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Launching the Workhorse

Vertical or Super-Short Takeoff Capabilities for the Next Theater Airlift Aircraft

Robert C. Owen





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Dedicated To

Muir S. Fairchild (1894–1950), the first commander of Air University and the university's conceptual father. Seneral Fairchild was part visionary, part keen taskmaster, and "Air Force to the core." His legacy is one of confidence about the future of the Air Force and the central role of Air University in that future.

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About the Author



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Introduction

This study is an assessment of whether the US Air Force (USAF) should anticipate modernizing its core theater airlift fleet with aircraft designed for super-short takeoffs or landings under rough-field conditions (SSTOL-RF) or aircraft designs focused on vertical takeoffs or landings (VTOL) with secondary SSTOL-RF capabilities (V/SSTOL-RF). Several considerations speak to the timeliness of this issue. Most importantly, the ongoing evolution of USAF and Army (USA) war-fighting concepts increase their demand for mobility and sustainment support in quantities and places that the aircraft in the present airlift fleet cannot provide. Also, the present mainstay of the theater airlift fleet, the C-130, has been an inadequate platform for vital missions for decades. It is too small to link effectively and efficiently with large intertheater airlifters, such as the C-5, C-17, and civil reserve air fleet (CRAF) jumbo cargo aircraft at intermediate staging bases. Also, the C-130's runway requirements limit its ability to connect to battlefield airlift helicopters or deliver forces and sustainment at forward-most points of need and effect (PON/E) themselves. Intratheater airlift, consequently, is the weak link in the USAF's ability to provide a smooth flow of air and land combat forces and their sustainment in the early stages of conflicts and crises. Finally, although the USAF has not published a formal plan for theater airlift modernization, most officials interviewed for this study suggested sometime in the 2040s as the window for the next aircraft to appear. Given the experience of the C-17 program, which took 19 years to move from development contract to the first squadron reaching initial operational capability, a program aimed at putting a squadron of future theater airlifters on line by the middle 2040s should begin sometime in the early 2020s. As a contribution to conceptualizing the best path to a modern theater airlift fleet, then, this study will assess the SSTOL-RF and V/SSTOL-RF design approaches in terms of their ability to fulfill critical USA and USAF requirements and their operational risk profiles.

Background Considerations

Several considerations should underpin any comparison of SSTOL-RF and V/SSTOL-RF design options. First, readers should review this report with a clear idea of how it uses key terms, notably *theater airlift*, *VTOL*, and *SSTOL*, and *rough-field*. Also, a synopsis of the history of SSTOL-RF and V/SSTOL-RF research, development, and flight characteristics will be useful to set the stage for understanding future options. Finally, this section will discuss the general threat environments in which these aircraft will operate.

Definitions

The definition of theater airlift is more about command relations and missions than it is about aircraft. US joint doctrine describes theater (or intratheater) forces as those assigned to and commanded by geographic combatant commanders, such as the commanders of the US European Command (USEUCOM) and US Indo-Pacific Command (USINDOPACOM) or their subordinate joint force commanders. Those commanders have the authority to allocate and direct their airlift forces to accomplish their assigned missions. The command relations of intertheater airlift forces differ from those of intratheater, in that they generally operate under the authority of US Transportation Command (TRANSCOM) commanders, who allocate resources comprising the bulk of the US airlift fleet on a common-user basis in support of other combatant commands. In their roles as the national command authorities (NCA), the president and the secretary of defense (SECDEF) set the terms and priorities of those force allocations. In terms of missions, most theater airlift operations are logistical, moving people and cargos between developed bases. Movements and support of combat-ready ground and air units within battle zones are also common features of intratheater airlift operations. Depending on the circumstances and the capabilities of supported units, theater airlift forces may deliver them to their destinations by parachute drops (airborne) or from or into aircraft parked on the ground (airland). The SECDEF may assign any type of airlift aircraft to geographic commands to perform intratheater missions. However, apart from INDOPACOM, the NCA have assigned only C-130s to geographic commands on a permanent basis. Because of the large distances involved in its area of operations, which covers half of the planet, INDOPACOM also operates much larger and longer-range C-17s. When needed, the NCA can temporarily loan or more permanently assign any type of aircraft from TRANSCOM to other combatant commands to handle exceptional demands they may face.¹

Regarding the operational definitions, US official doctrines provide only an uncertain foundation for discussing theater airlift capabilities with precision. *VTOL* has such an intuitive meaning—the ability of aircraft to take off and descend to a landing vertically over a given spot—the editors of the US *Department of Defense Dictionary of Military and Associated Terms* have not bothered to define it formally. The Department of Defense (DOD) dictionary does include a definition of *Short Takeoff and Landing (STOL)* as "the ability of an aircraft to clear a 50-foot obstacle within 1,500 feet of commencing takeoff or, in landing, to stop within 1,500 feet after passing over a 50-foot obstacle." However, the relevance of the 1,500 foot cutline is obscure in origin and application, because it is not tied to any operational requirement, and the V/ SSTOL-RF V-22 is the only transport aircraft in the current US military inventory able to make such takeoffs and landings at full gross weight. It also does not specify the critical meteorological conditions, that is, the density, altitude and obstacle-clearance criteria that would influence the ability of an aircraft to perform STOL operations. Beyond that, the DOD does not have official definitions for SSTOL or rough-field. These terms are implied, however, in numerous studies of desirable capabilities and of permissible runway surfaces for airlift operations. The USA's 2003 Transformation Roadmap, for example, called for an SSTOL-RF aircraft able to carry two 20 ton Future Combat Systems into a 750 foot long road or field.² Other USA and USAF studies presume that runways utilized for a few times by theater transports will be generally smooth, have California Bearing Ratios of 5 for C-130s and 12 for C-17s.³ The military also expects such airfields to have rutting, gouging, jet blast trenching, and pothole anomalies limited to just a few inches deep.⁴

Given the inadequacies of the official lexicon, therefore, this study is obliged to define SSTOL and rough field more precisely. SSTOL, the study offers, is *the ability of an aircraft to clear a 50-foot obstacle within 1,000 feet of commencing takeoff or, in landing, to stop within 1,000 feet after passing over a 50 foot obstacle at full gross weight in international standard mean sea level conditions of 59°F (15°C) and pressure altitude of 29.92 inches (1013.25 mb) of mercury.* A rough field is defined here as unpaved with a California bearing ration of less than 10 and vertical surface anomalies of up to 12 inches. A visualization of what these numbers mean would be an aircraft landing, taxiing, and then taking off across the rows of a moist plowed field. As will become clear, these capabilities have been and will be attainable by SSTOL-RF and V/SSTOL-RF aircraft. Also, SSTOL-RF or V/SSTOL-RF aircraft capable of operating from such landing zones will be more relevant to future air and land operations than any aircraft in the current inventory.



Figure 1. Early SSTOL-RF/STOL/VTOL wheel chart. (Reprinted from AHA International)

Early SSTOL-RF/STOL/VTOL Programs

As this "wheel chart" (fig. 1) indicates, the US and other countries have developed and tested many SSTOL-RF and V/SSTOL-RF transport aircraft designs since the end of World War II, with the most active period of experimentation falling between the early 1950s through the 1980s. Since most of these test programs did not produce successful aircraft, many engineers also call the chart the "wheel of misfortune." Most designers sought SSTOL-RF or VTOL takeoff capability by vectoring their propulsion thrust lines to the vertical mode for VTOL takeoffs or to lesser angles for SSTOL-RF operations. The most successful design sequence along these lines was that of the tiltrotor Bell XV-3 (1955–66), Bell XV-15 (1977–2003), and Bell/Boeing V-22 *Osprey* (1989–present). The V/SSTOL-RF V-22 achieved exceptional success by becoming the only such type of aircraft to enter quantity production and routine service. Several manufacturers also tested tiltwing concepts in the 1950s through the 1970s, with the LTV XC-142 (1964–70) being the largest and most generally successful.



