stores integration", "Laser integration", and "Safety interlocks", where "stores" refers to "missiles, rockets, bombs, nuclear weapons, mines, fuel and spray tanks (permanently attached and/or detachable), torpedoes,[etc.]".[24] An armament is certified after passing a plethora of certification source data, which varies from type to type, but is generally around forty documents and tests.

Official testing procedures, which agree with the regulations, can be found in other military handbooks and standard documents. For example, the integrations of guns and rockets on an aircraft must be certified through testing procedures described in the MIL-HDBK-1763.[27] Tests are performed to ensure that the aircraft using guns and/or rockets is safe in the action of firing the armaments. Several key safety areas are clearly defined in the MIL-HDBK-516C, starting with "Gun/rocket induced environments". This section states that the military must "verify that environment induced by gun/rocket operation is compatible with the air vehicle's limitations for muzzle blast and overpressure, recoil, vibroacoustics, cooling, egress, human factors, and loads of the air vehicle."[24] The main hazards of gun/rocket gases are buildups from explosive gases, gases near the proximity of the engine, and detonation at a safe distance from the vehicle.[24] Accidents involving guns and rockets near an aircraft are a danger to the people on board.

Continuing with armaments, the subsection on "Gas impingement" regulates the erosion of aircraft skin and systems from armaments to an "acceptable" rate, which is defined in separate handbooks.[24] Although the environmental impact of firings is disregarded among certification standards, there are safety boards reviewing the certification of armaments. Some examples are the Non-Nuclear Munitions Safety Board, the Weapon System Explosive Safety Review Board, the Developmental Test and Evaluation, and the Operational Test and Evaluation; see Fig. 8.

Fig. 8 A-10 Warthog experiencing heavy gun smoke after firing. The smoke erodes the skin and more dangerously can flame out the engines.

Fig. 9 Example of internal and external weaponry on an F-22 Raptor.

Moving on to how the armaments are stored, they must be integrated either internally or externally on the vehicle so that safe conditions for takeoff, landing, and desired in-flight maneuvers are still met; see Fig. 9. Whether mounted underneath the aircraft wing or on the fuselage or internally located prior to firing, the military must ensure that "clearance between store and surroundings […] is sufficient to allow for stores loading, aircraft/munitions servicing, in flight vibration and deployment without contacting air vehicle."[24] Transitioning to when the armament is fired, the "Safe separation" subsection outlines regulatory action to certify that the armament does not endanger the aircraft that fires it immediately upon firing.[24] The goal is to prevent any dangers to the engine, surface, or aerodynamic loads and moments. This is done by "Computational Fluid Dynamics (CFD) models, wind-tunnel testing, safe separation flight testing, and requirements of MIL-STD-1289 and guidance specified in MIL-HDBK-244 and MIL-HDBK-1763".[24] The US Air Force happens to have their own certification and testing for stores integration under the SEEK EAGLE program (AFSEO). Their purpose is to use simulations, wind tunnel, and flight test data to analyze the safety and effectiveness of a store (weapon, countermeasure, equipment, etc.).[28] These criteria blend with non-firing situations such as jettisoning and work hand-in-hand with structural integrity, induced environments from stores, and store malfunctioning safety regulations. This shows that stores certification is based around situations where the store is either on the aircraft or in close proximity, including its induced environment after being fired/jettisoned. Where the stores end up going is outside of the certification jurisdiction and is then based on measures of effectiveness

Fig. 10 Boeing YAL-1 with laser integrated testbed. It successfully destroyed an ICBM in 2010 and was eventually scrapped. Its technology, test data, and applicable regulations will be very valuable for years to come.

Fig. 11 Air Force engineer testing a laser weapon in a wind tunnel. The laser is to be installed on fighter jets.

and performance. Involving many different types and presenting a crucial safety challenge, stores certification is one of the most important certifications in military aircraft.

The next certification topic discussed for armaments and stores integration is "`Laser integration`".[24] Until recently, the use of lasers for military warfare applications was a science-fiction dream. There is now a high chance that within the next couple of decades we will see laser weapon systems deployed. Specifically, airborne laser weapon systems were first tested by the Air Force in 2010. The aircraft that conducted the integrated laser test was known as the Boeing YAL-1 – a modified version of the military Boeing 747-400F; see Fig. 10. In a test to successfully destroy a ballistic missile near Edwards AFB in California, the YAL-1 "fired its beam which heated the target missile's surface causing it to fail."[29][30][31] The realization of laser weapon effectiveness drove aerospace defense company Lockheed Martin to recently engineer their own airborne laser weapon system, which was delivered to the Air Force Research Laboratory in February of 2022; see Fig. 11.[32]

With technological advancement being inevitable, MIL-HDBK-516C has prepared a set of guidelines for laser weapons integration on military aircraft.[24] As these were likely created for the YAL-1, we expect them to be more prevalent in the coming years. Most of the regulations are similar to those for armaments, however laser weapons are a different class of weaponry and require emphasis on a few unique areas. One of these is radiation exposure to crew and maintenance personnel. Laser weapon systems are to be thoroughly tested and inspected before implementation in the armed forces.[24] Labelled as the "foundation of laser safety programs for industry, military, research and development", the ANSI Z136.1 is a non-government document that outlines key safety and testing procedures for lasers.[33] It is prominent in regulation, as classic military handbooks and standards do not address laser weaponry.

When fired in flight, byproducts of lasers are chemical and exhaust gases. The main focus on these is their respective chemical concentrations not exceeding safe values. Other qualities of focus are to ensure that the crew can tell when the laser is operating and which direction it is operating in, that the crew has full authority over laser operation and direction, and that the laser has no chance of incidental contact with the airframe of the operating aircraft. A very important regulation that completes "`Laser integration`" is "`Ground lasing`". This subsection of MIL-HDBK-516C addresses safety mechanisms used to ensure that the laser cannot fire while the aircraft is on the ground.[24] Any type of armament, lasers included, is and will be thoroughly reviewed by the respective branch of the military, using the MIL-HDBK-516C and the according supporting documentation on a case-by-case basis.

IV. Military Flight Operations – Airspace

Airspace requires standard designations for flight speed and altitude. All United States aviation sectors agree on how speed and altitude is displayed in the cockpit and communicated. This allows for clarity with Air Traffic Control for any aircraft. Airspeed classification begins with a standard ground track distance, the nautical mile. Adopted from naval navigation, nautical miles are defined as "`one minute of change of latitude anywhere on the earth and one minute of change of longitude at the earth's equator.`"[34] This customary distance is translated into velocity as knots indicated airspeed, KIAS, where a KIAS of 250 is equivalent to 250 nautical miles per hour. It considers how pressures drop with increasing altitude. Thus, flying at the same ground speed with a higher altitude results in a lower indicated airspeed due to the drop in dynamic pressure q. 14 CFR § 25.1303 requires an airspeed indicator in commercial aviation.[35] The MIL-STD-1303B also states that this is the accepted norm for military aircraft. On most post-WWII aircraft velocity is displayed in the cockpit as KIAS, while it is imperative for high-performance aircraft to also feature a Mach meter. It is also required in 14 CFR §

25.1303 for "airplanes with compressibility limitations" to present a Mach meter.[35] A Mach meter displays the speed that the aircraft is traveling at with respect to the speed of sound at a given altitude. A Mach number of 1 is equivalent to traveling at the speed of sound at a given pressure altitude. Mach meters are common in military aircraft, as many are capable of flying in the supersonic, and even some in the hypersonic regime. At these speeds, a Mach meter is one of the most important tools for a pilot.

