V-22 Architecture & Civil Transport Options

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Systems Architecting and Engineering SAE 549
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The architecture of the V-22 "Osprey" Tiltrotor aircraft is the culmination of a systems architecting process involving several experimental aircraft over a period of 4 decades. The goal was to achieve a tiltrotor aircraft for both military and civilian aviation usage—a vehicle providing the vertical takeoff & landing and maneuvering capability of helicopters but also providing the speed, range, and durability of fixed-wing propeller aircraft. This combination required substantial systems architecting, technology development, and maturation to solve significant technology challenges in materials, engine systems, and airframe integration techniques for tiltrotor aircraft.

New civil aviation missions could be made possible with an aircraft that possess both the vertical take-off and landing (VTOL) and hover capability of a helicopter and the speed, range and durability of a sub-sonic propeller-driven aircraft. This requires substantial economic analysis and risk assessment of such aircraft operating in a civil aviation ecosystem in order to demonstrate publicly-acceptable and cost/effective application for various proposed operational use cases. The most viable mission is shown to be regular shuttle services of personnel and supplies to off-shore oil platforms, and the "best value" aircraft for that mission is shown to be a same-sized civilian version of the military V-22 "Osprey" Tiltrotor.

I. INTRODUCTION & BACKGROUND INFORMATION

There are several general types of powered aircraft, including fixed-wing, rotary-wing, and hybrids. Typical fixed-wing aircraft include sub-sonic propeller-driven vehicles and sub-sonic/supersonic jet engine-driven vehicles. Typical rotary-wing aircraft include helicopters. Each type of aircraft has advantages and disadvantages: compared to most helicopters, sub-sonic propeller-driven aircraft typically operate at a higher speed, have a longer range, provide a larger load capacity, can operate at higher altitudes, and require less maintenance per flight hour. But helicopters have vertical take-off and landing (VTOL) and hover capability, whereas most fixed-wing aircraft require a landing strip for take-off and landing, and cannot operate below a specified airspeed (except for specialized ducted-thrust jets such as the AV-8B and F-35).

Certain military missions would be made possible with an aircraft that possessed both the VTOL capability of a helicopter and the speed/range and other capabilities of a sub-sonic propeller-driven aircraft. The military missions include naval long-range ship to objective maneuver (STOM), personnel & combatant search-and-rescue (SAR, CSAR), personnel evacuations (EVAC), special operations force (SOF) support, mobile forward area re-fueling and re-arming operations, and other logistics support.

Certain civil aviation missions would be made possible with an aircraft that possessed both the VTOL capability of a helicopter and the speed/range and other capabilities of a sub-sonic propeller-driven aircraft. The civil aviation missions include the capability of ferrying passengers and their luggage from nearby large regional airports to smaller, local airports or landing areas without using ground transportation through congested cities. Other civil aviation missions include shuttle services to remote seaports or off-shore oil platforms, medical evacuation and ferrying of patients to hospitals, and shuttle services between local airports. In each case the mission includes both passengers, luggage, and potential cargo.

Starting in the 1950s, a number of experimental aircraft (e.g. the XV-1, XV-3, and XV-15) were developed to satisfy these special missions, through joint efforts of the U.S. Department of Defense (DoD) and the National Advisory Committee for Aeronautics (NACA), which later became the National Aeronautics and Space Administration (NASA). The design requirements, tradeoffs, flight experiments, and lessons-learned from these experimental vertilift aircraft formed the foundation for the architecture of the V-22 "Osprey" Tiltrotor aircraft.

This paper demonstrates how this architecting process led to the architecture of the V-22 and variants for its users. This includes both a quantitative and qualitative evaluation of the technical characteristics, benefits, and limitations of the resulting V-22 system, including several descriptive and prescriptive heuristics. [1] [2]

II. ARCHITECTING THE XV-1

The first of the practical vertilift aircraft was the McDonnell Aircraft Corporation Helicopter Division's XV-1 (Figure 1), a joint research program by the U.S. Air Force and the U.S. Army from 1951 to 1957. The intent of the XV-1 was to develop and test technologies for a compound gyroplane with VTOL like a helicopter but could fly at faster airspeeds (with a goal of up to 200 mph), similar to a conventional fixed-wing airplane. Two experimental XV-1 aircraft were designed, manufactured, and tested.

Figure 1: The McDonnell Aircraft Corp., Helicopter Division's XV–1 Convertiplane [3]

Although details of this experimental vehicle are still classified, the chief architect appears to be Dr. Kurt Heinrich Hohenemser (born 1903, died 2001), the chief aerodynamics engineer at that time of the helicopter division of McDonnell Aircraft in St. Louis, Missouri. [4] The XV-1 differed from conventional helicopters in that it was designed as a convertiplane: a compound helicopter with pressure jet tip drive rotor, plus a wing and a rear propeller. [3] This enabled the XV-1 to operate in three pilot-selectable modes: helicopter mode, autogyro mode, and airplane mode. In *Helicopter Mode*, the 31-foot diameter 3-blade rotor was powered by three pressure jet tip drive units and the aft propeller was not used. In this mode, the blade pitch was controlled by the pilot to fly like a traditional helicopter. It appears that the architectural choice for powering the rotor in helicopter mode was made in an effort to simplify the power train design from a more traditional helicopter mid-body engine and transmission, capable of rotor speeds of up to 600 rpm, down to the less-complex and lighter weight pressure jet tip drive units capable of a maximum rotor speed of about 410 rpm. This tradeoff of complexity and weight vs. performance was likely made in recognition that the XV-1 only used helicopter mode for VTOL and occasional hover operations. In *Airplane Mode*, the rotor speed was reduced to about 110 rpm, the rotor pitch set to zero, and the rear pusher-propeller was engaged to provide forward thrust to achieve an airspeed of about 150 mph—a speed comparable to World War I era propeller-driven aircraft. The *Autogyro Mode* was used to transition between helicopter mode and aircraft mode, and vice versa. The rear pusher-propeller was spun up and the rotor tip drive units were turned off to allow the rotor to autorotate at 325 rpm with rotor pitch set to 6 degrees.