Figure 2. V-22 Osprey, US Navy (left). XC-142, National Aeronautics and Space Administration (NASA) (right).

The operational contrasts between the V-22 and XC-142 were rooted in the way they produced lift in vertical flight and, consequently, thrust in horizontal cruise flight. As a design emphasizing vertical-lift efficiency, the V-22 employed 38 foot diameter helicopter blades, which were the largest that engineers could use and still fit the aircraft onto the flight deck of an amphibious assault ship. These low-speed proprotors turned at a maximum of 330 RPM in cruise and 412 RPM in vertical flight.⁵ Despite the lower RPM in cruise, the V-22's proprotors rapidly built drag with increasing speed, due to their larger size and increasing compressibility drag at their tips. In contrast, the 15.5 foot diameter propeller blades of the XC-142 turned at 1200 rpm to produce lift and cruise thrust. To overcome the higher torque needed to spin the blades at the higher disk loading (i.e., weight of the aircraft divided by the total area of the disk swept out by the blades) of its propellers, the XC-142 required a higher power-to-weight ratio than the V-22 for vertical flight.⁶ In return, its more efficient propellers and higher power-to-weight ratio gave the XC-142 a significantly faster cruise speed and payload-range advantages over the V-22, but at the cost of a lower overall fuel efficiency and productivity. Its highlyloaded propellers also produced a hurricane of downwash in vertical flight that created clouds of flying debris, even when operating from prepared surfaces. But, with the wings tilted to an angle of around 40-45°, the XC-142 demonstrated exceptional SSTOL-RF capabilities, taking off and clearing a 50

foot obstacle in less than 700 feet at full weight, with the negative effects of its propeller downwash deflected to the rear and so clear of the aircraft.⁷

A few conventional, fixed-wing/fixed-powerplant military transport aircraft have achieved SSTOL-RF or near-SSTOL-RF capabilities as well. Their designs emphasized high-lift wings, complex flap systems to divert wing air flows, wing "blowing," and other technologies to enhance lift. The deHavilland Canada DHC-4 is a notable example. Serving with the USA and USAF from 1959 to the early 1980s, the aircraft had a maximum weight of 28,500 lbs., but could clear 50 foot obstacles within 1,000 feet only at 24,000 lb. or less.⁸ The Breguet 941, a handful of which served with the French Air Force, was a particularly capable design. Tests of the prototype in 1964 convinced the USA that the production aircraft would be able to take off and clear a 50 foot obstacle at about 900 feet at full gross weight, and that the aircraft had better low-speed handling characteristics than any other aircraft then under consideration for the "assault airlift" mission.9 Finally, the National Aeronautics and Space Administration's (NASA) Quiet Short-Haul Research Aircraft (QSRA) remains the only pure jet transport tested for SSTOL. Ultimately, the aircraft delivered minimum takeoff and landing distances in the 800-1200 feet range at its maximum weight of 49,000 lb., partly by using aggressive landing techniques.¹⁰ Importantly, NASA did not test the aircraft under tactical or rough-field conditions.



Figure 3. DeHavilland Canada DHC-4



Figure 4. Breguet 941 landing on city street

From these early development programs, several design realities of relevance to theater airlift modernization emerged. The most obvious of these is that SSTOL-RF and V/SSTOL-RF performance at high gross weights requires thrust vectoring. Augmented flight control systems are also essential to overcoming the low-speed control difficulties that plagued most early SSTOL and V/SSTOL designs.¹¹ Engineers also discovered in the early programs that the structural elements and increased engine power demands of SSTOL and V/ SSTOL-RF were heavy and degraded their speed and payload-range characteristics in comparison to fixed-wing designs of similar size and weight. Modifying the DeHavilland of Canada DHC-5A *Buffalo* into the QSRA for example, added almost 11,000 lb. to its empty weight, without increasing its gross weight of 49,000 lb. Not surprising, the QSRA had inferior range, payload, and takeoff performance, and only modestly improved landing performance, compared to the Buffalo. A more subtle but important discovery was that the weight penalties inherent in SSTOL and V/SSTOL designs tended to converge when the former were expected to take off and land in distances shorter than about 1,000 feet.¹² On the surface, then, there was no payload/gross-weight advantage to be gained from choosing to design an aggressive SSTOL-RF rather than a more operationally flexible V/SSTOL-RF aircraft.



Figure 5. Quiet Short-Haul Research Aircraft, NASA

Operationally, comparisons of the fixed-wing SSTOL-RF, tilt-wing V/SS-TOL-RF, and tiltrotor V/SSTOL-RF design tracks are more complex than simple comparisons of weight penalties. As the data in figure 1 indicate, each design track tends to produce aircraft occupying distinct realms of interconnected speed, range-payload, and productivity characteristics. The conventional takeoff and landing C-130, for example, enjoys a lift/drag (L/D) ratio of 14, which reflects in greater speed and productivity than the designs emphasizing vertical or SSTOL-RF operational flexibility. By comparison, both the Breguet 941 and XC-142 had L/D ratios of about 9, which gave them similar fuel efficiencies. But the simpler and lighter fixed-wing/engine geometry of the Breguet's design allowed it to fly on less engine power and carry a higher percentage of its gross weight as payload than the XC-142. Consequently, while the XC-142 had VTOL performance and higher speed, it profoundly underperformed its fixed-wing SSTOL-RF counterpart in range-payload and productivity. Employing proprotors instead of the XC-142's pure propellers, the V-22 could lift more weight per unit of power in vertical flight, but that efficiency was offset by higher aerodynamic drag of the vehicle in cruise, lower propulsive efficiency from the proprotors, and consequently lower cruise speed and much-reduced payload-range characteristics.

Aircraft	C-130J	Bregeut 941	XC-142	V-22	CH-47
Design track	Fixed-wing STOL	Fixed-wing SSTOL	Tilt-wing V/ STOL	Tilt-rotor V/ STOL	Helo
Cl/d	14	9	9	6.5	4.5
Max. weight (1,000 lb)	122,000 STOL	58,400	45,000 Stol	57,000 STOL	50,000
Power weight (lb/ hp)	4 x 4,637 6.5	4 x 1,500 9.6	4 x 2,850 3.9	2 x 6,150 4.6	2 x 4,900 5.1
Cruise speed (kts)	340	220	280	240	140
Max. payload (lbs)	36,000 Stol	22,000 SSTOL	12,000 SSTOL	24,000 SSTOL	24,000/ 16,000 practical
Range with 8,000 lb cargo (nm)	3,500	1,370	500	170 (internal payload)	160
Fuel burn (lb/hr)	5,000	2,890	3,900	3,750	3,200
Efficiency (lb fuel per/nm @ max. weight	14.7	13.1	13.9	15.6	22.8
Productivity (lb fuel per/ton-mile) w/ max cargo	0.8	1.19	2.32	1.44	2.5 (16,000 lb.)