Both airspeed indicators and Mach meters are calibrated in flight test of an aircraft. This is where the US military is distinctive. According to *Pitot Statics and the Standard Atmosphere* by Russell E. Erb, to calibrate the velocity instruments the test must be performed on a day with calm winds.[36] This is because any sideslip experienced by the aircraft delays the airspeed calculation from the starting point to the ending point; see Fig. 12. The testing equipment cannot account for this, as the pitot-static tube connected to the aircraft is trailing in-line with it.[36] Another source of error in testing is calibrating the temperature system. De-icing the aircraft before flight affects the temperature probe and creates calibration issues. Likewise, in the words of Erb, "IT IS IMPOSSIBLE TO MEASURE AMBIENT AIR TEMPERATURE IN FLIGHT!"[36] Thus, we can only determine the air temperature with correction factors for surface heating. When the aircraft is in motion, the temperature probe is heated by the airflow, resulting in there being no way to measure the ambient air temperature directly. Once a proper testing environment is established and testing has begun, the military has specific methods for calculating the calibrated aircraft velocity, and subsonic and supersonic Mach numbers. First, using the temperature system, the altitude-dependent speed of sound is calculated from Eq. (1):

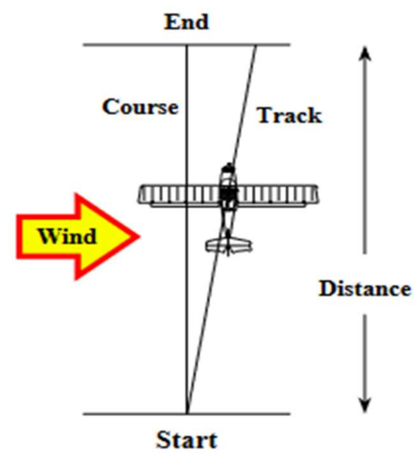

Fig. 12 Sideslip winds divert the aircraft off course and lead to miscalibrations in the speed instrumentation.[36]

$$a = \sqrt{\gamma R T_a} \tag{1}$$

Here T_a is the ambient air temperature. The equation is used to find the true and equivalent airspeeds in Eqs. (2) and (3).

$$V_t = Ma \tag{2}$$

$$V_e = V_t\sqrt{\sigma} \tag{3}$$

Above, σ is the density ratio of the ambient air. The Mach number appears in Eq. (2), but how do we know what that is equal to in real time during instrument calibration? This will be addressed below when a complete set of equations is established.

To obtain calibrated airspeed it is customary to use a table of pressure correction factor f values. These account for the pressure difference as a function of both airspeed and altitude that the calibration system is otherwise unable to accurately calculate on its own; see Fig. 13. Erb presents these pressure correction factor values in Table C1 of the 4th edition. The relation between equivalent and calibrated airspeed is shown below in Eq. (4).

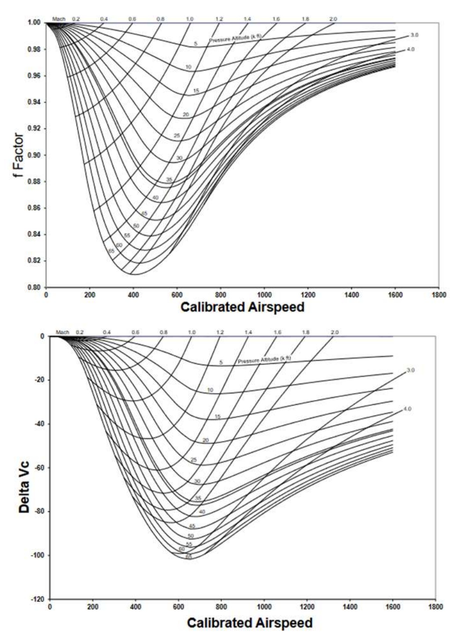

Fig. 13 Carpet plots of calibrated airspeed and the pressure correction factor f and ΔV_c as functions of the flight Mach number and pressure altitude. While interpolated, f and ΔV_c make it possible to determine airspeed.[36]

$$V_c = \frac{V_e}{f} \tag{4}$$

As $f \leq 1$, calibrated airspeeds "should generally be greater than equivalent airspeed."[36] The approximations of this method start to pile up in the subsonic and supersonic Mach calculations in Eqs. (5) and (6) below. Erb states throughout his work that if the air speed indicator in the cockpit only reads to the nearest knot, then the calibration techniques are sufficient to be accurate to the nearest knot.

Table D2 from Erb's work is shown to the right.[36] Using Taylor Series expansion to calculate the flight altitude error, we see that the errors can be rather large at a given calibrated airspeed position error ΔV_{pc} and instrument corrected indicated airspeed V_{ic}. The "1 term % Error" and "2 term % Error" columns correspond to terms of the Taylor Series expansion. Erb notes that there are times where only one term in the Taylor Series is used for military flight test instrument calibration, which is highly inaccurate at airspeeds less than 500 knots compared to using two terms. Calibrated airspeed position error will generally increase with increasing calibrated airspeed, so as an example let's use a ΔV_{pc} of 2% of the calibrated airspeed. At 300 knots, this corresponds to a ΔV_{pc} of 6 knots. Interpolating the % Error results in a 1 term % Error of **-2.11%** and a 2 term % Error of **-1.22%**. Now let's test this at 800 knots. A 2% ΔV_{pc} of 800 knots is 16 knots. The respective 1 term and 2 term Errors are now **-7.74%** and **-6.50%** after interpolating. What a massive jump! This becomes a problem with high-speed flight testing. Although historically with supersonic and hypersonic experimental military aircraft, it is desired to calibrate flight instruments in a wind tunnel. Solving the sideslip testing issue discussed above, this method was preferred over traditional drogue testing; see Fig. 14. However, drogue testing is always performed in military calibration applications as a baseline procedure.[37] We notice that Erb only provides position errors and not distinct calibration errors as a function of known variables. But the errors go hand-in-hand using calibration instrumentation on the aircraft in flight. To combat this, an alternative is to track ground speed via GPS navigation. The ground speed error of GPS is approximately 0.19 knots. This is less than our desired accuracy of 1 knot, but the conversion from ground speed to airspeed presents glaring inaccuracies otherwise.

Table 1 Sea Level Position Altitude Errors

Vc knots	ΔVpc knots	Vic knots	1 term % Error	2 term % Error
100	0	100	0	0
	10	90	-5.66%	-0.32%
	20	80	-11.81%	-0.62%
	30	70	-18.56%	-0.91%
	40	60	-26.04%	-1.18%
	50	50	-34.41%	-1.43%
300	0	300	0	0
	10	290	-3.02%	-1.04%
	20	280	-5.98%	-2.04%
	30	270	-8.88%	-3.01%
	40	260	-11.74%	-3.94%
	50	250	-14.56%	-4.83%
500	0	500	0	0
	10	490	-3.51%	-2.03%
	20	480	-6.82%	-3.95%
	30	470	-9.96%	-5.76%
	40	460	-12.93%	-7.48%
	50	450	-15.77%	-9.11%
600	0	600	0	0
	10	590	-4.08%	-2.71%
	20	580	-7.87%	-5.22%
	30	570	-11.40%	-7.57%
	40	560	-14.71%	-9.76%
	50	550	-17.82%	-11.81%
700	0	700	0	0
	10	690	-4.63%	-3.50%
	20	680	-8.94%	-6.66%
	30	670	-12.97%	-9.53%
	40	660	-16.77%	-12.12%
	50	650	-20.37%	-14.45%
800	0	800	0	0
	10	790	-5.00%	-4.22%
	20	780	-9.56%	-8.02%
	30	770	-13.73%	-11.47%
	40	760	-17.58%	-14.61%
	50	750	-21.14%	-17.47%

With velocity defined, the expressions for the dimensionless pressure ratio δ depend upon whether one flies below or above the tropopause:

$$\delta = (1 - 6.87559 * 10^{-6} H_c)^{5.2559} \qquad \text{If } H_c \leq 36089\ ft \tag{5a}$$

$$\delta = 0.223360 e^{[-4.80637*10^{-5}(H_c - 36089.24)]} \qquad \text{If } H_c > 36089\ ft \tag{5b}$$

From this we can determine the Mach number:

$$M = \sqrt{5\left[\left(\frac{1}{\delta}\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{7/2} - 1\right\} + 1\right)^{2/7} - 1\right]} \tag{5c}$$

$$M = 0.881284\sqrt{\left(\frac{q_c}{P_a} + 1\right)\left(1 - \frac{1}{7M^2}\right)^{5/2}} \tag{6}$$