The first XV–1 was completed in January 1954 and began operational flight testing in April 1956. Although the aircraft performed as expected, several serious drawbacks were observed: [3]

1. The Helicopter Mode used 3 times more fuel per hour than the Airplane Mode
2. The pressure jet noise was very loud: over 130 db near the aircraft, about 116 db in the cockpit, and about 90 db at distances of up to ¼ mile
3. Performance shortcomings included excessive drag, excessive weight empty, an under powered reciprocating engine of 550 hp and an under-sized propeller
4. Severe oscillatory load conditions and resulting severe vibrations in high-speed flight [5]

Also, the XV-1 could not repeatedly achieve the objective of a 200 mph airspeed—at a typical max speed of 150 mph, it achieved only 75% of the airspeed goal. The design characteristics resulting from technologies available at that time showed some improvement over helicopters of that era, but the measured performance did not justify the expense and complexity of the XV-1. Still, this experimental vehicle provided lessons-learned and technical performance measurements that were invaluable in the conduct of the trade studies for the eventual V-22 aircraft systems architecture. [6]

III. ARCHITECTING THE XV-3

The next experimental vertilift aircraft was the Bell XV-3, another joint research program by the U.S. Air Force and the U.S. Army from 1951 to 1966. The intent of the XV-3 was to develop and test technologies for a convertiplane: a fixed-wing aircraft with propellers that could rotate from vertical for VTOL to horizontal flight at speeds up to 200 mph. Two experimental XV-3 aircraft were designed, manufactured, and tested. [7]

Figure 2 shows one of the two Bell Helicopter Corporation XV–3 Tiltrotor planes on the ground, with wingtip rotor assemblies rotated for VTOL. [8] Figure 3 shows an XV-3 in flight, with wingtip rotor assemblies rotated for forward flight. [9] Mr. Robert (Bob) L. Lichten, a principal advocate of the tiltrotor concept, served as the chief architect of the Bell Model 200, designated the XV-3 by the U.S. Army and Air Force. Mr. Lichten died after an unfortunate automobile accident in 1971. Lichten's lead engineer for the XV-3, Mr. Kenneth "Ken" G. Wernicke, later served as one of the architects of the subsequent Bell XV-15 and Bell/Boeing V-22 Osprey. The XV-3 differed from the XV-1 in that the engine was mounted in the fuselage, with drive shafts transferring power to wingtip rotor assemblies which could tilt 90 degrees from vertical (helicopter mode) configuration down to horizontal for forward flight mode. This allowed the XV-3 to take off and land like a helicopter but fly at faster airspeeds than a helicopter in forward flight mode, similar to conventional fixed-wing aircraft.

Figure 2: Bell Helicopter XV-3 Tiltrotor Aircraft. (3-blade version from Bell Photograph 209854) [8]

Figure 3: Bell Helicopter XV-3 Tiltrotor Aircraft in Flight (improved 2 blade version). [9]

The first XV–3 was completed in October of 1953 and began flight testing in August of 1955, several months in advance of the XV-1 development and flight testing. However, the original three-bladed, 25-ft diameter articulated rotor experienced severe dynamic instability and resulted in several testing mishaps, the most severe being a crash on October 25, 1956 during flight testing. The original three-bladed rotor was replaced with a two-bladed stiff-inplane rotor. Flight testing of the modified design began in July of 1957. Further design modifications were made to improve stability—requiring the reduction of the rotor diameter to 23 feet, addition of external struts to stiffen the wing, and a significant increase in the stiffness of the rotor controls. The second (modified) XV-3 accomplished the goal of completing a dynamically stable full conversion from helicopter VTOL mode to the airplane forward flight mode in December of 1958, well after the competing XV-1 design completed its fairly-successful flight test program. Then, after about 10 years of intermittent operational flight testing, the second XV-3 experienced massive structural failure in wind tunnels tests at about 230 mph. The design was simply not robust enough to withstand the vibrational loads without significantly increasing the weight of the aircraft. Analysis of the failure and 13 year results of flight, ground, and wind tunnel painted a dismal summary of the XV-3 performance: [5][8]

1. The severely underpowered XV-3 had limited hover capability and cruise performance
2. The maximum level flight speed of 132 mph (175 mph in a dive) was not adequate to prove that the tiltrotor had a useful airplane mode capability
3. The XV-3 also suffered from handling qualities problems, including lateral and roll instabilities when hovering in ground effect (IGE), and a directional divergent oscillation and poor control responses in the longitudinal and directional axes at low airspeeds
4. A complex gear shifting process, required to reduce rotor RPM after converting to the airplane mode (to improve rotor efficiency), produced an unacceptably high pilot workload (poor human-systems integration)

The design characteristics resulting from technologies available at that time showed some improvement over helicopters of that era, and some improvement over the XV-1, but flight instabilities indicated the need for technology improvement and re-design. Still, this experimental vehicle provided lessons-learned and technical performance measurements that were invaluable in the conduct of the trade studies for the eventual V-22 aircraft systems architecture. The major benefit was the:

> "Demonstration of the ability of the tiltrotor aircraft to perform in-flight conversion from the helicopter configuration to the fixed-wing (airplane) configuration and back to the helicopter mode in a safe, stable, controllable manner. This was accomplished with sufficient airspeed margins and maneuverability and adequate tolerance to gusts and turbulence throughout the process." [8]

This success provided the foundation for the next-generation tiltrotor aircraft: the XV-15.