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Also, worth noting, the slow speed and high fuel consumption of the CH-47 typifies current and future helicopter performance and exemplifies why helicopters are not good candidates for theater airlift missions. Helicopters can lift more weight per unit of power than other VTOL designs, but they cannot carry payload very far. Even large-rotor V/STOLs, like the V-22, share the helicopter's inherent inefficiencies in horizontal flight. Addressing the mythology that the V-22 makes up for its inefficiency as a helicopter with fuel efficient cruise flight, one specialist in rotary wing aerodynamics points out that "tilt rotors, like the V-22, offer. . . speed advantages but, over shorter distances, their productivity is offset by smaller payloads, greater a/c [aircraft, au.] weight, and higher acquisition costs."¹³ Comparing the V-22 to the fixedwing C-130, another analyst points out that, in cruise flight, V-22s carrying their maximum cargo loads produce about 0.12 ton-miles of useful lift per hour per engine horsepower, while the C-130J produces 0.36 ton-miles under the same conditions.¹⁴



Figure 6. CH-47, DOD

Threat Environments

According to Air Force doctrine, "Air mobility operations can be flown in threat environments that include conventional military forces, insurgents, and terrorists; adversary capabilities can range from basic small arms to. . . radar guided surface-to-air missiles."¹⁵

The one persistent theme in the literature of contemporary and future military threat environments is that the world is and will be a dangerous place to conduct theater airlift operations. Most discussions presume increasing threats from legacy kinetic systems, such as missiles, artillery, and air interceptions, with the addition of new realms of cyber, space, and robotics. Depending on the circumstances, kinetic threat systems will include long-range air-, sea- and land-launched weapons of precision accuracy, closer-in attacks by mid-range missiles, air attacks by directly- and remotely-flown aircraft and artificially-intelligent drones, electromagnetic weapons from space, direct actions by special operations forces (SOF) and fifth-column elements, and cannon and missile artillery fires at forward locations. Cyber attacks can come from many sources and media, and the successful ones could incapacitate airlift command and control nodes and communications, shut down support activities, and even disable digital aircraft controls. The summary meaning of all these threats for airlift planning and future operations is that all personnel, bases, facilities, units, and support infrastructures will be subject to attack, whether they are based in the homeland, forward landing strips, or anywhere in between.¹⁶ There will be no inviolable sanctuaries for airlift air and ground operations.

The threat environment for theater airlift forces can be divided usefully into three realms reflecting the persistence and lethality of the weaponry they will face. The first is the general "air" situation. This realm includes the threats that encompass entire areas or theaters of operations, such as enemy air and space reconnaissance and surveillance capabilities, air forces, space weapons, cyber capabilities, long-range missiles, and even SOF and fifth column elements. If not countered effectively, these general threats can inflict high loss rates on theater airlift forces, whether operating in the air or at their bases. In the extreme, when enemy forces dominate any of these threat areas, theater airlift operations can be impossible and even pointless. The second realm embraces the en-route environment when airlift aircraft are en route from main or intermediate operating bases or locations to their forward destinations. In circumstances where enemy and friendly areas of control are distinct, this threat realm may present no additional dangers to airborne aircraft apart from the "general" ones just discussed. Where areas of control are not welldefined, however, additional threats may appear in the form of regular and SOF combat units, robotic air defense systems, and the like dispersed in the interstices of uncontrolled territories between opposing forces. The third threat realm facing theater airlift forces is the destination realm where they are operating within range of enemy, high-density, quick-reaction tactical-fire systems, particularly indirect and direct field artillery cannon and missile fires and short-range air defense systems.¹⁷

The uneven persistence and lethality of the general and enroute threat zones will make theater airlift operations dangerous but at times still possible. In the general realm, even major militaries will have difficulty keeping friendly forces and bases under continual threat of effective attack. The long-range aircraft, missiles, launch bases, ships, submarines, satellites, and over-thehorizon radar systems, and command and control systems that enemies will need to find and strike their targets, will all be in limited supply and subject to detection, attack, deception, aiming mistakes, and command decision errors. If they work as advertised, modern long-range weapon systems may appear to pose overwhelming threats to individual targets. But their general warfighting potential can only be understood in the full context of the interactions of opposing forces, real-world weapon reliabilities, and the usual fogs and frictions of armed combat. En-route airlift forces will face varying threat levels, influenced mainly by the locations of counterair-capable enemy forces along their routes of flight and, in the future, robotic counterair systems. Good intelligence and friendly air support could mitigate the threat posed by scattered enemy ground elements. If friendly airlift forces know the locations of enemy elements, they likely will be able to choose routes and tactics to evade them or defeat them with onboard defensive systems. Counterair ground "mines" could be particularly problematic since enemies could sow them anywhere in a battle zone. Further, their initial detection systems could be aural, electro-optical, infrared, or otherwise undetectable until the moment the mines activated their weapon guidance systems and launched their weapons.¹⁸ Again, the chief defenses against such systems will be good intelligence and onboard defensive systems.

In contrast, the threat environments near and on theater airlift destinations could be acute and persistent. Within about 30 nautical miles of enemy forces, theater airlift forces will risk detection by numerous short- and medium-range radar and other surveillance systems and from attacks by a host of high-probability-of-kill surface-to-air missile systems, fixed- and rotary-wing air-craft, drone aircraft, and so on. They also will be vulnerable to attack by rocket and tube artillery, which can strike in the air with proximity-fused projectiles or shower landing areas with massed fires within minutes of detection. Airlift forces will be especially vulnerable if obliged to repeatedly utilize known or predictable locations, such as prepared landing strips, parking, and "hide" areas. If presented with such predictability, future enemies may periodically fire short-range weapons at them "in-the-blind" on the chance of either hitting aircraft or their ground-handling equipment and personnel.

Mission Requirements

Theater airlift mission requirements are the sum of a complex interplay of many desired mission and performance criteria. Mission requirements generally reflect the scale and equipment dimensions of force movements and sustainment, desired delivery terminals, and the necessary densities of delivery in geography and time. The performance criteria of airlift operations are largely based on aircraft cruise and maximum speeds, range, payload, terminal agility, and survivability. Terminal agility is not a common term, but in this study, it relates to the range of terminal points (airports, air bases, unsurfaced airfields, landing zones, and so forth) that an aircraft can utilize. Fixedwing aircraft of high-terminal agility can operate into and from shorter, rougher, and more weakly-surfaced runways and parking areas than aircraft of lower terminal agility. Helicopters, which can operate from areas not much larger than their rotor diameters, have maximal terminal agilities. Large commercial jets, in contrast, have minimal airfield agilities because they are tied operationally to major airports and air bases with long and paved runways and acres of hard-surfaced parking areas.

Survivability is also a variable quantity among different types of aircraft, depending on the match between their performance specifications, mission requirements, threats they face, and the friendly air support available to them. As one example of the relationships involved; SSTOL transports capable of a 380 knot cruise would be more survivable than 240 knot V/SSTOL aircraft because they would spend less time in enemy territory, be easier for friendly air-defense-suppression and combat air patrol jets to pace and support, and they would possess significant airfield agilities.

For the Army

Current and evolving USA operational concepts require the high-capacity support of airfield-agile theater transport aircraft. The USA's movement and maneuver doctrine, for example, is predicated on task-organized ground units maneuvering, concentrating, fighting, and then dispersing in concert with similar units, to "force enemies. . . to fight against multiple types of attacks from multiple directions and domains.¹⁹ Such maneuvers, the USA believes, must be along multiple avenues of approach, be unpredictable in their use of departure and arrival points, and be conducted over "strategic distances." The USA also expects ground unit air deployments to terminate as close as possible to their tactical PON/Es to reduce the delays and dangers of long ground movements. Predictably, many of these PON/Es will be beyond

land lines of communication and not near major airfields. Therefore, airdeploying units and their subsequent logistical support must come from high-capacity airlift aircraft, and possesses as much airfield agility as practical considering other requirements of range, payload, speed, and so on. These aircraft also must be able to survive in the presence of the enemy threat capabilities they must necessarily face.²⁰

USA and USAF studies have highlighted the importance of airfield agility to the USA's ability to get to the fight. In an access study of a large African country, the Army's Capabilities Integration Center estimated that only about 24 percent of its territory lay within 50 km of airfields capable of handling the C-17s and C-130s needed to move Stryker units.²¹ Further, a USAF study found only 16 surveyed airfields in Sub-Saharan Africa possessing the runways and aircraft parking capacities necessary for them to serve as hubs to facilitate the transfers of cargos from C-17s into C-130s for onward movement to less-developed airfields.²²

The deployment of a single Stryker Brigade Combat Team (SBCT) provides an instructive example of just how much movement capacity the Army needs. The brigade itself consists of 4,200 Soldiers and 15,000 tons of materiel and requires about 400 C-17 or 200 C-5 sorties to lift.²³ But this number does not include the support elements drawn from higher echelons, such as aviation, military police, additional artillery units, and others. These must go with the SBCT to tailor it for specific missions and to give it sustained fighting power. These support elements could add hundreds of airlift sorties to the brigade's deployment bill. Additionally, SBCTs engaged in maneuver and combat will require around 350-400 tons of sustainment each day, in the form of water, food, fuel, munitions, engineer supplies, replacement vehicles, and so on.²⁴ Compared to the size of the airlift fleet, about 220 C-17s and 52 C-5s, these are very large demand signals, particularly given that the USAF's plans on extracting an average of only 18 and 45 tons of lift from each C-130 and C-17 sortie, respectively.²⁵ An IBCT movement from the continental US to northeastern Europe, for example, could tie down 20 percent of the available C-17 fleet, about 40 aircraft, for 14 days, assuming an out-and-back cycle time of 36 hours and the availability of enough developed and undamaged airfields to accept such a flow of aircraft. In a major conflict with Russia in that region, any presumptions of such airfield availabilities likely would reflect strategies based on hopefulness rather than reasonable risk management.