In the above equations, H_c is the pressure altitude, a_{SL} is the sea level speed of sound (661.48 knots), q_c is the differential pressure, and P_a is the ambient air pressure. Eqs. (5a) to (5c) represent the subsonic pressure ratio and respective Mach calculations, where the Mach number is based on the calibrated velocity. For supersonic calibration, Eq. (6) must be used when the measured $\frac{q_c}{P_a} > 0.89293$ which designates supersonic, fully compressible flow. Erb tells us that "the sharper ones in class immediately recognize that [Eq. (6)] is not explicit in Mach number."[36] This equation cannot directly measure the flight Mach number and errors propagate as $M \to \infty$. We will find an alternative to this below. In all of this discussion, the calibrated velocity is our desired measurement, and is trapped in Eq. (5c) above. In modifying Eq. (5c) to obtain Eq. (7), this is how the US military calculates calibrated subsonic airspeed in flight instrument testing and supersedes the method in Eq. (4).

$$V_c = a_{SL}\sqrt{5\left[\left(\frac{q_c}{P_{SL}}+1\right)^{2/7}-1\right]} \quad (7)$$

For supersonic airspeeds, Eq. (7) is modified and is implicit in V_c, so it must be solved for by iteration at these speeds. With V_c solved for in calibrating the indicated airspeed dial, we now need an equation that the Mach meter uses in its calibration.

$$M = \sqrt{5\left[\left(\frac{q_c}{P_a}+1\right)^{2/7}-1\right]} \quad (8)$$

Fig. 14 Static drogue flight instrument calibration testing on an F-18/A. The drogue sags beneath the wake of the aircraft to determine the pressure and temperature of the freestream flow.[38]

We see that Eq. (8) is easily derived from (7). These are the measurement equations that are used in the instrumentation. For subsonic flight, we have a complete set of equations – one corresponding to the airspeed indicator and one corresponding to the Mach meter. They are independent of each other, but both depend on the measured pressure differential from a static pitot probe; see Fig. 14. Referring to Eqs. (2), (3), and (4), it is simple to obtain equivalent and true airspeeds from the measurement equations. Errors in position altitude, calibrated airspeed, and Mach stem from the measurement equations and instrumentation accuracy. In reality, if the cockpit mounted instrument reads exactly 300 KIAS, you are not actually flying at 300 KIAS or 300 KCAS.

Speaking of inconsistencies in the instrumentation, this problem becomes worse for commercial aviation. Their instrument calibration requirements are found in the advisory circular AC-25-7D.[39] Generalized and with no inherent equations, commercial flight instruments lack the same rigor of testing and calibration techniques compared to military! This translates into lesser instrument reading accuracy for the pilots. While acceptable methods of calibration are similar to military testing, including "airspeed boom, static trailing cone, and radar range", the procedure is highly unregulated.[39] This is because commercial testing only requires calibration at five airspeeds within the flight envelope. The lowest speed is not to exceed $1.23V_{SR}$, which is 1.23 times the reference stall speed. The highest speed cannot exceed V_{MO}, which is the maximum operating speed. AC-25-7D defines a reasonable spread of the five speeds tested in § 33.3.2.1.[39]

The FAA does favor operational safety of the airspeed indicator near the plane's stall and maximum operating speeds. An approved calibration must demonstrate that when transitioning from a speed less than $1.23V_{SR}$ to stall warning speed, that the ratio of $1.23V_{SR}$ to the stall warning speed does not exceed 1.33.[39] There is a similar requirement near maximum operating speed, and these two together reveal that the FAA actually places no importance on the accuracy of the value of the stall warning speed, just that it is close enough in relation to stall reference speed. That fully defines climb and cruise speed calibration. There are few error boundaries for this!

The other area of interest in calibration is airspeed lag from the probe to the cockpit. Airspeed lag is a significant issue for takeoff and landing, and the FAA accounts for it in acceptable takeoff V_1 speeds so the pilots can compare in real time. It is defined as the "correction for the range of gross weights and corresponding accelerations at V_1."[39] When the correction is applied, the FAA states that the calculations must not increase takeoff or landing distances by 100 ft or more in any weather or runway condition. During ground acceleration, the error from the airspeed lag should not exceed 3 knots in conjunction with the 100 ft error. There's the answer - the FAA's primary concern is with airspeed calibration consistency for takeoff and landing, to prevent unintentional stall. The following discussion shows that the FAA places a greater importance on altimeter accuracy for the purpose of vertically separating aircraft.

A pilot needs to know airspeed and needs to know altitude, orientation of the aircraft notwithstanding.

Altitude designation is either in feet or flight level. At altitudes less than 18,000 ft above ground level (AGL), the altitude is commonly reported in feet in aviation. At 18,000 ft AGL or above, altitude designation shifts to flight levels. When climbing past 18,000 ft AGL as a pilot, it is required to set the altimeter to 29.92-in Hg for pressure altitude readouts, and vice versa when descending.[40] Flight levels are reported like FL300 for a pressure altitude of 30,000 ft in the cockpit and in the airwaves, for example. These are easily interchangeable with feet for a common understanding across all aviation sectors. They are measured with calibrated pressure altimeters in the aircraft. The preferred model in aviation is pressure altitude for flight level altimeter readings. Pressure altimeters connect to a static probe sensor on the aircraft which uses a static pressure reading to fit the altitude pressure profile. This profile has historically been known as the International Standard Atmosphere (ISA), created in 1962.[31][41] It calculates altitude in feet and is based on several qualities of the static air. It also utilizes a base, sea level "Standard Day" temperature of 59°F to model the atmosphere from this temperature, up. The ISA and flight speed designations apply as stated above, which includes military operations. However, military operations aim to be more cautious with atmospheric models; see Fig. 15.[42] A Hot Day model will assume the sea level temperature as 102.92°F and model the atmosphere accordingly. A Polar Day model assumes sea level temperature as -15.70°F. Like the previous two, a Tropical Day model assumes 89.78°F at sea level with high relative humidity from 95 to 100%.[42][43][44] These are used as the relative temperatures and humidity of the operating climate can change pressure altitude readings significantly.

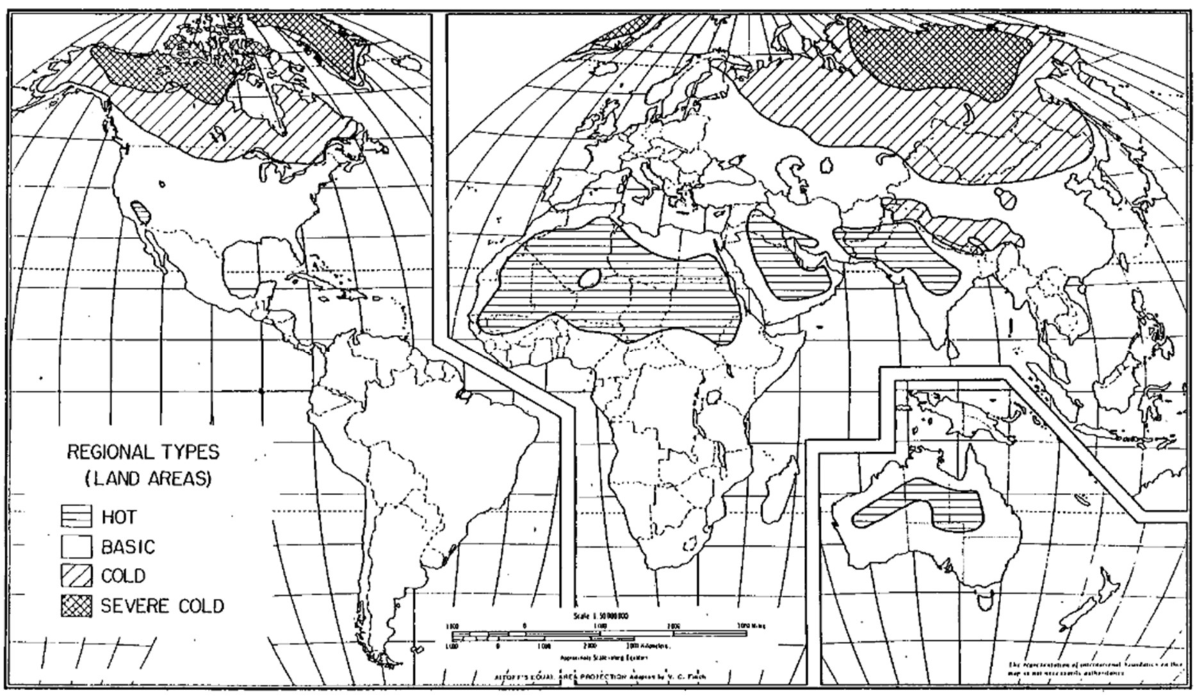

Fig. 15 Region designation from the MIL-STD-210C to account for Standard Atmosphere correction.[42]