IV. ARCHITECTING THE XV-15

The next experimental vertilift aircraft was the Bell XV-15, a NASA program developed by the Ames Research Center from 1971 to 1977, which led to a joint NASA/Army Tilt Rotor Research Aircraft (TRRA) program. Unlike the predecessors, this was a competitive program between Sikorsky, Grumman, Boeing, and Bell Helicopter. The latter two companies were awarded contracts in September 1973 for two vertilift concepts, each with different tiltrotor designs. After evaluation, the Bell design was selected for detailed design, manufacturing and flight testing of two vertical/short take-off and landing (V/STOL) tiltrotor research aircraft based on the Bell Model 301 design—to be designated the XV-15. Flight testing began in 1977 and although conducted primarily in the 1980s, testing was extended all the way to 2003. The XV-15 aircraft included new technologies and techniques available at the time of development, and demonstrated significant improvement over the XV-3, especially in resolving performance stability issues experienced during XV-3 flight testing.

Figure 4 shows one of the Bell Helicopter Textron Inc. original XV–15 TRRA planes in V/STOL hover mode. Figure 5 shows one of the Bell XV-15 Flight Test Vehicles with the engine nacelles rotated forward in horizontal flight (airplane) mode.

Figure 4: Bell XV-15 TRRA (Tilt Rotor Research horizontal Aircraft), Ship 2. [10]

Figure 5: Bell XV-15 Flight Test Vehicle in flight (airplane) mode. [11]

Mr. Kenneth "Ken" G. Wernicke served as the lead architect of the XV-15 in order to apply lessons-learned from his role as lead engineer of the earlier XV-3. The XV-15 differed from the XV-3 in order to solve high speed aeroelastic stability problems which resulted in the failures, poor performance and handling qualities encountered with older designs. The key design difference was the result of trade studies of tilt-rotor options, including (1) wingtip rotor assemblies driven by a central engine, i.e. an evolution of the XV-3 design, (2) a new integral engine/rotor/pylon nacelle capable of pivoting 90 degrees on a fixed wing structure, and (3) a new stop/fold tiltrotor that:

> "… eliminated the rotor/pylon/wing aeroelastic instability by stopping the rotor while in the airplane configuration. The aerodynamic drag of the stopped rotor blades was then reduced by folding them back along the nacelle while a convertible engine was used to produce the jet thrust required for airplane-mode flight up to higher speeds than would be attainable with a rotor as the thrust-producer…the stop/fold tiltrotor, however, had the additional penalties of the increased complexity and increased weight of the stop/fold mechanism." [8]

Trade option 2 was chosen on the basic of lower risk and lower complexity, even though trade option 3 promised much higher performance.

The XV-15 also conducted a trade study of landing systems, partly to address drag and stability issues and partly to enable short take-off and landing in areas not suited for helicopter-mode VTOL. Three options were evaluated: (1) a redesigned XV-3 skid, (2) retractable landing gear into the interior cabin space, and (3) external landing gear pods based on existing Canadair CL-84 landing gear designs. [8] Option 3 was chosen to reduce development risk and avoid a substantial reduction in cabin interior space, even though it resulted in higher drag, thus reducing the maximum airspeed in the airplane mode.

The XV-15 was used to explore a new capability: civilian transportation of people and cargo at Vertiports. The stated intent was to relieve airport congestion in terms on aircraft take-off & landings and ground transportation in and around major airports and near-by cities. In this scenario, remote airports would offload some of the air traffic (especially for large-capacity aircraft) from regional airports. In April 1995, the XV-15 became the first tiltrotor aircraft to operate at the world's first operational vertiport, the Dallas Convention Center Heliport/Vertiport, as shown in Figure 6. [8] This new capability is a testament to the prescriptive heuristic *"Architect systems to accommodate change and support future extensions that go beyond current needs of stakeholders."* [1] But a key problem that emerged [8] is the public's tolerance of the relatively-high noise of an XV-15 when approaching and landing at the Vertiport—evidence of the prescriptive heuristic *"If social cooperation is required, the way in which a system is implemented and introduced must be an integral part of its architecture."* [1]

Figure 6: XV-15 at the Dallas Convention Center Heliport/Vertiport. (from Bell photograph 042869) [8]

The XV-15 accomplished nearly 20 years of flight testing via the NASA, various DoD services, and the Bell contractor. Although there were several mishaps (including loss of one vehicle), flight testing and demonstration of the XV-15 was extensive, including public demonstration at the 1981 Paris air show and the annual summer airshow at the Moffett Field Naval Air Station for several years during the 1980s. However, the XV-15s payload capacity was only about 3,000 pounds, the cruising airspeed was about 260 mph, the typical range was only 320 miles, and the maximum service ceiling was 29,500 feet. Both civil aviation and military users needed more cargo capacity, speed, and range.

A new lesson learned through the XV-15 program was:

> "…the advantage of multiple or joint participation, in this case the Army and NASA. This became an important factor in maintaining the continuation of project funding when one agency was able to provide funds during a period that the other agency was experiencing a temporary funding shortfall. This was further emphasized when the Project Office was able to accommodate a request by the Navy for sea trial evaluations of the XV-15 tiltrotor research aircraft to evaluate it for Navy ship board applications. As it happened, this provided further funding at a time of critical need. Yet another important "funding" lesson learned was to include the contractor as a participant in the project funding. In the case of the XV-15 TRRA, this was accomplished contractually by an incentive fee arrangement tied to contractor cost performance." [8]

This led to the useful new prescriptive heuristic to *"Maximize the Program's Constituency Base to Minimize the Chance of Program Cancellation."*