These movement tasks and tonnages give some indication of the necessary size and capacity of the next theater airlifter. Most importantly, the aircraft must be able to carry all types of logistics, support, and protected firepower vehicles assigned to the Army's most deployable brigades; airborne, infantry, and Stryker. Currently, these protected firepower vehicles are enhancedarmor Strykers, which weigh about 22 tons, and M-2/3 Bradley Fighting Vehicles, which weigh about 30 tons. The USA also is committed to acquiring a new generation of medium-weight combat vehicles for air-deployable units and a next-generation combat vehicle to replace its M-1 Abrams tanks and Bradleys.²⁶ Recent USA steps to acquire test versions of available light tanks and infantry vehicles suggest that the next-generation theater airlifter should be able to lift at least 35 tons, although 40 tons would allow for weight growth as the program progresses.²⁷ The cabin sizes of the aircraft should accommodate the weight and dimensions of such vehicles and allow for efficient movement of lighter vehicles, medium-size helicopters, and cargo pallets.

USA commanders will also want theater airlift to pick up or deliver their combat forces with suitable *movement density*. Although not a commonlyused term, *movement density* usefully expresses the vital importance of quickly moving USA forces into and out of areas threatened by enemy counteractions, in condition to fight on arrival, and thereafter maintain local force dominance. Such movements minimize the disruption and vulnerabilities caused by transitioning units across domain boundaries, as from air movement to ground operations. Light infantry helicopter assaults are classic examples of dense deliveries because they involve the simultaneous arrival of complete companies and battalions ready to fight. In the future, given current USA vision documents, USAF airlift planners must anticipate supporting dense movements of airborne, infantry, Stryker, and post-Stryker protectedfirepower units.

Dense air deliveries of USA combat and support units will depend wholly or in part on airland procedures, that is, walking or driving out of or back into aircraft on the ground. Even airborne forces will depend on airland operations to bring in much of their combat support and combat service support elements, which are not parachute capable. Infantry, Stryker, and Heavy brigade combat teams have no parachute capabilities at all. So, in many force movements, theater airlift forces must be capable of putting hundreds of sorties into the vicinities of PON/Es, usually without the availability of enough developed airfields to accept them in the delivery densities required by the probabilities of enemy counteractions. So, if the USA is to have the mission capabilities it wants, it must have the support of airlift forces that can operate into austere networks of small and/or rough fields.

From the perspective of supporting dispersed ground operations in significant threat environments, the baseline operational range objective for the next-generation theater airlifter will be the product of several considerations. Most importantly, the future aircraft must have the range to connect intermediate support bases (ISB) to the PON/Es of transported units. The ISBs will be necessary to receive inbound intertheater airlifters carrying cargoes that theater airlifters will onload and move to forward locations. The limited numbers of such airfields in many parts of the world, in turn, will make aircraft operating on them predictable and lucrative targets for enemy air, missile, and SOF strikes. Consequently, in conflicts with enemies possessing weapon systems such as medium-range ballistic missiles, cruise missiles, and strong air-strike forces, these ISBs should be at least 800 nm back from the launch sites and bases of such weapons. Even this distance will not make ISBs invulnerable to attack; it will just oblige enemies to expend greater numbers of scarce weaponry and accept greater uncertainty in attacking them and increase warning times to friendly forces. Ideally, then, the next-generation theater airlift aircraft should have an unrefueled operational radius of about 1,000 nautical miles with an approximately 35 ton payload (i.e., a medium-weight armored vehicle) air dropped or airlanded at midpoint.²⁸

For the Air Force

At first glance, the USAF's theater mobility support requirements are modest in comparison to those of the USA in quantity and quality. Most importantly, USAF combat squadrons, apart from those of A-10s and C-130s, must operate from developed airfields, usually capable of handling C-5s and C-17s as well. With air refueling support, fighters and bombers can operate over great distances, which increases the number of appropriately developed airfields available to them. The deployment bills for air combat units are also modest in comparison to ground combat units. For example, deploying a fighter squadron and its support elements to an austere base, one with a runway but few if any support facilities, requires movement of somewhere between 300–500 tons of personnel and equipment.²⁹ Fire trucks likely would be the largest single items moved in such deployments, weighing between 20 tons for P-19-series vehicles to "Striker"-series trucks weighing more than 40 tons. At normal planning loads, the upper end of this deployment load roughly equates to a dozen or so C-17s or half that number of C-5 sorties. Because developed airfields usually are located near large cities and ports, air combat units likely will draw most of their sustainment from surface transport modes. But if they need air transport for such things as repositioning munitions or jumping over at-risk or damaged surface lines of communication, the airlift demand signal for a single combat squadron could reach several hundred tons or more per day for fuel, munitions, and general supplies.

In conflicts with peer competitors, the logistics picture might not be so rosy. In the first place, the competition for strategic airlifters will be intense in the early phases of a major conflict, with deleterious impact on their availability to support air combat bases. Air combat bases that can park a lot of fighters and handle a steady flow of transport aircraft also might be in shorter supply or more remote from battle zones than hoped for by commanders. In the context of a South China Sea conflict, for example, the island of Luzon would be a logical region for forward basing, but it possesses only five airfields with runways at least 7,000 feet long and parking ramps to handle a dozen fighters and one or two C-17s.³⁰ Further, in peer conflicts, all or at least most US air bases will be threatened or damaged by enemy attacks, if not from distant missile bases or formations of penetrating strike aircraft, then possibly from SOF, submarines and aircraft launching cruise missiles, or even electromagnetic or kinetic weapons from space. An enemy sympathizer with a cell phone might be all the surveillance and target cueing needed by future enemies to ambush a munitions-laden C-17 taxiing past a row of fighters or parked in an established aerial port area. Indeed, it would be a foolish adversary who was not willing to risk a submarine to launch a devastating cruise missile volley against a main base with its parking ramps full of the transports, air refueling, fighter, and support aircraft so essential to the American way of war.

In such circumstances, airfield-agile and high-capacity theater transports, SSTOL-RF or V/SSTOL, will be essential to air combat operations. Because they can operate off concrete, those aircraft would reduce the competition for paved parking space, which might allow combat aircraft to disperse and present less attractive targets to enemy weaponeers. Indeed, these types of aircraft may not operate on primary airfields at all. They might, instead, operate from small airfields, highway strips, or unsurfaced rough fields nearby; far enough away from supported bases to reduce their vulnerability to enemy targeting and attack but close enough to minimize the burden of transporting their loads from intertheater transports operating through main bases to theater airlifters ready to take those loads forward. If alternate landing strips are not available, SSTOL-RF and V/SSTOL transports could still use the paved or unpaved margins of main bases, at least somewhat further away from combat operations areas.