Altimeters use the method of pressure altitude in their readings. Calculating pressure altitude requires calibration testing like for airspeed. Altimeter calibration testing doesn't have as much of a runaround compared to airspeed calibration. There are a few acceptable methods that the military uses according to Erb's work.[36]

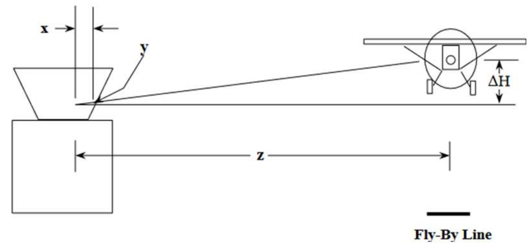

Fig. 16 Tower Fly-By for altimeter calibration. The observer peers through a grid to accurately mark the aircraft's true altitude as it passes.[36]

The first method is a Fly-By; this is demonstrated in Fig. 16.[36] The observer in the tower uses triangulation to determine the true altitude of the aircraft which is compared to the altimeter as the aircraft flies past the tower in steady and level flight. The altimeter can be adjusted based on error. This is the lowest maintenance of the methods. This method also only works at low altitudes, which is not practical for high-performance military aircraft high-altitude calibration. The second method is the Pace method, where an already calibrated aircraft flies in-pace with the aircraft to calibrate.[36] This method works best for similar aircraft that can fly within the same flight envelope. The third method is the Trailing Cone method. This method is exactly like how a drogue would be deployed behind an aircraft to measure airspeed. For altimeter calibration, the trailing cone is fitted with static pressure ports to measure the pressure altitude. The fourth method is to verify the geometric altitude via tracking radars. With prior knowledge of the relationship between geometric and pressure altitude over a certain region, obtaining the true geometric altitude via radar is a useful calibration technique at high altitudes.

With the only in-flight calibration technique being the trailing cone/drogue option, there are only two equations, derived from Eqs. (5a) and (5b), that need to be used to define pressure altitude.

$$H_c = \frac{1 - \sqrt[5.2559]{\delta}}{6.87559 * 10^{-6}} \qquad \text{If } H_c \leq 36089\ ft \qquad (9a)$$

$$H_c = \frac{\ln\left(\frac{\delta}{0.223360}\right)}{-4.80637 * 10^{-5}} + 36089.24 \qquad \text{If } H_c > 36089\ ft \qquad (9b)$$

Since the altitude is based on pressure and the static pressure ports can measure the pressure ratio, we see this is a relatively simple calibration.

Recalling Table 1**,** pressure altitude calibration errors vary dramatically based on airspeed and instrument error. The official error tolerances of the military are not readily available for us to show. But how accurate do the instruments need to be? In both military and commercial transport aircraft, the altimeter reading below 18,000 ft AGL should be accurate to the nearest foot and accurate to the nearest flight level above that height. Across the life of an aircraft, there is no way of trivially knowing if the calibrated instrument is still accurate. For this reason, periodic testing is important.

Commercial transport airworthiness for altimeter calibration is limited to a few sentences in AC 25-7D.[39] In § 33.4.1.1 and § 33.4.1.2 of this advisory circular, the FAA states that it is acceptable to use "`the theoretical relationship between airspeed error and altimeter error […] to derive an altimeter calibration from the airspeed calibration, or vice versa.`"[39] The FAA claims that altimeter accuracy is of the utmost importance. The military demonstrates that altimeter accuracy is of the utmost importance. Again, the FAA lacks credibility in this area by showing no distinct methodology for calibration accuracy.

Military aircraft are used for many purposes at bases around the country and extending around the world. While military bases have their own restricted airspace designated for pilot training, combat maneuvers, and routine operations, certain flight activities require a military operations area (MOA) to cover a larger and desired region; see Fig. 17. US military aircraft are allowed to fly anywhere within the United States. However, these permanent areas must be approved and regulated by the FAA so that flight logging and proper air traffic adjustments can take place, if needed. MOAs are defined by the FAA as "`airspace established outside of Class A airspace`"[45], where Class A airspace is "`from 18,000 feet MSL to FL 600 [18,000 to 60,000 ft], including the airspace overlying the waters within 12 nautical miles (NM) of the coast of the 48 contiguous States and Alaska.`"[45] They are named with short, easily communicated names (usually one word) followed by "MOA" and the two-letter state abbreviation. In defining the MOA, there are some requirements regarding its proximity to the ground and airports. Most often a MOA must not extend below 1,200 ft over land and private airports and 1,500 ft if within a 3-mile radius of a public airport.[46]

Fig. 17 Several cohesive MOAs. Aircraft flying through these must acknowledge them with caution and will be escorted away during testing and training procedures.

MOAs must also be located in a strategic manner. They are to be established within 12-nM of US territory, if extending offshore. It is best advised by the FAA to have MOAs within 100 miles of the base that requests a MOA. This helps with organization and allows for effective communication with the base and air traffic control (7400.2 § 25-1-5). Within the MOA, commercial and private transport aircraft may be routed through the area, if presented with a significant inconvenience otherwise. This is a reason why MOAs are coordinated with the FAA.

If a MOA is needed for temporary use, they can be filed under most of the same regulations. Their use must not exceed 45 days from the date of establishment, and "`the military is responsible for publicizing the exercise within 50 miles of the affected airspace.`"[46] The FAA also states that scheduled, seasonal MOAs should be established as permanent MOAs, as the temporary MOAs have a "single use only" functionality. Otherwise, the regulations are the same as for permanent areas.

If MOAs are for routine training and flight operations, then where do the more extreme military tests get performed? Operations involving the testing of armaments and flight at speeds greater than Mach 1 occur in restricted airspace. For example, Edwards Air Force Base in California has their own R-2508 restricted airspace that has a rich history of experimental aircraft and armament testing; see Fig. 18.[47] The most relevant feature pertaining to this paper of restricted airspaces is the ability to fly supersonically, without special clearance, in them. Designated military airspaces are free from FAA airspace regulations. So military aircraft in restricted airspace have no limits on speed or the sound intensity they produce at high speeds. This is where sonic booms are produced, when aircraft moving in excess of Mach 1 break the sound barrier and emit a sonic boom shockwave from their position in the air, outward. The shockwave travels until it contacts another object, which is ear-shattering near the aircraft. It has a reputation for disturbing structures and breaking windows on the ground. Due to this, restricted airspace is constructed to minimize the impact of sonic booms on society. However, with the growing interest in reintroducing supersonic commercial transportation we are reminded of the sonic boom regulations in 14 CFR § 91.[4] The FAA has long maintained a ban on any aircraft traveling supersonically or having the capability to travel supersonically in its maximum operating Mach number M_{MO} within the United States.[48] The term "within the United States" refers to the mainland United States and Alaska, with an extension of the coastal seas to 12 nautical miles.

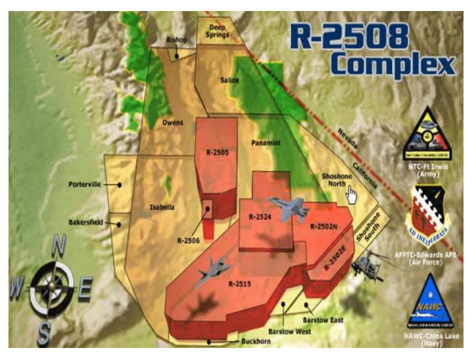

Fig. 18 R-2508 MOA airspace near Edwards AFB.[47]

The “Catch-22” of all of this is that any civil aircraft capable of supersonic flight can apply for FAA special flight authorization for flying greater than Mach 1 over land.[49] However the aircraft must comply with noise regulations, which are very stringent for a large, high-powered engine with afterburners on takeoff. In 14 CFR § 36 Appendix B, noise regulations depend on aircraft classification, organized by “Stages”.[50] For realistic, large, commercial transport supersonic aircraft, they need to abide based on maximum takeoff weight. The CFR states that the noise limitations for direct flyover of a location are “108 EPNdB for maximum weight of 600,000 pounds or more; for each halving of maximum weight (from 600,000 pounds), reduce the limit by 5 EPNdB”.[50] Half of 600,000 pounds is 300,000 pounds, so an aircraft with an $MTOW$ of 300,000 pounds or less (until the next halving of 150,000 pounds) has a limit of 103 EPNdB, where EPNdB is the effective perceived noise in decibels. For takeoff and landing, the constraints are the same except the limit only needs to be reduced by 2EPNdB for every weight halving. If an aircraft happens to reach supersonic speeds over the US, then it must comply with the noise limitations. Putting this into perspective, the only successful supersonic commercial transport aircraft was the Concorde, having a sonic boom of 105 PLdB with regulation limiting to 75 PLdB. Here, PLdB signifies the perceived loudness in decibels, which is a substitute for EPNdB.[51] This is no surprise for an aircraft with very powerful engines. It is why the Concorde did not fly supersonically over land. We will see if noise abatement strategies greatly improve in the coming years since Concorde, but it is a big hill to climb to change the future of air travel.