V. ARCHITECTING THE V-22

The success of the XV-15 tiltrotor concept enabled the V-22 "Osprey" Tiltrotor Program, which was the result of a competition by the U.S. DoD for a Joint Services Advanced Vertical Lift Aircraft (JVX) in 1981. The Bell Helicopter and Boeing Helicopter companies teamed together to bid on this program, using an expanded XV-15 concept. As potential competitors did not have access to proprietary XV-15 design data, only the Bell-Boeing Team bid, and after considerable controversy the Bell-Boeing team was awarded a contract in May of 1986 to design, manufacture, and test six prototype aircraft. Meanwhile, back in 1985, the JVX program was re-named to be the V-22 "Osprey" Tiltrotor by then Secretary of the Navy, John Lehman. The V-22 program was delayed for several years due to a "turf battle" between the U.S. Secretary of Defense and the Congress [12], but eventually began flight tests in 1989. After experiencing several problems (including several crashes resulting in fatalities), the V-22 was introduced into operations in 2007. At present, over 200 V-22s have been produced and used in various military operations by the U.S. Marine Corps and U.S. Air Force. Additional V-22s are being considered by the U.S. Navy and Israel.

Mr. Kenneth "Ken" G. Wernicke, who served as the lead architect of the XV-15, continued as the initial V-22 chief engineer and lead architect until the program experienced several fatalities in the year 2000. Wernicke had a reputation as an irascible but impassioned leader [13] who publicly espoused his variations of the descriptive heuristic *"The choice between architectures may well depend on which set of drawbacks the client can handle best."* [2] After a lengthy transition period, Mr. John Thatcher of the Boeing Company served as the "return to flight" chief engineer from March 2008 – April 2015.

The V-22 differs from the XV-15 primarily in size, weight, and cargo-carrying capacity. This difference is strikingly demonstrated in Figure 7, which shows a V-22 (center) and XV-15 (right) at the 1995 Paris Air Show.

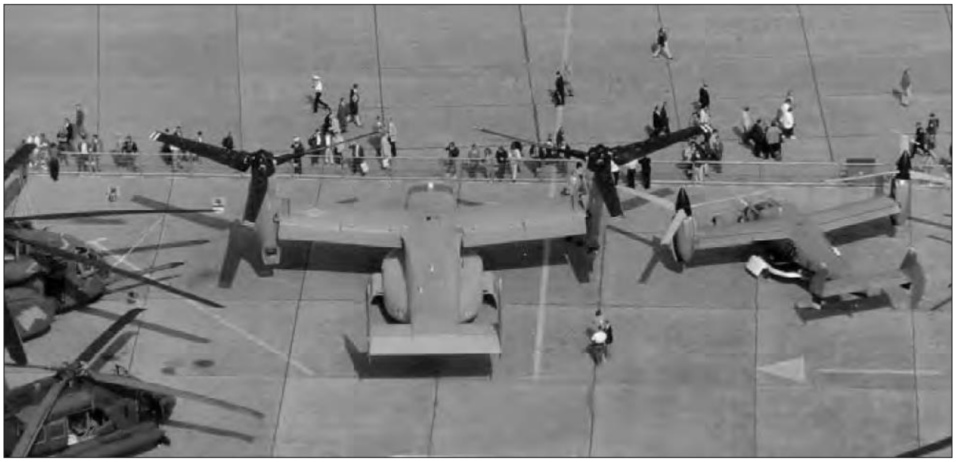

Figure 7: V-22 and XV-15 at the 1995 Paris Air Show. (from Bell photograph 042900) [8]

At present there are two primary variations of the V-22: the U.S. Marine Corps (USMC) MV-22B and the U.S. Air Force (USAF) CV-22. A U.S. Navy (USN) variation, the CMV-22B, has been proposed for the FY18 Budget. These and other variations are made possible by the program's recognition of the prescriptive heuristic *"Build in and maintain options as long as possible in the design and implementation of complex systems."* [2]

The MV-22B can transport up to 24 fully-equipped Marines or 10,000 pounds of cargo at a cruising speed of about 288 mph with a range of 575 miles without aerial re-fueling—about twice as fast and with five times greater operating range than previous USMC helicopters. The CV-22 is designed to carry 18 USAF Special Operations Command troops with a combat radius of 500 miles without aerial re-fueling. The CV-22 has about 90% airframe commonality with the MV-22B; the primary differences between the two variants are their avionics. [14] The proposed CMV-22B is a long-range version, capable of 1300 miles without aerial re-fueling to support USN Carrier Onboard Delivery (COD) missions. Each variation has a crew of up to four: pilot, copilot and one or two flight engineers, depending of the mission performed. Figure 8 shows a notional V-22 in V/STOL mode, forward flight (airplane) mode, and transition mode to go from vertical to forward flight and vice versa.

Figure 8: V-22 Flight Modes: Forward Flight, Conversion, Takeoff/Hover/Landing. [15]

Several major architectural changes were required from earlier planes: (1) transition from prototype to design for mass production, (2) much larger size with aerodynamic considerations, (3) survivability & armor, (4) suspended external loads capability, loading ramp, cargo stowage capability and mid-air deployment of troops, (5) aerial re-fueling—both ways, (6) offensive/defensive weapons capability, and

(7) compact storage configuration (folding rotors and rotating wing). Each of these problems overlapped the others, as the classic boundaries and rigid interfaces between subsystems had to be replaced with a more holistic approach to an integrated V-22 aircraft architecture, as learned from the predecessor experimental systems. This required system architecture conceptual tradeoff analyses [1] as described in the following, and not just individually-focused subsystem trade studies.