The Air Force's movement toward disaggregated air operations places an additional premium on support from airfield-agile transport aircraft. So far, its evolution of Rapid Raptor/Agile Combat Employment exercises in the last several years has relied on C-17s to transport the supplies, weapons, and even fuel needed to support flights of fighters operating from austere bases for

short periods of time.³¹ On the one hand, this reliance makes logistical sense, given the more restricted capabilities in speed, range, and payload of the C-130 transports available as the alternative. On the other hand, using C-17s as rolling magazines for handfuls of fighters will reduce their productivity at times when they will be precious assets to support other logistics and movement demands. Moreover, while dispersal airfields able to accommodate standard fighters will be long enough for C-17s also, they might not have the necessary width or strengths to handle the big aircraft. C-17s have aircraft classification numbers equivalent to many large civil airliners and significantly higher than those of fighter-type aircraft.³² Consequently, loaded C-17s have proven in tests and operations to damage or destroy runways paved to lower strength standards than major airports and air bases after just a few landing and takeoff cycles.³³ Each C-17 also requires an acre-size parking area, which may be all of or more than the ramp space available at many regional airports or even overseas military bases.



Figure 7. The main gear of this C-130 has crushed the asphalt surface of this taxiway.

Mission Fit

Calculating the ability of a category of aircraft to satisfy theater airlift requirements, or its "mission fit," requires an assessment of a complex interplay of performance characteristics typical of that category. For this comparison of the relative theater airlift mission fits of SSTOL-RF and V/SSTOL aircraft, these performance characteristics include their range-payload capabilities, abilities to carry required payloads, airfield agilities, and general survivability. When understood as an interconnected system, these performance characteristics determine the ability of each category of aircraft to deliver required payloads to desired destinations and in delivery profiles that satisfy the tactical and logistical requirements of the forces they support.

Range-Payload Characteristics

The data in figure 2 indicate that the main determinant in the relative range-payload and general productivity characteristics of SSTOL-RF and V/ SSTOL aircraft is the way they produce vertical lift. The tiltwing XC-142, which employs mostly conventional propellers for lift could carry 8,000 pounds of cargo for 500 miles, while the V-22, which utilizes proprotors, can carry the same load for only 170 nm. The XC-142's advantage derives from its better vehicle lift/drag ratio over the V-22, about 9 versus about 6.5, respectively, and from the greater propulsive efficiency of propellers over proprotors in high-speed cruise. Nevertheless, the XC-142 had only half of the productivity of the V-22 in terms of fuel burned per ton-mile of transportation provided. This was because of the relative inefficiency of the 142's propellers in vertical flight, which necessitated a much smaller aircraft in gross weight and concomitant reductions in its fuel and cargo loads. A summary of the comparative performances of the two concepts would be that the aerodynamics and power ratios of the V-22 favored more vertical-lift capacity at the expense of cruise speed and range, while those of the XC-142 emphasized more cruise speed and range at the expense of VTOL efficiency and productivity.³⁴

Consideration of the performance characteristics of the Breguet 941, however, suggests opportunities to extract greater productivity from SSTOL-RF designs. Without the necessity of carrying the large engines needed to lift the aircraft vertically, the 941 outperformed the XC-142 and V-22 in range and productivity and did comparatively well in maximum payload and airspeed performance. On half of the power of the other two aircraft, the Breguet design carried nearly twice the payload as the XC-142 and 8,000 lb. of cargo eight times further than the V-22. These comparative performance numbers reinforce the notion presented earlier in this study that VTOL capabilities require major tradeoffs in the payloads, range, and productivity of theater airlift aircraft designs.

Ability to Carry Required Payloads

The practicality of developing a SSTOL-RF or V/SSTOL aircraft able to carry the payloads required by the USAF and especially the USA is not clear. No aircraft with these capabilities has ever flown with anything near the 40 ton armored combat vehicles or 20-40 ton fire trucks representing the highend USA and USAF single-item air movement requirements for forward operations. Moreover, the useful load of the future aircraft must allow for fuel, which will outweigh the payload on longer flights. For example, the SSTOL-RF Breguet 941 was the most aerodynamically efficient and productive of the aircraft examined above. Based on the data in figure 2, the aircraft would have required more than 26,000 lb. of fuel to move 8,000 lb. of cargo for 2,000 nm, had it been able to perform such a mission, which it was not. A simplistic extrapolation of this performance to an aircraft carrying an 80,000 lb. load, would indicate a required fuel load of something like 250,000 lb. Based on these numbers and another extrapolation of the 40:60 payload-to-aircraft gross weight ratio of the Breguet 941, the future theater airlifter would have a gross weight of at least 420,000 lb. or almost three times the normal gross weight of a C-130J. Given the high specific fuel consumptions of the XC-142 and V-22, the challenge of designing V/SSTOL-RFs with strategic range and the ability to carry large equipment items seems daunting or even impossible.

If engineers could develop a SSTOL-RF or V/SSTOL aircraft with aerodynamic efficiency closer to fixed wing aircraft, however, the challenge of achieving the USA and USAF's range/payload requirements could be reduced substantially. In comparison to the V-22 carrying one-third of its maximum payload (8,000/24,000 lb.) for 170 nm, a C-130J could carry one third of its maximum payload (14,000/42,000 lb.) for 2,800 nm or about 35,000 lb. over the 2,000 mile range. The plane would fly the 2,000-mile trip in 5.9 hours and burn 29,000 lb. of fuel, while a notional V-22 able to fly 2,000 miles and carrying 8,000 lb. would burn about 26,000 lb. in an 8.3-hour flight. Putting the two aircraft in a common frame of reference; the C-130J's fuel/payload weight ratio for that trip would have been 1.1:1 while that of the notional V-22 would have been about 3.32:1. Once again, the range and payload penalties of SSTOL-RF and particularly V/SSTOL are clear and likely to be the crucial challenge to future engineers trying to accommodate the full span of theater airlift missions.



Figure 8. SSTOL landing strips in randomly-selected area in northeastern Europe. Using Google Earth's street-level feature, the author scanned most of these fields to determine that they were level with no significant obstructions or ditches.

Airfield Agilities

In terms of airfield agility, the operational advantage of V/SSTOL over SS-TOL-RF aircraft likely will not be as significant as would first appear. Certainly, VTOL-capable aircraft can land almost anywhere not covered by heavy vegetation, jagged terrain, or man-made objects. But, as this map at figure 3 indicates, the number of SSTOL-RF landing strips available in other kinds of terrain also can be practically limitless. The map depicts a randomly selected area in northeastern Europe near the Baltic Sea, approximately 2-by-4 kilometer in its dimensions. Within that area are more than 40 likely SSTOL-RF landing zones, each at least 1500 feet long. Presuming the availability of a class of SSTOL-RF aircraft able to move a medium-weight mechanized battalion in, say 96 sorties, 48 SSTOL-RFs operating from a debarkation base located 1,000 miles away could deliver the entire battalion in two lifts within one period of darkness. With each of these lifts consisting of five formations of eight aircraft each and all aircraft in a formation landing simultaneously on adjacent airstrips, no aircraft would stay on the ground more than 15 minutes, no sequential formations need land on the same set of strips, and the total ground time of each lift would be less than 45 minutes. Moreover, the second lift might well use an entirely different group of landing strips located in another set of fields along the battalion's line of advance. So, in most parts of the world, SSTOL-RF transports could achieve delivery densities of equivalent tactical

values as those possible from VTOL aircraft, presuming that VTOLs could cover the necessary distances.