V. Flight Operations – Cue Speeds, Takeoff and Landing Distances

Military and civilian rules for aircraft “cue speeds” – those speeds the pilot will maintain during takeoff, climb out, approach and landing – and what constitutes a safe runway for takeoff and/or landing differ amongst themselves. A complicated history explains the subtle nuances that divide 14 CFR § 25, 14 CFR § 23 and various generation military aircraft from one another.[3][6][43][52][53]

A. Icing and Adverse Weather Conditions

The earliest days of aviation saw little regulation or safety standards. Manufacturers were not required to build aircraft to meet any sort of performance or safety requirements. Neither were operators required to perform any rigorous flight planning. This situation applied equally to military and civilian operators.

The first step towards the modern regulatory framework for aircraft design and operations occurred when congress promulgated the Air Commerce Act of 1926.[54] Prior to its passage, there were no official duties of the Federal Government towards commercial aviation. The act charged the executive branch of the Federal Government through the Department of Commerce (initially the Aeronautics Branch and later the Bureau of Air Commerce) to promote the safety of flight.[54] The executive branch assumed the responsibility to promulgate and enforce safety regulations, including the licensing and registration of aircraft, to produce aeronautical charts, to supply meteorological advice and reports, to investigate accidents, and to certify and medically examine pilots.[54]

In the early days of federally regulated aviation, there were sparse icing regulations. The initial Air Commerce Regulations of 1929 only mention weather in Section 79 where they hold that “air-traffic rules may be deviated from when special circumstances render a departure necessary to avoid immediate danger when such departure is required because of stress of weather.”[55] Certainly, the Douglas DC1 and DC2 of 1933 and 1934 respectively do not appear to have any sort of anti-ice or de-ice equipment on their aerodynamic surfaces.[56][57] However, the Douglas DC3 of 1935 features prominent inflatable rubber de-ice “boots” on the leading edges of the main wing, horizontal and vertical stabilizers.[58]

The passage of the Civil Aeronautics Act of 1938, later amended to its final form in 1940, revamped the regulatory framework for commercial air travel.[59] We see a change in the Civil Aeronautics regulations promulgated for the 1938 edition of 14 CFR.[60] Civilian transport category aircraft are expected to operate in icing conditions. Hence, we find new regulations such as:

- 14 CFR § 04.53814 (1938) [61] “Safety Equipment Installation – De-Icers” require positive means to deflate any wing de-icing boots.

- 14 CFR § 13.12 (1938) [62] "Aircraft Engine Airworthiness - Design requirements." Requires a provision "for the installation of a means for preventing the formation of ice in the carburetor."

The modern 14 CFR § 25 [3] defines many icing related regulations. Strict regulations regarding ice accretion from Supercooled Large Droplets (SLD) were added in late 2014, in response to the fatal crash of American Eagle Flight 4184 on October 31, 1994.[63]

Interestingly, the FAA does not specifically certify aircraft for takeoff or landing field performance distances in icing conditions. It declines to officiate and provide manufacturers guidance to determine an appropriate stopping distance for icy or contaminated runways. However, the FAA does require aircraft performance engineers to consider the effects of icing. Icing conditions may degrade aircraft performance in two ways. First, engine power may be reduced when significant hot bleed air is diverted from the high-pressure compressor to feed cowl and leading-edge anti ice systems. Second, ice accretion – even in the presence of a functioning anti-ice or de-ice system – may lead to an increase in stall speeds and a change in minimum control speed.

For civilian aircraft, scheduled landing speeds and distances need not take into consideration a slick runway; yet the scheduled approach speed may well be elevated to account for icing degraded stall characteristics.[64] Conversely, a MIL certified aircraft will have much less attention given to its anti-ice and de-ice systems but will have detailed landing distances scheduled for degraded traction runways.

B. Stall Speed Definition

The classical MIL-STD-1797 defines a 1-g normal stall speed V_S as the highest of three cases: (1) speed of steady, straight flight at CL_{max}, (2) speed of unprovoked pitching, rolling, or yawing, and (3) speed of intolerable buffet.[14] To determine V_S with MIL rules, the aircraft is to "be initially trimmed at approximately $1.2V_S$ with the following settings, after which the trim and throttle settings shall be held constant".[14] The trim settings at each flight phase can be found in § 3.4.2, with

$$V_S = \frac{V}{\sqrt{n_f}} \tag{10}$$

Where V is the calibrated airspeed and n_f is the normal load factor. The FAA recommends in the same section to reduce speed by 0.5 knots per second or less to minimize dynamic lift effects during stall flight test. Comparing to 14 CFR § 25.103, it is recommended to reduce speed by 1 knot per second or less in testing.[14][65]

Compared to military standards for stall speeds are the CFR regulations for normal category aircraft and commercial transport aircraft. 14 CFR § 23.2110 states that the pilot must determine the stall speed of the airplane his or herself. It describes this procedure as "the stall speed […] determination must account for the most adverse conditions for each flight configuration power set at - (a) Idle or zero thrust for propulsion systems that are used primarily for thrust; and (b) A nominal thrust for propulsion systems that are used for thrust, flight control, and/or high-lift systems."[66]

Commercial transport regulations found in 14 CFR § 25.103 are much more technical.[65] Reference stall speed V_{SR} is a calibrated airspeed that designates when an aircraft should expect to feel stall characteristics. It is defined in Eq. (11) below.

$$V_{SR} \geq \frac{V_{CL_{max}}}{\sqrt{nZ_w}} \tag{11}$$

Where $V_{CL_{max}}$ is the calibrated airspeed of the load factor corrected maximum lift coefficient, and nZ_w is the $V_{CL_{max}}$ load factor normal to the flight path. We know what accuracy is like for FAA airspeed calibrations. They clearly state for V_{SR} that it may not be less than a 1-g stall speed.[65] For a stick pusher device, V_{SR} may not be less than the speed at which the stick pusher operates by 2 knots or 2% - whichever value is greater.

Comparatively, the FAA AC 25-7D defines when a stall occurs in § 8.1.3.[39] They recommend testing procedures for stall speed calibration without the use of a pitot-static tube. This method is not accurate for stall testing and testing is to be performed with "properly calibrated instruments".[39] What exactly comprise "properly calibrated instruments" is quite unclear. The FAA leaves considerable discretion with stall speed calibration.

C. Minimum Control Speed in the Air (Critical Engine Inoperative) Definition

Minimum control speed came into the aircraft designer's lexicon in 1940. A high-profile crash of a Pan Am Sikorsky S-43 (NC16933) in 1939 prompted this change. If an engine fails and the aircraft can neither climb nor maintain heading, as was the case here - it most certainly will crash. The FAA introduced regulation 14 CFR § 04.723 in 1940.[67] It required aircraft manufacturers to submit engine-inoperative climb performance data to the certifying authority; aircraft must be scheduled to operate at a speed that "ensures full control with the critical engine-inoperative."[68] Today, an interlocking set of Federal Regulations: 14 CFR § 25.107 [69], 25.125 [64], 25.143,[70] 25.145,[71] 25.147,[72] 25.171,[73] and 25.175 [74] introduce specific requirements that transport category aircraft must meet in order to guarantee safe flight in all (including adverse) weather conditions. Broadly speaking, weight and payload restrictions limit the fl90le center-of-gravity range so that the aircraft is always "safely controllable and maneuverable during— (1) takeoff; (2) climb; (3) level flight; (4) descent; and (5) landing" by ordinary pilots.[70] with all engines operating and with a critical engine failure.