One fundamental impact on the V-22's architecture was the transition from prototype to design for mass production—a generic problem inherent in moving from any prototype "X-Plane" and test program to a fully-operational aircraft system (including logistics, training, sustainment, etc.). A new descriptive heuristic is that *"the people, equipment, and organizational structures that favor research are often diametrically opposed to those required for effective production."* [16] Research aircraft are typically fabricated one-at-a-time using specialized shops and highly-skilled personnel. Production aircraft require a different approach. Design for Manufacturing & Assembly (DFMA) and Six-Sigma Statistical Process Control techniques were used on the V-22 to evaluate architectural options that would minimize the risk of manufacturing process variability, increase production yield, and select an optimal balance between life cycle cost, schedule, operational capability, and the various 'ilities' required by the U.S. DoD (e.g. maintainability, survivability, reliability & operational availability, trainability, etc.). The V-22 program underwent this transformational process *twice*—each time with significant architectural changes! The first transition was from the XV-15 to the six full-scale development (FSD) aircraft—which also meant a transition from obsolete 1970s-era technology and techniques to the 1980s. The V-22 then underwent a significant delay due to a lengthy "turf battle" between the U.S. Secretary of Defense and the Congress [12] which required transitioning from obsolete 1980s-era technology and techniques used in the FSD aircraft to the production aircraft of the 2000s—at a time where significant upheavals occurred in such areas as computers, avionics, structural materials, modeling & simulation, and computer-aided design methodologies. This led to the realization that the fundamental architecture of the V-22 had to be resilient in spite of changing circumstances. [1] Although not explicitly stated by the V-22 program office, this demonstrates the stakeholder management prescriptive heuristic to *"Architect systems to accommodate anticipated change and support potential extensions that go beyond current stakeholder needs."* [1]

An additional significant impact on the V-22 architecture is the MUCH larger size, with resulting structural and aerodynamic considerations. [17] The XV-15 was designed to house a crew of only two: the pilot and co-pilot, whereas the V-22 typically provides space for a crew of four, plus 24 web-seated passengers. The XV-15 body was 12 ft. 8 in. in height and 42 ft. 1 in. in length, with a 25 ft. 0 in. wingspan (excluding rotors), whereas a MV-22B body is 22 ft. 1 in. in height (1.7x larger) and 57 ft. 4 in. in length (1.4x larger), with a 45 ft. 10 in. wingspan (1.8x larger, excluding rotors). This significant size change required re-evaluation of the aircraft structure. Advances in composite construction technologies enabled size growth while keeping weight growth (relative to the XV-15 outer skin and structure) to a minimum. [17] But this came at a cost of increased manufacturing complexity and aircraft production cost. Also required was a re-analysis and re-formulation of aero characteristics, which in turn drove a complete re-design of the proprotors (propeller in airplane mode; rotor in helicopter mode) used on the V-22 [18]. However, these size changes had an unexpected side benefit, as it forced the designers to use new design and evaluation techniques (including Computational Fluid Dynamics or CFD) to accomplish a complete structural and aerocharacteristic redesign rather than attempting to "scale up" from the XV-15 structural design and aerocharacteristics that were largely achieved using engineering rules-of-thumb and extensive wind-tunnel testing. [19][20] This fortuitous choice of modern design methodologies greatly enabled the ability to readily accomplish the next four architectural changes as part of a resilient system architecture, applying where possible elegant design principles, especially the descriptive heuristic that *"In nature, the* *optimum is almost always in the middle somewhere. Distrust assertions that the optimum is at an extreme point."* [1]

The original V-22 architecture was to include survivability & armor capabilities, which was not the case for the XV-15. This increased the complexity and weight of the original V-22 configuration [17] to be similar to survivability requirements for military transport helicopters. However, following a 17 month grounding of all aircraft in 2000 after an accusation of maintenance falsification [12], several of the survivability requirements were relaxed, resulting in yet another round of significant architectural changes:

> "In conjunction with resuming flight testing, the Navy Department modified certain V-22 requirements. For instance, the V-22 is no longer required to land in helicopter mode without power (also known as 'autorotation'), protection from nuclear, chemical and biological weapons has been eliminated. The V-22 is no longer required to have an 'air combat maneuvering' capability; instead it must demonstrate 'defensive maneuvering.' Also, the requirement that troops be able to use a rope or rope ladder to exit the cabin at low altitudes has been eliminated." [21]

But the design methods and tools used on the V-22 allowed rapid re-design or modifications to accommodate such "whip-saw" changes in requirements, and is also valuable in the adaptation of V-22 variants to be optimized for varying operational missions, e.g. for the U.S. Marine Corps, Navy, Air Force; for future foreign military sales, and for future civil transport missions.

The V-22 architecture includes suspended external loads capability, a loading ramp, cargo stowage capability, and allows mid-air deployment of parachute-equipped troops through that ramp while in flight, [17] whereas the XV-15 had no such capabilities. Suspended external loads capability include one light-weight M777 howitzer or a fully-equipped military High Mobility Multipurpose Wheeled Vehicle (HMMWV). This greatly increased the complexity of the lower and rear structure of the fuselage and added weight for a ground-or-air deployable ramp plus opening/closing/latching mechanisms plus a 600 pound-capable hoist through an open ramp. This also added new aerocharacteristics while in flight for stability and deployment clearances so that hoisted or parachuting troops or equipment could safely clear the airframe, extended ramp, and proprotor-wash. Again, the design tools available in the 1970s would not have likely been capable of quickly accomplishing these new capabilities without exhaustive (and expensive!) customized software models and wind tunnel testing.