There are many reasons to believe that SSTOL-RF aircraft could reliably and safely achieve the airfield agility just described. Historically, numerous engineering efforts have produced landing gear concepts that successfully improved the rough-field capabilities of conventional and STOL aircraft. The Arado 232 of World War II, for example, combined high-lift wings and flaps, wing blowing, and multibogie landing gear that allowed operations on strips characterized by deep mud, ditches up to five feet across, and obstacles up to 18 inches high.³⁵ American engineers experimented in the 1950s with track landing systems and pneumatic air-cushion systems that also improved the ability of aircraft to traverse soft ground. Large, low-pressure tires also lower the aircraft classification numbers and soft-terrain trafficability of aircraft. The C-130, for example, has an aircraft classification number range of 29–33, and can utilize soft fields down to the consistency of wet sod many times without making them unusable through rutting and gouging.³⁶ Exceptional fixed-wing STOL aircraft, like the DeHavilland Canada DHC-5 and -6 have ACNs of 6-12 and 3-5 respectively, and operate on surfaces that humans would struggle to traverse on foot.³⁷ Finally, the slow landing speeds of SS-TOL-RF aircraft are an important assurance of their ability to go into places that conventional wisdom informed by current aircraft capabilities might think impossible. Many videos are available on the web and show SSTOL-RF transports landing and taking off from dirt roads, roughly graded rocky terrain, uncleared sagebrush, and so on.³⁸



Figure 9. The Arado 232 could operate into and from exceptionally rough and soft airfields. For normal operations, the auxiliary load wheels under the fuse-lage were removed and the massive main gear were retractable.



Figure 10. Tracked landing gear experiments in the late 1940s were technically successful and gave aircraft as large as the 410,000 lb B-36 the capability to operate on otherwise understrength airfields and even on open fields, as in this photo. These landing gear also were retractable.

Survivability

The survivability of future theater transports will depend on airfield agility, surprise, speed, and general air situations. Airfield agility likely will be of first importance, since it will allow them to bed down in unpredictable locations in the rear, exploit shifting networks of landing areas, and spend minimum time on the ground at forward destinations. Artillery, long-range missiles, and other weapons have finite effects. Consequently, aiming errors of even a few hundred yards can mean the difference between a hit or a miss on a transport moving around or stopped for a few minutes somewhere on an array of airstrips. Transport aircraft flight speeds and short ground times will minimize exposure to enemy weapon engagement zones and affect their ability to integrate with combat air operations. Faster aircraft will be better able to exploit the cover and distraction provided by friendly air forces, when they surge in offensive operations. While the shooters occupy an enemy air force's attention, fast and airfield agile transport formations can penetrate to and withdraw from forward landing zones or air bases. Faster aircraft will also be easier and less time demanding for friendly fighter and air defense suppression aircraft to escort. The freedom of theater airlift forces to exploit their capabilities will depend, of course, on the general air situation. If enemy warning and control systems can maintain more-or-less continuous overwatch of air battle zones, then sustained airlift operations will be difficult, even impossible. But even if friendly combat air forces can establish only periods of localized air dominance, airlift aircraft with the characteristics discussed here will be capable of supporting Army maneuver and Air Force agile combat employment operations.

In general, then, both SSTOL-RF and V/SSTOL aircraft will be survivable in future peer-on-peer conflicts. Both design types should have the necessary airfield agilities to achieve and retain surprise for themselves and the forces receiving their support. In some circumstances, the marginally greater airfield agilities of V/SSTOL aircraft may enhance their survivability. But that advantage would be too costly to attain, if it was unavoidably offset by significant range and productivity reductions and reduced delivery densities. As evidenced by the XC-142, both types of aircraft are capable of moderate to high cruise speeds of from around 220 to 400 knots and perhaps higher for jet powered aircraft. But, experiments of larger jet aircraft in the SSTOL transport role, so far limited to the QSRA, indicate that jet powered aircraft can be faster than turboprop and helicopter-type aircraft, but likely will have reduced airfield agility, with secondary reductions in productivity and survivability.

Recommendations

This study addressed the question of whether the USAF should anticipate modernizing its core theater airlift fleet with SSTOL-RF or V/SSTOL-RF aircraft. In general terms, its exploration of this choice indicates that while both types of aircraft can meet some key mission requirements of the USA and USAF, each also present design characteristics and performance tradeoffs that limit its utility in some specific mission areas. More specifically, this study presents insights that:

- Both the USA and the USAF will benefit in future peer-on-peer conflicts from the availability of theater air transports able to carry 35–40 ton payloads over 2,000 miles and capable of SSTOL-RF or V/SSTOL-RF airfield operations.
- SSTOL-RF capabilities are a proven technology option.
- V/SSTOL-RF aircraft employing helicopter-like blades are efficient in vertical flight but much less efficient in cruise flight than V/SSTOL-RF aircraft utilizing smaller, higher-speed propellers.
- The structural and powerplant features of V/SSTOL-RF and SSTOL-RF aircraft are heavy and adversely affect their speed-payload and productivity capabilities.

- SSTOL-RF aircraft not burdened by the larger powerplants and structural provisions for VTOL flight can carry a greater fraction of their gross weight as fuel and cargo.
- For most operational purposes, SSTOL-RF and V/SSTOL-RF aircraft can have equivalent airfield agilities, speeds, and survivability.
- The utility of jet-powered aircraft in SSTOL-RF and V/SSTOL-RF operations are less explored than the use of blade and propeller-driven aircraft.
- Reducing range requirements would provide greater leverage over the size and weight of future theater airlift aircraft than other design adjustments.

Given these insights, this study makes several recommendations. First, the time has come for the DOD to conduct a joint-service analysis of the employment and necessary design features of the next theater airlifter. Given the dangerous inadequacies of the present theater airlift fleet, modernizing it should have a high priority, perhaps even over-recapitalizing the aging longrange airlift fleet. The theater airlift shortfall undermines the USAF's ability to accomplish key war-fighting responsibilities, and no combination of existing aircraft can close it. The aging state of the C-5 and C-17 fleets, in contrast, represent marginal operational and capacity challenges that can be addressed either through service life extensions of those aircraft or even by starting production of improved versions of them. Secondly, the defense community should approach intertheater, intratheater, and battlefield airlift modernization as the integrated operational system that they are. Presently, the USA's Future Vertical Lift program is ahead of the USAF's airlift modernization effort, such as it is. But interviews for this study and the absence of a relevant literature on the subject suggests that the services are continuing their hidebound habit of not working well together to ensure the effectiveness of the national air mobility system, particularly its theater airlift component.³⁹ Third, this study recommends that the USA and the USAF look hard at whether the marginal airfield flexibility benefits of V/SSTOL-RF over SSTOL-RF are worth its additional financial costs and operational offsets. V/SSTOL-RF may be the theoretical ideal for airfield agility, but SSTOL-RF offers almost the same tactical utility, likely would be less expensive to develop, and could support a wider range of missions in terms of range and payload needs.

While it is too early to predict the design characteristics for a future SS-TOL-RF with confidence, the data explored in this study do suggest a general approach. The key to theater airlift's success in the future likely will be an aircraft that blends high-speed, aerodynamic efficiency, and good rangepayload characteristics. A SSTOL-RF aircraft with a *partially* tiltable wing and employing high-speed propellers may well turn out to be the best option for optimizing this blend of performance characteristics. A tilt wing would provide the thrust vectoring needed for SSTOL performance and slow landing and takeoff speeds to improve rough-field performance. The propellers would provide wing blowing for additional lift and top speeds in the 400 knot range, as they do already for modern turboprops like the Airbus A400M. Powerplant configuration options could include the traditional option of linking engines directly to their propellers and interlinking engines with cross shafting, or one of distributing electrical power from turbine-powered generators to multiple motors and high-speed propellers along the wings. This second option would allow designers to provide for continuous wing blowing of higher aspect ratio wings, which would further improve the aerodynamics of the aircraft. Undoubtedly, there will be other aerodynamic and powerplant design approaches to explore. But designers probably should avoid any effort to give the aircraft even modest VTOL capabilities, given the increased power demands, dangers from debris damage, and propeller-rotor tradeoffs that such a compromise would likely entail. Above all else, the DOD and relevant stakeholders need to get the process of acquiring a new theater airlifter underway now, lest the present gaps between requirements and the present fleet's operational capabilities grow wider and potentially lead to operational handicaps and even disasters in the future.

Notes

(Notes appear in shortened form except where indicated. For full details, see the appropriate entry in the bibliography.)