The minimum speed needed to trim with One-Engine-Inoperative in the take-off condition is known as *VMCA*; with two engines inoperative on the same side, the minimum controllable airspeed is known as *VMCA*2.[75] The minimum speed needed to trim with One-Engine-Inoperative in the landing condition in known as *VMCL*; with two engines inoperative on the same side, the minimum controllable airspeed is known as *VMCL*2.[75]

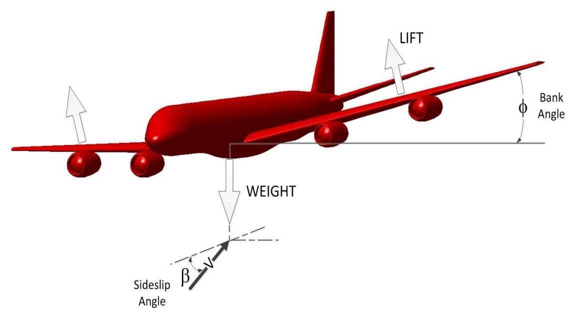

Fig. 19 Engine Inoperative Flight.

FAA AC 25-7D requires the airframe manufacturer to demonstrate compliance using a flight test demonstration, especially showing flight at *VMCA* where "constant heading is maintained without exceeding a 5-degree bank angle;" see Fig. 19.[39]

MIL 8785B [76] from 1969 models its definition of minimum control speed for take-off climb out upon then current civilian requirements of 14 CFR § 25.149.[77] To comply with this standard, pilots shall "without a change in [aerodynamic] configuration" be able to retain control after "a sudden asymmetric loss of thrust from the most critical" engine and "maintain straight flight throughout the climb-out." As with the earlier civilian regulation, "the rudder pedal force required to maintain straight flight … shall not exceed 180 pounds."[77] Moreover, "aileron control shall not exceed … force limits … 75 percent of available control power."[77] In addition "the airplane may be banked up to 5 degrees away from the inoperative engine."[77] Rudder trim-tabs should be able to null the rudder pedal force as long as the pilot flies 140% or more of the scheduled minimum flight speed. Commentary to the changes to MIL-8785B states that since "the pilot must have at least 25% excess roll control power … MIL-F-8785 … is more stringent than the" corresponding civilian regulation.[78]

Thus, so long as pilots follow scheduled flight speeds per the Aircraft Flight Manual, neither military nor civilian pilot should operate their aircraft beneath the flight-test specified minimum control speed.

D. Minimum Control Speed on the Ground (Critical Engine Inoperative) Definition

When establishing minimum control speed on the ground, civilian and MIL rules diverge. Both certifying agencies concur that the Ground Minimum Control Speed is the minimum speed during the ground takeoff run at which the most critical engine can fail and directional control can be maintained.[43] 14 CFR 25.149 states that VMCG is the "calibrated airspeed during the takeoff run at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane using the rudder control alone (without the use of nosewheel steering), as limited by 150 pounds of force, and the lateral control to the extent of keeping the wings level to enable the takeoff to be safely continued using normal piloting skill."[75] MIL-STD-1797A notes that yaw axis control power during takeoff and landing needs to be assessed under aft-center-of-gravity conditions where there is "less weight on the nose gear."[14] In general MIL-STD-1797 permits additional rudder pedal forces of up to 250 pounds.[14] The FAA does not allow independent nose-wheel steering, but allows "rudder pedal nose wheel steering ... provided the runway surface for the test represents the worst case anticipated for operation."[39] Whereas the MIL rules actively allow the certifying agency to take credit for "nose wheel steering and differential braking."[14] While MIL rules lead to a more stringent (i.e. faster) VMCA than the same aircraft certified to civilian standards, the opposite is true for VMCG. By allowing the higher pilot workload associated with nosewheel steering, MIL rules will result in a lower VMCG speed which may enable high dispatch payloads with some reduction in implied safety.

E. Takeoff Safety Speed Definition

Under obsolete U.S. civilian regulations for aircraft certified before 2002,[79] the scheduled second segment climb speed for take-off, *V2*, is governed by:

$$V2 = \max(\ 120\%\ Vstall, 110\%\ VMCA\ ) \tag{12}$$

Under current civilian regulations,[68] the scheduled second segment climb speed for take-off, *V2*, is governed by:

$$V2 = \max(\ 113\%\ Vstall, 110\%\ VMCA\ ) \text{ for turbojet / 2 and 3-engine propeller powered} \tag{13a}$$

and

$$V2 = \max(\ 108\%\ Vstall, 110\%\ VMCA\ ) \text{ for 4 or more engine propeller powered aircraft} \tag{13b}$$

In MIL-C-5011A (November 1951) [52], the Military specified that standard scheduled aircraft performance for Air Force aircraft would be computed using a takeoff speed stabilized at 50-ft AGL of 120% of the power-off stall speed for the takeoff configuration; Navy aircraft are held to a different standard at 50-ft AGL of 120% of the power-on stall speed for takeoff. It did not expressly call out any concerns for minimum controllable airspeed.

Subsequently, with the advent of MIL-8785 VMCA set a floor to takeoff speed: [76]

$$VOBS = \max(\ 120\%\ Vstall, VMCA) \tag{14}$$

MIL C-5011B (June 1977) [53], revises these speeds somewhat and explicitly introduces the concept of minimum control speed. It calls for the second segment climb speed to be:

$$VOBS = \max(\ 115\%\ Vstall, VMCA\ ) \tag{15}$$

The current MIL-STD-3013 (February 2003) [43] requires scheduled performance to comply with further revised speeds. Today, obstacle climb out speed should be:

$$VOBS = \max(\ 120\%\ Vstall\ power\text{-}off, 105\%\ VMCA\ ) \tag{16}$$

Operational experience has led both agencies to set the speed floor for takeoff to be 13 to 20% above the certification demonstrated stall speed and 0% to 10% above the published minimum control airspeed. Today, U.S. military rules give more speed margin for stall during take-off than do civilian certifying agencies. Conversely, the most recent U.S. military rules (MIL-STD-3013) give less speed margin for engine-inoperative trim during takeoff than does the FAA.

F. Final Approach Speed Definition

Similarly, under obsolete civilian regulations for aircraft certified before 2002,[70] the scheduled final approach speed for landing, $VREF$, is governed by:

$$VREF = \max(\ 130\%\ Vstall,\ VMCL\ ) \tag{17}$$

Whereas, under current civilian regulations,[64] the scheduled final approach speed for landing, $VREF$, is governed by:

$$VREF = \max(\ 123\%\ Vstall,\ VMCL\ ) \tag{18}$$

While not explicitly called out, in 14 CFR § 25.107, fourth segment and en-route climb speeds are customarily scheduled for speeds far above the minimum control airspeed.[69] Prudent performance engineers would not schedule flight beneath *VMC* as appropriate for the aircraft flap configuration.

Under older MIL rules,[53] for landing, since no mention is made of asymmetric thrust controllability, the final approach speed is simply:

$$VAP = 120\%\ Vstall \tag{19}$$

MIL C-5011B (June 1977),[53] revises these speeds somewhat and explicitly introduces the concept of minimum control speed. It calls for a final approach speed of:

$$VAP = max(\ 120\%\ Vstall,\ VMCL\ ) \tag{20}$$

where *VMCL* is the minimum control airspeed with landing flaps.

MIL 8785C [13] from 1980 does not materially change the definition of minimum control speed involving lateral-directional control with asymmetric thrust.

And a final approach speed of:

$$VAP = max(\ 120\%\ Vstall\ power\text{-}off,\ 105\%\ VMCL\ ) \tag{21}$$

Where *VMCL* is the minimum control airspeed with landing flaps as defined by MIL-HDBK-1797A.[14] MIL 1797A reiterates the verbiage of the earlier MIL 8785 standard and requires analysis to predict (and flight test to confirm) lateral-directional trim with asymmetric thrust with the 5° bank limit and 75% of available lateral control power.