The V-22 architecture includes the capability for aerial re-fueling, both ways: for the V-22 to be re-fueled in-flight [17] (as was demonstrated in Iraq and Afghanistan, and for disaster relief/humanitarian aid in the Philippines & Liberia for disaster relief operations) and an option for the V-22 to be an aerial tanker to re-fuel other aircraft. The latter required a trade study to leverage and evaluate various options, including the older hose-and-drogue and the newer flying boom proven on other aircraft. [22] The significant relative simplicity, lower weight, and operational control of the hose-and-drogue option resulted in the selection of that option, in spite of the resulting stability challenges for receiving aircraft. However, not all aerial-refueling enabled aircraft can safely accommodate hose-and-drogue receptacles (e.g. most USAF fixed-wing aircraft) or else cannot safely fly as slow as the V-22's maximum rated airspeed of 315 mph. [17]

The V-22 architecture includes the capability of offensive and defensive weapons. Due to political pressures from other US DoD programs (especially combat helicopter systems for the US Army and USMC), the initial V-22 architecture did not include offensive capabilities such as anti-tank missiles or cannons. [12] The current V-22 does include a single rearward-facing .50-caliber machine gun that can be manually operated by a crewmember when the ramp is lowered, as shown in Figure 9. Other more advanced defensive capabilities, such as the Interim Defense Weapon System (IDWS), a retractable undercarriage remotely operated 7.62 mm gun turret system were added later for operational use in Afghanistan, as shown in Figure 10. Advanced offensive/defensive weapons typically add to the vehicle weight and avionics complexity, as well as impacting the overall aerocharacteristics when deployed and operated in flight. For example, the IDWS requires an operator inside the aircraft to view forward looking infrared imagery (FLIR) obtained from an externally-mounted pod in order to acquire and engage targets. Specific attention to Human Systems Integration is required to overcome human operator limitations, especially for decision-making under stress. [1] More advanced weapon systems have been proposed and will be the subject of future trade studies, such as a nose turret with a three barrel 12.7mm Gatling type gun. [24]

Figure 9: Standard V-22 Defensive Capability. [23]

Figure 10: V-22 Remote Guardian Turret Gun. [24]

As the V-22 has to be stowed in hangers and on board ships, the normal configuration would occupy a lot of space. A trade study of various space-savings options was performed, resulting in today's compact storage configuration, with a 90-second automated operation of folding rotors and rotating wing as shown in Figure 11. [25]

Figure 11: V-22 Compact Storage Configuration on the Ground and on a Carrier Deck. [25]

This necessary configuration for preserving precious hanger and carrier deck space comes at a significant cost to V-22 aircraft complexity and reliability, not to mention the added weight for mechanisms and cockpit displays and controls.

A publicly-available video [26] demonstrates the resulting V-22 ability to achieve the capabilities described above (convertiplane hover & flight, exterior & interior including ramp and crew deployment, aerial refueling, defensive weaponry, passenger seating, and compact storage configuration.)

A lower-cost, non-military variation of the V-22 or other tiltrotor aircraft has been proposed for use in civil aviation [27][28] for transportation between proposed remote airports (e.g. in the California Mojave High Desert) and local Vertiports, or landing areas near local airports (e.g. Los Angeles International Airport) and major surface transportation hubs (e.g. Los Angeles Union Station). Civil aviation variants of the V-22 could be used to ferry passengers, crew, and luggage between a remote airport and various local landing areas in close proximity of local airports and major surface transportation hubs.

Figure 12 shows a comparison of the operating flight envelope (altitude vs. airspeed) of an example civilian tiltrotor aircraft, the Agusta AW609 [33], versus typical civilian helicopters and typical civilian fixed-wing aircraft. This shows that a tiltrotor aircraft's capability exceeds that of a helicopter, and also provides some of the capability of fixed-wing aircraft, except at altitudes above 25,000 feet (~7,600 meters), or a speeds above 300 knots true airspeed (Ktas), or about 550 kilometers per hour.