1. Department of Defense, Joint Publication 3-17.

2. US Department of the Army, *United States Army 2003 Transformation* Roadmap, 8–15; and Pernin et al., *Lessons from the Army's Future Combat Systems Program*, 54–66.

3. A California bearing ratio (CBR) measures the resistance of unpaved surfaces to compression. A CBR of 100 equates to a surface of crushed California limestone and nearly equivalent to concrete in its strength. A CBR of 5 equates to wet loamy soil, while 10 equates to a mixture of wet sand and soil. The number of aircraft passes (landing + takeoff) supportable by a given surface depends on several factors, particularly its CBR, the weight of the aircraft, and the ground pressure of their tires.

4. Wieder and Shoop, *Landing-Zone and Drop-Zone Criteria*, 5–12 and 32–41; and Lockheed Martin Corporation, "C-130J Super Hercules."

5. Farrell, "Aerodynamic Design of the V-22" 2-4; and Mashman, "Tiltrotor Offers a Choice," 2.

6. Gaebe, "Some Important Design Considerations," 9–10; and Quigley, Innis, and Holzhauser, A Flight Investigation of the Performance, 5.

7. Gaebe, "Some Important Design Considerations," 11-12.

8. T.O. [Technical Order] 1C-7A-1-1, 71.

9. USA Materiel Command, Test and Evaluation Command, "Flying Qualities and Performance, 56.

10. Eppel, "Quiet Short-Haul Research Aircraft Familiarization," 1, 33–36; and Cochrane, *Overview of the Quiet Short-Haul* Research, 39. The "aggressive landing techniques" included flying close to the aircraft's minimum control speed and following an approach glide slope angle of 7.5° (compared to the 3° instrument landing system glide slope used in normal civil airline operations.)

11. Anderson, "Historical Overview of V/STOL, 9-4.

12. Meese and Millett, "21st Century Tactical Airlifter," 409.

13. Leishman, *The Helicopter: Thinking Forward, Looking Back*, 4. I am indebted to Dr. Leishman for his patient tutoring on rotary-wing aerodynamics and his careful editing of my efforts to express complex aerodynamic principals and relationships in terms apprehensible to other non-engineers. Dr. Leishman presently is a professor of Aerospace Engineering at Embry–Riddle Aeronautical University's Daytona Beach, Florida campus.

14. Owen, "Theater Airlift Modernization," 17.

15. Curtis E. LeMay Center for Doctrine Development and Education, "Annex 3-17," 34.

16. Among the many future threat discussions, one of the more succinct and comprehensive is Vick, *Air Base Attacks and Defensive Counters*, 19–37; UK Ministry of Defence, *Strategic Trends Programme*, 13–21; Owen, *Shaping Air Mobility Forces for Future Relevance*, 14–16; and Gordon et al., *Enhanced Army Airborne Forces*, 16–28.

17. The general-enroute-terminal construct is the author's creation. In the absence of anything more than short and shallow discussions of threat environments in key publications, such as Air Force Doctrine Document 3-17, 34–37, the need for more detailed threat categorizations and analyses are obvious. The author's construct is also consistent with what remains the best open-source discussion of airlift operations in threat environments: Skorupa, *Self-Protective Measures to Enhance Airlift Operations*.

18. As of writing, the author could find no publicly-available description of fully autonomous and *air deployable* counterair mine systems, but the technical elements of such a system have been in existence for many years in such systems as the Boeing Avenger, BAE Systems Rapier, and Rheinmetall's Skyshield and Mantis Unmanned Air Vehicle systems. The ideal autonomous air defense "minefield" likely would be populated by much lighter systems based on nonemitting detection and targeting systems and short-range missiles or electromagnetic weapons. See "NBS Mantis Air Defence Protection System"; and Freedberg, "Army Races to Rebuild Short-Range."

19. US Department of the Army Training and Doctrine Command, U.S. Army Functional Concept for Movement and Maneuver, 13–15, 25.

20. These requirements are laid out in many documents, but no more succinctly and completely than in the Air Mobility Command, *Joint Future Theater* Lift, 16–18.

21. US Army Training and Doctrine Command, Capabilities Integration Center DPMO, "Global Deployment Assessment," slides 13–14.

22. Jones, email to author, 29 December 2015. At the time, Captain Jones was an operations research scientist at the combined headquarters of United States Air Forces Europe (USAFE), Air Forces Africa, and USAFE A9/A9A.

23. Precise movement data varied among the several sources reviewed for this study, but the most authoritative was US Military Surface Deployment and Distribution Command, Transportation Engineering Agency, Deployability Division, *Deployment Planning Guide* Scott AFB, IL, December 2011, 15 and 52-5, https://www.sddc.army.mil.

24. These numbers are approximate and are the outcome of telephone conversations the author had with staff members at the US Army Center of Maneuver Excellence, Fort Benning, Georgia, on 23 March 2018. The notes from these conversations are in the author's files. 25. US Department of the Air Force, Air Force Pamphlet 10-1403, 12.

26. US Army Training and Doctrine Command, US Army Combat Vehicle Modernization Strategy, 1–12; and US Army Training and Doctrine Command News Center, "Initial Prototypes for Next-Gen."

27. Judson, "Army's New Light Tank Competition"; and South, "Army Looks to Add a Light Tank."

28. 1,000 nm is at the upper limit of DOD estimates for this mission but justifiably so. After assessing an Army requirement for a 500-nm radius of action as too limited, the Air Force raised the goal to 1,000 nm in its "Initial Capabilities Document for Joint Future Theater Lift (JFTL)," 12 October 2009, 5–6, 9, author's files. Seeking to meet the Army's desire for a large vertical takeoff and landing theater transport to support its mounted vertical maneuver concept, the Air Mobility Command later took a 540 nm radius as representative of the mission in its *Joint Future Theater Lift* study, 17, 40-1.

29. This data is hard to find in unclassified channels. This estimate is drawn from Myron Hura and others, *Interoperability: A Continuing Challenge in Coalition Air Operations* (Santa Monica, CA: RAND Corporation, 2001): 217. Also, see Matthew W. Goddard, *Estimating Deployed Airlift and Equipment Requirements for F-16 Aircraft in Support of the Advanced Logistics Project*, thesis, Air Force Institute of Technology, Wright Patterson AFB, OH, 2001, 75.

30. These airfields are Ninoy-Aquino, Subic, Clark, San Fernando, and Laoang.

31. McCullough, "Ace in the Hole," 24–25.

32. Aircraft classification numbers (ACN) are the international standard for measuring the stress aircraft place on paved surfaces. See *Air Force Pamphlet 10-1403*, for a representative list of ACNs, 10.

33. The C-17's tested effects on soft fields are discussed in Department of the Air Force, Civil Engineer Support Agency, "Engineering Technical Letter 97-9; Criteria and Guidance for C-17 Contingency and Training Operations on Semi-Prepared Airfields," 15 October 1997, 10, https://www.wbdg.org/ffc/af-afcec, 33. For the aircraft's tendency to damage regional airfields, see *Dallas News*, "Nepal Runway Damage Holds up Aid Aircraft," May 2015, https://www.dallasnews.com; and Rene Romo, "Las Cruces Puts Runway Damage at \$1 Million," *Albuquerque Journal*, 1 September 1 2004, https://www.abqjournal.com.

34. The author extracted or developed the numbers presented in figure 2 from several sources, including aircraft performance manuals, various editions of *Jane's All the World's Aircraft*, NASA project reports, manufacturer brochures, and data provided by Army and Air Force sources. Consequently, these data are close enough for the comparative purposes of this study but should not be taken as definitive.

35. Mrozik, German Air Force Airlift Operations, 40-1.

36. Lockheed Martin Corporation, "C-130J Super Hercules."

37. Transport Canada Technical Evaluation and Engineering Department, *Aircraft Classification Numbers*.

38. For examples of SSTOL-RF performance, see, "Ling-Tempco-Vought (LTV) XC-142," 26 September 2009, https://www.youtube.com/watch?v=j7VGzpfL-gY; and "CC-115 STOL," accessed 6 May 2018, https://www.youtube.com/watch?v=EaXwE2ngRBk.