We can therefore see that MIL and Civilian Rules, while not identical, have evolved together. Both agencies set the speed floor for final approach to be 20 to 30% above stall speed and 0% to 5% above the published minimum control airspeed. Today, U.S. military rules give slightly less speed margin for stall during landing than do civilian certifying agencies. Conversely, the most recent U.S. military rules (MIL-STD-3013) gives more speed margin for engine-inoperative trim during landing than does the FAA.[43][64]

G. Braking Traction (RCR)

Generally speaking, runways are considered dry if they are clear of visible moisture.[71] A damp runway, with a non-reflective moisture layer, is also considered dry. Conversely, a runway is considered to be wet when there is sufficient moisture to cause it to appear reflective, but the depth of the water is not more than 1/8 inch. A runway surface is considered **contaminated** when more than 25% of the runway surface area is covered with standing water, slush, loose snow (dry or wet), compacted snow or ice.

While the FAA does not specifically call out the traction level available on dry or snowy runways, the US military characterizes contaminated runway operations in terms of the Runway Condition Reading, **RCR;** see Fig. 20.[43] The International Civil Aviation Organization, ICAO, which is part of the United Nations, also specifies both qualitative and quantitative estimates of runway traction in a manner consistent with the US Military.[80] This metric varies from RCR=23 representing a standard hard-surface runway in the dry to RCR=7 which represents a wet, icy runway. MIL-STD-3013 specifies default values the engineers should use for computing rolling resistance (μ) and braking capability. In each case the coefficient is defined as the ratio of the total retardation force of the wheels (either inherent in the tires and bearings, or due to the brakes) over the weight on wheels (the aircraft weight less any aerodynamic lift). Thus, for commercial aircraft operations, towers will typically report the runway as Dry Good or Wet Medium as opposed to calling out a specific RCR or RSC value.

RCR	Condition	Rolling resistance (μ)	Braking Capability (w/ anti-skid) (μ)
23	Dry	0.025	0.38
15	Wet	0.050	0.25
11	Wet Snow	0.090	0.18
7	Wet Icy	0.050	0.12

RCR	ICAO Report	Braking Capability (μ)
23	GOOD	> 0.40
	MEDIUM TO GOOD	0.36 to 0.39
12	MEDIUM	0.30 to 0.35
	MEDIUM TO POOR	0.26 to 0.29
5	POOR	< 0.25

Fig. 20 Runway Condition Ratings and associated coefficients of friction (μ).

RCR affects the stopping performance of the aircraft and must be accounted for when computing field performance. If actual test data can document better stopping power than that implied by the default coefficient, many certifying agencies will not force the manufacturer to use the pessimistic default values for stopping friction.

In 14 CFR § 25.109, the FAA calls out speed dependent braking coefficients for accelerate-stop certification testing on wet runways.[81] The FAA lists two sets of equations, one for operation on smooth wet runways and an even higher value for grooved wet runways. The FAA data is dependent upon tire inflation pressure; the more pressure in the tire, the lower its traction. What is curious about this trend is that, under 100 KTAS, the FAA certified braking friction values are significantly higher than those used by the military!

H. Takeoff and Landing Distances

Military and Civilian rules for aircraft "TOLD," takeoff and landing field length requirements, differ amongst themselves. As with minimum flight speeds, a complicated history explains the subtle nuances which divide 14 CFR § 25, 14 CFR § 23 and various generation military aircraft from one another.

Early civilian 14 CFR rules and military rules are identical; they consider the takeoff distance to be that from brake-release to when the aircraft rises 50-ft above ground level. Today, 14 CFR § 25 certified distances consider the end of the air-phase to be when the aircraft is 35-ft above ground.[82] This change was introduced in 1957 under Special Civil Air Regulation 422, used to certify of the Boeing 707.[83] Modern 14 CFR §23 rules for low-speed aircraft, like modern military rules, retain the 50-ft above ground level definition.[6][43] Modern 14 CFR §23 rules for high-speed aircraft use the 35-ft standard similar to a 14 CFR 25 aircraft.

Both civilian and military rules for critical field length are broadly similar. However, 14 CFR §25.113 stipulates that critical field length is the greater of: 1) 115% of the basic takeoff distance with all engines operating; 2) the accelerate-stop distance with the decision speed set to the published V1 speed and 3) the accelerate-go distance with an engine failure timed so that the pilot first notices the engine failure just as the aircraft passes its V1 speed.[82] MIL rules are somewhat simpler, MIL 3013 stipulates that critical field length is the greater of: 1) the basic takeoff distance with all engines operating; 2) the accelerate-stop distance with the decision speed set to the published V1 speed and 3) the accelerate-go distance with an engine failure timed so that the pilot first notices the engine failure just as the aircraft passes its V1 speed.[43] In this case, the FAA rules potentially give additional safety margin as they may lead to a longer minimum runway length for dispatch as compared to MIL rules.

Both civilian and military rules for landing field length are broadly similar. Both begin with the aircraft 50-ft above ground level, assume a touchdown on the "stripe" (984-ft downwind of the runway threshold) and end with the aircraft stopped. They differ in terms of the final approach speed and in terms of the credit allowed for reverse thrust.[43][84][64]

Presently, the FAA forbids the use of thrust reversers when calculating the certified landing distance or takeoff accelerate-stop distance. In the United States, if reverse thrust is available, pilots will use it to help stop the aircraft quickly saving wear and tear on the brakes. In the European Union, community noise standards discourage the use of reverse thrust in normal operations. Conversely, US Military rules explicitly allow the use of reverse thrust. Thus, identical aircraft certified to FAA and MIL standards will have noticeably different stopping distances; the MIL aircraft having shorter distances.

The reason why reverse thrust is taboo in certification has to do with nuance in the way regulations are worded and interpreted. In 14 CFR § 25.125, reverse thrust is neither explicitly allowed nor disallowed.[64] The FAA specifically disallows engineers to take credit for "any device is used that depends on the operation of any engine … if the landing distance would be noticeably increased when a landing is made with that engine inoperative."[64] However, it is common practice, at least on two-engine airplanes, to interpret the phrase "means other than wheel brakes may be used to determine the accelerate-stop distance if that means … is such that exceptional skill is not required to control the airplane" as disallowing reverse thrust in the event of a critical engine failure.[39]

Taken together we can see the otherwise identical aircraft flown under MIL vs 14 CFR rules will have slightly different cue speeds and have slightly different minimum runway lengths declared for safe dispatch.

VI. Case Studies

A. Bell X-1

Aviation has seen accelerated progress in aircraft and spacecraft design that is truly remarkable in its brief history. Along with outstanding progress come groundbreaking moments that shatter boundaries some thought could never be reached. When these boundaries are broken, how does it affect the laws of future air travel? One of the most important advances in aeronautical sciences was breaking the sound barrier. Aircraft stability at supersonic speeds was worrisome before the first plane achieved Mach 1, as back in the 1940s "you either broke the sound barrier or it broke you!"[85]

On October 14, 1947, Chuck Yeager was at the controls of the Bell X-1 and broke the sound barrier for the first time in history; see Fig. 21. Upon the aircraft surpassing Mach 1, a loud boom roared over Edwards Air Force Base in California. In an Air Force article describing the event, Katherine Franco writes, "the phenomenon known as the 'sonic boom' was first experienced."[86]

Fig. 21 Bell X-1 preserved in the Smithsonian National Air and Space Museum and being mated to the bomb bay of a B-50. It would be airdropped at a steady speed and altitude.

Due to the significant impact of sonic booms, supersonic aircraft should not travel close to cities and residences. This is why Edwards AFB became the epicenter for USAF and NASA high-speed, experimental test flights. Franco's article also states that "conditions suited for supersonic flight testing to break the sound barrier in 1947 still exist at Edwards today."[86] Today, Edwards has a restricted zone around the base and surrounding area that allows them to safely test supersonic vehicles without disrupting the public; refer back to Fig. 18.

Although the first supersonic flight was under the supervision of the FAA and USAF in a restricted zone, it presented the opportunity for commercial supersonic flight. This introduces the Concorde, which was the first supersonic commercial transport aircraft. To prepare for the new wave of supersonic flight, in 1973 the FAA finalized a regulation to prohibit civil aircraft at speeds greater than Mach 1 where a sonic boom could reach the United States. This includes flying directly over the US or close enough to the shore supersonically where a sonic boom could reach the land. This regulation, with minor changes, still stands today as 14 CFR § 91.817.[47] The FAA also states that "there is a procedure that allows supersonic operation under certain conditions granted on an individual basis." In addition, any new aircraft would need to meet current airworthiness and noise certification requirements.[49]

With a lot of the hype in the aerospace industry centered around potential future supersonic commercial transport aircraft like Boom Supersonic's Overture and Lockheed Martin's X-59 experimental plan dedicated to reducing the impact of sonic booms, we will see if supersonic transport will become available again and surpass the days of the Concorde. However, we are reminded that this all started with the Bell X-1 flying over Edwards AFB, a restricted area. Being one of the many times in history military aviation has influenced public aviation, we might be able to feel like Chuck Yeager did, breaking the sound barrier ourselves in the future.