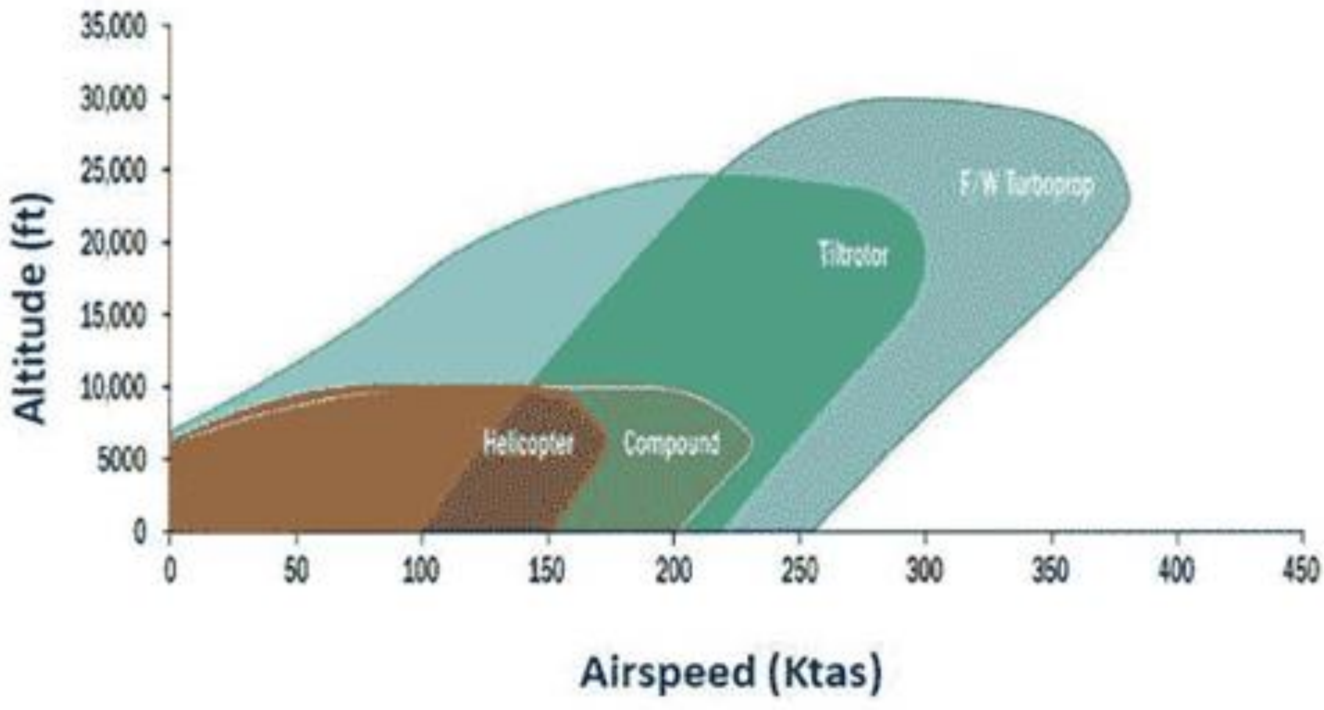

Figure 12: Operating Flight Envelopes of Typical Civilian Helicopters, Tiltrotors, and Fixed-Wing Aircraft. [33]

One study was accomplished in 1987 to:

> "… assess the broader implications of the V-22 aircraft development to the nation as a whole. This includes the potential for other versions and sizes, both civil and military, civil certification issues, civil production impact on the defense industrial base and any indirect technology spinoffs…" [29]

This study and its follow-on [30] identified and evaluated six configurations, ranging from XV-15 size (the CTR-800) through V-22 size (the CTR-22B) and "stretched" configurations, as shown in Figure 13 and Table 1: (note that all table calculations are shown in the Appendix as embedded spreadsheets.)

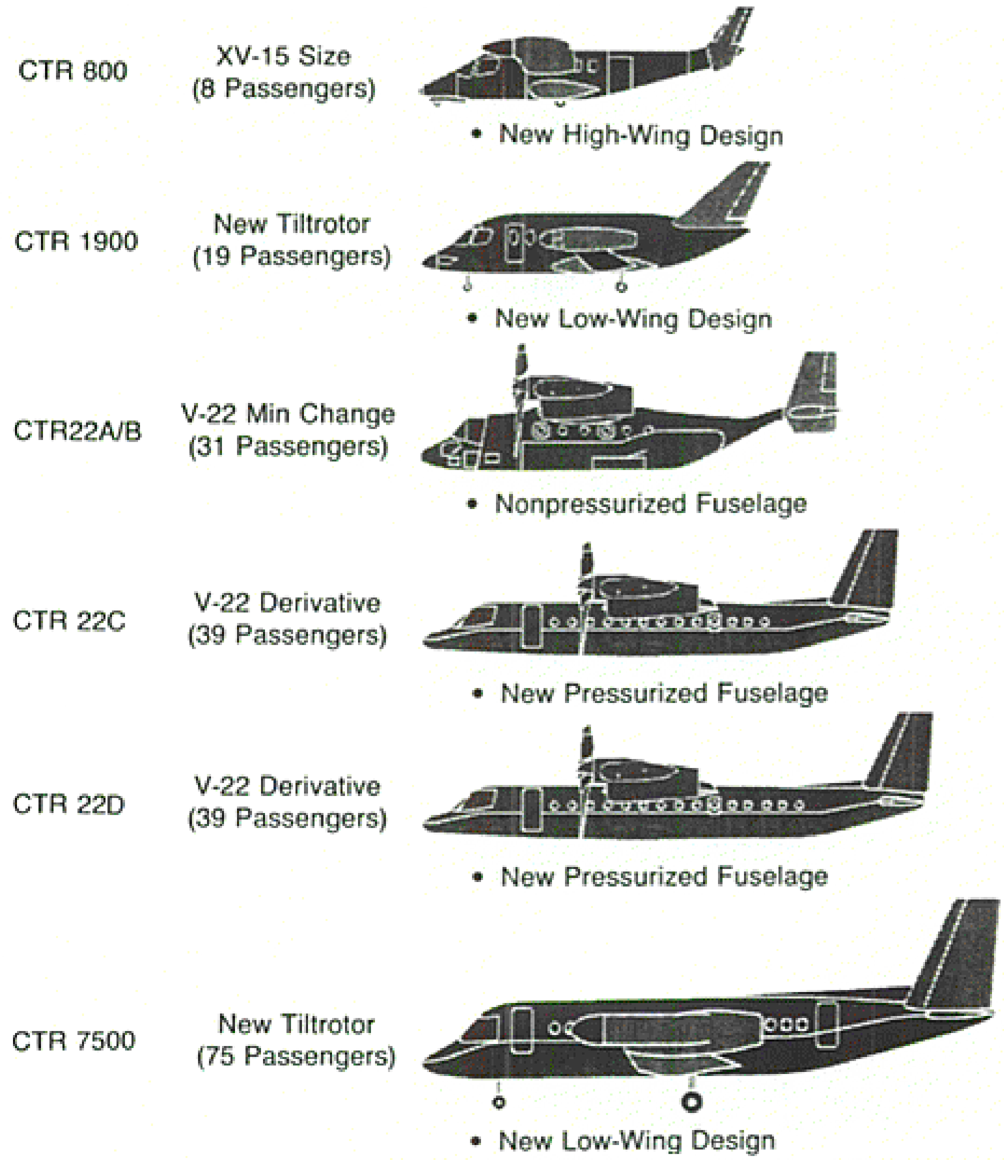

Figure 13: Potential Civilian Tiltrotor Configurations. [29]

Table 1: Comparison of Potential Civilian Tiltrotor Configurations. (Derived from [29])