39. Owen, *Air Mobility: A Brief History*, 105–16, 139–55, 220–23, 279, and 293–94; Williams, *An Airlift Odyssey*; and Owen, "Air Force Airlift and the Army's Relevance."

Bibliography

- Air Force Pamphlet 10-1403. *Air Mobility Planning Factors*, 12 December 2011.
- Anderson, Seth B., "Historical Overview of V/STOL Aircraft Technology," NASA Technical Memorandum 81280, March 1981.
- Curtis E. LeMay Center for Doctrine Development and Education, "Annex 3-17, Air Mobility Operations," 14 October 2011.
- Dallas News. "Nepal Runway Damage Holds up Aid Aircraft." May 2015.
- Department of the Air Force, Civil Engineer Support Agency. "Engineering Technical Letter 97-9; Criteria and Guidance for C-17 Contingency and Training Operations on Semi-Prepared Airfields." 15 October 1997.
- Eppel, Joseph C. NASA. "Quiet Short-Haul Research Aircraft Familiarization Document, Revision 1." NASA Technical Memorandum 81298. Washington, DC: NASA, 1981.
- Farrell, Michael K. "Aerodynamic Design of the V-22 Osprey Proprotor." Presentation, American Helicopter Society, 22 May 1989.
- Freedberg, Sydney J. Jr. "Army Races to Rebuild Short-Range Air Defense: New Lasers, Vehicles, Units." *Breaking Defense*, 21 February 2017.
- *Gaebe*, H. M. "Some Important Design Considerations on the XC-142 Triservice VSTOL." *Journal of Aircraft* 2, no. 1 (January–February 1965, 9–10.
- Goddard, Matthew. *Estimating Deployed Airlift and Equipment Requirements* for F-16 Aircraft in Support of the Advanced Logistics Project. Master's thesis, Air Force Institute of Technology, Wright Patterson AFB, OH, 2001.
- Gordon, John et al., *Enhanced Army Airborne Forces: A New Joint Operational Capability* (Santa Monica, CA: RAND, 2014).
- Hura, Myron et al. *Interoperability: A Continuing Challenge in Coalition Air Operations.* Santa Monica, CA: RAND Corporation, 2001.
- Joint Chiefs of Staff, Joint Publication 3-17: *Air Mobility Operations*. 30 September 2013.
- Joint Future Theater Lift: Technology Study Final Report. Scott AFB, IL, 20 February 2013.
- Jones, Christopher M. Email to author. 29 December 2015.
- Judson, Jen. "Army's New Light Tank Competition Kicks Off." *Defense News*, 22 November 2017.
- Kimmons, Sean. *Army News Service*. "Initial Prototypes for Next-Gen Combat Vehicle to Focus on Manned-Unmanned Teaming," 23 March 2018.
- Leishman, J. Gordon. *The Helicopter: Thinking Forward, Looking Back*. College Park, MD: College Park Press, 2007.

- Lockheed Martin Corporation. "C-130J Super Hercules: Whatever the Situation, We'll Be There."
- Mashman, Joe. "Tiltrotor Offers a Choice," *Flight Safety Foundation Helicopter Safety* 14, no. 6. November/December 1988.
- McCullough, Amy. "Ace in the Hole." *Air Force Magazine*, 2017 Air Warfare *Symposium Special Edition*, February 2017.
- Meese, J. R. and Millett, Jr., M., "The 21st Century Tactical Airlifter." SAE Technical Paper 872339, 1987.
- Morzik, Fritz. US Department of the Air Force Historical Division. *German Air Force Airlift Operations*, Washington, DC: USAF, 1961, 40-1.
- "NBS Mantis Air Defence Protection System." Army Technology.
- Owen, Robert C. *Air Mobility: A Brief History of the American Experience*. Lincoln, NE: University of Nebraska, 2013.
 - ——. Shaping Air Mobility Forces for Future Relevance. Maxwell AFB, AL: USAF Research Institute, 2017.

 - ------. "Theater Airlift Modernization: Options for Closing the Gap." *Joint Force Quarterly* 75. October 2014.
- Pernin, Christopher G. et al. *Lessons from the Army's Future Combat Systems Program.* Los Angeles, CA: RAND Corporation, 2012.
- Quigley, Hervey C., Innis, Robert C., and Holzhauser, Curt A. A Flight Investigation of the Performance, Handling Qualities and Operational Characteristics of a Deflected Slipstream STOL Transport Airplane Having Four Interconnected Propellers. Washington, DC: National Aeronautics and Space Administration (NASA). March 1964.
- Romo, Rene. "Las Cruces Puts Runway Damage at \$1 Million." *Albuquerque Journal*. 1 September 2004.
- Shoop, Sally A. and Wieder, Wendy L. US Army (USA) Corps of Engineers. Engineer Research and Development Center, *Landing-Zone and Drop--Zone Criteria*, ERCD/CRREL SR-17-1. Vicksburg, MS: Cold Regions Research and Engineering Laboratory, 2017.
- Shovlin, Michael D. and Cochrane, John A. NASA. *An Overview of the Quiet Short-Haul Research Aircraft Program*. NASA Technical Memorandum 78545. Washington, DC: NASA, November 1978.
- Skorupa, John A. Self-Protective Measures to Enhance Airlift Operations in Hostile Environments. Maxwell AFB, AL: Air University Press, 1989.
- South, Todd. "Army Looks to Add a Light Tank to Its Formations. Army *Times*. 1 January 2018.

- T. O. (Technical Order) 1C-7A-1-1. *Flight Manual Performance Data: USAF Series C-7A Aircraft*, Change 4-2. October 1972.
- Transport Canada Technical Evaluation and Engineering Department. *Aircraft Classification Numbers (ACNs)*. Ottawa, Ontario: Transport Canada, 2001.
- UK Ministry of Defence. *Strategic Trends Programme: Future Operating Environment*. London: MOD, 2015.
- US Army Materiel Command, Test and Evaluation Command. "Flying Qualities and Performance Evaluation of the Breguet 941 Turbo-Prop Troop Transport." Edwards AFB, CA: USA Aviation Test Activity, 1964.
- US Army Training and Doctrine Command, Capabilities Integration Center DPMO. "Global Deployment Assessment: A Strategic Terrain Analysis Examining Deployment Considerations Within the Arc of Instability." Briefing by Jim Young. Ft Eustis, VA, 4 February 2009.
 - ——. *The US Army Combat Vehicle Modernization Strategy*. Fort Eustis, VA, 15 September 2015.
- US Department of the Air Force, Air Force Pamphlet 10-1403, Operations, Air Mobility Planning Factors, Washington, DC, December 2011, 12, static.e-publishing.af.mil/production/1/af_a3/.../afpam10-1403/afpam10-1403.pdf.

——. Doctrine Document 3-17, Air Mobility Operations (Maxwell AFB, AL: USAF, 14 February 2013), 25, https://www.doctrine.af.mil/Doctrine-Annexes/.

- US Department of the Army Training and Doctrine Command. *The U.S. Army Functional Concept for Movement and Maneuver, 2020–2040.* Fort Eustis, VA, 24 February 2017.
- US Department of the Army. *United States Army 2003 Transformation* Roadmap. Washington, DC: Department of Defense, 2003.
- US Military Surface Deployment and Distribution Command, Transportation Engineering Agency, Deployability Division. *Deployment Planning Guide*. Scott AFB, IL, December 2011.
- Vick, Alan J. Air Base Attacks and Defensive Counters: Historical Lessons and Future Challenges. Santa Monica, CA: RAND, 2015.
- Williams, Susan Mercer. An Airlift Odyssey: A History of Tactical Airlift Modernization, 1955–1983. Marietta, GA: Lockheed-Georgia Company, 1983.