B. North American X-15

Roughly fifteen years after the first supersonic flight took place at Edwards, major aeronautical advancements in the US Air Force had occurred since the Bell X-1. The Mach 3+ SR-71 spy plane was in its early stages of development to assist the U-2, and the early days of fighter jets were producing historic F-104 Starfighters and F-4 Phantoms. These advancements, due to the pressure of the Cold War, propelled flight technology at a very rapid rate. With the Soviets being the first to successfully orbit the earth, the clock was ticking for the US to answer. This introduces the North American X-15, an experimental rocket-plane that was the first US vehicle to achieve space flight; see Figs. 22 and 23. In a joint program between the USAF and NASA, the goal of the X-15 program was to achieve manned hypersonic flight and collect data on hypersonic propulsion, thermals, aerodynamics, and stability and control. Achieving hypersonic flight requires going faster than Mach 5, or five times the speed of sound. Hypersonic flight is necessary for traveling to space, and the X-15 was the first to ever scale these massive accomplishments – at the same time.

Fig. 22 USAF pilot William 'Pete' Knight posing in front of the X-15A-2. The rocket-plane was the most advanced, and arguably dangerous, aircraft of its time. Knight would earn astronaut wings flying the X-15 above an altitude of 50 miles.

On July 17, 1962, pilot Robert M. White was the first person ever to fly into outer space in a non-ballistic vehicle, setting the stage for space flight later in the decade.[87] This marks new territory for the United States. While under the regulations for space flight by Title 51 of the USC and NASA, the X-15 flights had a designated pathway to complete their missions. As stated on the Smithsonian website, "the Air Force and National Advisory Committee for Aeronautics developed a special 485-mile long test corridor stretching from Wendover Air Force Base. Utah. to Edwards Air Force Base. California."[88] This was a special use of restricted airspace for the X-15 flights, with the pilots being protected from the ground up to the lengths of outer space, as long as they stayed within the test corridor.

Fig. 23 X-15 immediately after being airdropped from the wing of a B-52 Stratofortress. All missions occurred within the designated test corridor near Edwards AFB, even when the X-15 was in outer space. It would usually travel a terrain distance of 200-300 miles for a mission.

Today, spaceflight still follows the rules and regulations of Title 51 of the United States Code, whether commercial or government.[89] Many resources are being put in place to make spaceflight a reality to the public soon, such as SpaceX and Blue Origin. But what about hypersonic transportation in a vehicle that can land like a conventional aircraft and can be reusable? While commercial supersonic flight will inevitably want to travel faster and faster if re-implemented, hypersonic flight is a much more dangerous mode of travel compared to supersonic. Hypersonic aircraft are marginally stable even with the absolute best engineered stability and control equipment, so it is a far-fetched idea to travel from New York to Tokyo in less than two hours in the near future. Nevertheless, as hypersonic technologies advance in the coming years, it will be very prominent in the military and NASA.

C. KC-46A

The KC-46 is a further example of a blended FAA/Military aircraft, leaning even more towards pure civilian certification. The Boeing-built KC-46 tanker is a military version of the 767 commercial aircraft; is formally a Boeing 767-2C aircraft certified by the FAA under TCDS A1NM [21] It has been described as combining "the 767-200ER's fuselage, with the 767-300F's wing, gear, cargo door and floor, with the 767-400ER digital flightdeck and flaps".[90] Boeing states that "the KC-46A is the only tanker to meet the stringent Federal Aviation Administration and U.S. Air Force airworthiness and performance requirements."[91] This involves more than the basic airframe; in a press release dating from 2018, Boeing publicized that the FAA issued Boeing a Supplemental Type Certificate "verifying that its refueling and mission avionics systems meet FAA requirements."[92] Boeing also states that "not all military functions and equipment can be certified by the FAA. The U.S. Air Force also must grant a Military Type Certificate (MTC)."[92]

The Defense Acquisition University holds that "USAF Policy Directives (AFPD) 62-6, USAF Instruction (AFI) 62-601, Military Handbook (MIL- HDBK)-516C all state that when a military mission is compatible with a certified civil usage, the Air Force will utilize FAA type certified Military Commercial Derivative Aircraft to the maximum extent practical."[93] These aircraft are "initially approved for safety of flight by the FAA and may have an FAA approved Type Certification."[93]

Closer inspection of FAA type certificate indicates that the KC-46A is flown under an "FAA Approved Airplane Flight Manual" but "no pilot type rating or training, checking and currency requirement determinations have been made."[21] The TC states that "Boeing Document No. D6T11320 is the basic FAA Approved Airplane Flight Manual for Pratt and Whitney powered [767-2C] airplanes."[21] The TC also stipulates that "all model 767-2C aircraft must be flown with a Boeing pilot in command prior to the completion of that aircraft model's F&R testing."[21] The TCDS also stipulates that a number of KC-46A aircraft are now ineligible for a Standard Airworthiness Certificate: line numbers "34054, 41273-41275, 41852, 41855, 41856, 41983."[21]

Unlike the KC-10 tanker, which began life as a DC-10 commercial transport then modified to non-FAA approved standards, the KC-46A CONOPS presently requires the tankers to remain FAA certified throughout their lifecycle.[93] More importantly the KC-46A type certificate specifies that these aircraft be maintained "under 14 CFR §§ 43.16 and 91.403, unless an alternative program has been FAA approved."[21] The Defense Acquisition University states that the KC-46A program requires "a fully Commercial Logistics Support (CLS) program [to cover] all requirements except organizational (O-Level) maintenance ... to show compliance to 14 CFR Part 121 Section L (Maintenance, Preventive Maintenance, and Alterations) and 14 CFR Part 121 Section M (Airman and Crewmember Requirements)."[93] Aircraft must have a "Maintenance Management Program Plan (MMPP) approved by the FAA."[93] To preserve the FAA civilian type certificate of the airframe, "all repairs are done by a 14 CFR Part 145-approved contractor."[93] The USAF is expected to "to maintain the FAA approved Type Design,[Type Certificate] and [Air Worthiness] Certification using USAF regulations and policies to the greatest extent possible."[93]

This strategy is supposed to help reduce development time, allowing the military to adapt more quickly to changing technology; this will indirectly lower life cycle costs. Specifically, the military believes that "the potential cost benefit from obtaining and maintaining a TC/ATC or STC aircraft is the use of the FAA-certified parts pool and the FAA sustainment and maintenance baseline for [Commercial Logistics Support.]"[93] Keeping the KC-46A fully FAA certified "allows the USAF to ensures a minimum level of safety and [air worthiness] equivalent to the aircraft's commercial counterpart that allows the USAF to take advantage of Commercial-off-the-Shelf (COTS) training, support equipment, technical manuals, facilities, and the use of CFR Part 145 certified Maintenance Repair Organizations (MROs) and maintenance providers that use commercially exclusive aircraft."[93] Boeing advertises that they have "been the primary or associate provider of maintenance, logistics, and spares support for the KC-10 and KC-135 tankers since delivery to the U.S. Air Force."[92] With the KC-46A, Boeing is "responsible for repairs, logistics support and engine management."[92]

VII. Summary & Conclusions

In this work, we demonstrated similarities and differences between MIL certification and operation of aircraft and the civilian FAA based 14 CFR system. Like commercial transport regulation, military aircraft regulation has ensured safety, reliability, and progress within the field. In 2021, there were only 63 fatal accidents from the Air Force resulting from over 60 million flying hours.[94] Safety is a top priority for the military, Air Force aircraft are no exception. Understanding how regulatory action operates for military aircraft further shows that the many documents that are created serve a great purpose for organization and safety. Whether a routine operation is being held for the fourth time in a month, or a new experimental aircraft is being tested with next-generation technologies, the armed forces will follow the guidance from the documents and regulations discussed above. It's about doing things the right way to get the job done!

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