Vehicle	Passengers	Length (m)	Wing Span (m)	Rotor Span (m)	Max Takeoff Weight (kg)	Max Payload Weight (kg)	Speed (kph)	Range (km)
CTR-800	8	12.6	9.8	7.9	7,144	2,866	506	1,111
CTR-1900	19	14.2	11.3	8.5	10,342	6,807	524	1,180
CTR-22A/B	31	17.5	14.0	11.6	20,466	11,106	444	1,111
CTR-22C	39	20.9	14.0	11.6	20,970	13,972	522	1,111
CTR-22D	39	21.9	14.6	11.6	22,344	15,346	522	1,111
CTR-7500	75	25.5	19.2	14.0	36,206	26,869	556	1,111

The study concluded that the military V-22 required significant modification for the civil aviation marketplace, and that more traditional commercial aircraft design characteristics were required (e.g. less use of composites; pressurized and air conditioned cabin; airline-style seats; lavatory and galley; luggage stowage.) Furthermore, the military V-22 was just too expensive, and more traditional construction techniques were required (e.g. less use of composites). By accomplishing these changes, and with an estimated marketplace of about 16,000 aircraft, the study concluded that a civil tiltrotor would cost about 50% more than a turboprop aircraft of similar size range, and speed—but could use helicopter landing pads (rather than runways, as required by turboprop aircraft) and operate at significantly lower cost than most passenger helicopters: roughly 38% of the per-seat operational of a helicopter. The estimated total trip time for a 200 nmi. flight, portal-to-portal was 4 hours for a turboprop (of which only 1 hour was spent in the air) versus 2 hours for a civil tiltrotor versus 2.7 hours for a passenger helicopter. [29][30]

But a civil tiltrotor aircraft was just part of the equation. Other studies in the late 1990s showed the major impacts could be in attempts to reduce urban and seaport traffic: [31]

> "the displacing even a small fraction of short haul traffic from runways to … vertiports could dramatically reduce delays at capacity constrained airports…", "However, the primary reason people do not want a vertiport in their community is still noise.", "The combined factors of land cost, land-use planning, zoning, local political support and local community acceptance militate against converting existing built-up areas to Vertiport use." [15]

But a civil tiltrotor aircraft was just part of the equation. Other studies in the late 1990s showed the major impacts could be in attempts to reduce urban and seaport traffic. [31] Based on these studies, the potential classes of civil tiltrotor missions are listed in Table 2.

Table 2: Classes of Potential Civil Tiltrotor Missions.

Mission Name	Description	Typical Vertiport Flights	Typical Max Distance (km)	Passengers	Cargo (kg)
Urban	Urban Shuttle to Airport	15 flights/day	50	max	max
Platform	Shuttle to Remote Sea Platform	2 flights/day	500	max	max
Airports	Shuttle between Airports	20 flights/day	160	max	max
Transport	Shuttle between Ground Vertiports	20 flights/day	500	max	max
Medivac	Medical Transport to Hospital	2 flights/week	160	4	200

Each of these missions are helicopter-capable, albeit with helicopter limitations (such as number of passengers and cargo capacity.) Helicopters can and do accomplish all of these missions at the present time, but typically at a lower flight rate than shown above.

The economic analysis of the above civil tiltrotor configurations first requires assessment of the anticipated missions shown in Table 2. Only those missions which enable analysis of all five potential civilian tiltrotor aircraft for that mission are covered in this paper—several missions will be deferred for subsequent analysis on that basis.

The first analysis is a quantitative Performance Risk Assessment of these missions, using the Excessive Noise Level Risk [32] expressed in "Context, If-Event, Then-Consequences, Likelihood" format [34], plus a description of potential risk mitigation options. The general public objects to noise levels of aircraft in close proximity to their homes and places of work, especially during takeoff and landing. The FAA has determined certification standards for tiltrotor noise levels [35] and estimates noise certification costs of $588,000 in 2013 dollars, one-time for each vehicle model. If a civil tiltrotor mission exceeds approach, takeoff, or flyover noise levels as defined in Figure K4 "Tiltrotor Noise Limits" in reference [35], then that mission is not certified to operate in the U.S. National Airspace System (NAS) except for emergency purposes. The likelihood of this being the case is dependent on the mission, as assessed in Figure 14:

- Urban Shuttle to Airport: Risk is RED (very high likelihood, very high consequence), as rooftop or ground helipad takeoff and landings exceed the "center noise measurement point" noise limit in reference [35] for all but the smallest candidate vehicle (the CTR-800). For this reason, this mission is excluded from further analysis in this paper.
- Shuttle to Remote Sea Platform: Risk is YELLOW (moderate likelihood, moderate consequence), as vertiport takeoff and landings would be subject to local noise abatement restrictions, which are often stricter than FAA noise certification standards (assuming no noise restrictions at the remote sea platform)
- Shuttle Between Airports: Risk is YELLOW (high likelihood, moderate consequence), as airport takeoff and landings would be subject to local noise abatement restrictions, which are often stricter than FAA noise certification standards.
- Shuttle Between Ground Vertiports: Risk is YELLOW (high likelihood, moderate consequence), as vertiport takeoff and landings would be subject to local noise abatement restrictions, which are often stricter than FAA noise certification standards.
- Medical Transport to Hospital: Risk is GREEN (low likelihood, low consequence), as this is an emergency mission, similar to those performed by Medivac helicopters. But this mission is accomplished by the smallest candidate vehicle, and for this reason the medivac mission is excluded from further analysis in this paper.

The three remaining shuttle missions (Offshore, Airports, Transport) are shown with YELLOW (moderate) performance risk. These risks can be mitigated as shown in Figure 14 by excluding vertiport sites in local noise abatement restricted areas, i.e. restricting vertiports to more remote areas, away from houses and business areas (other than those involved in vertiport operations.)

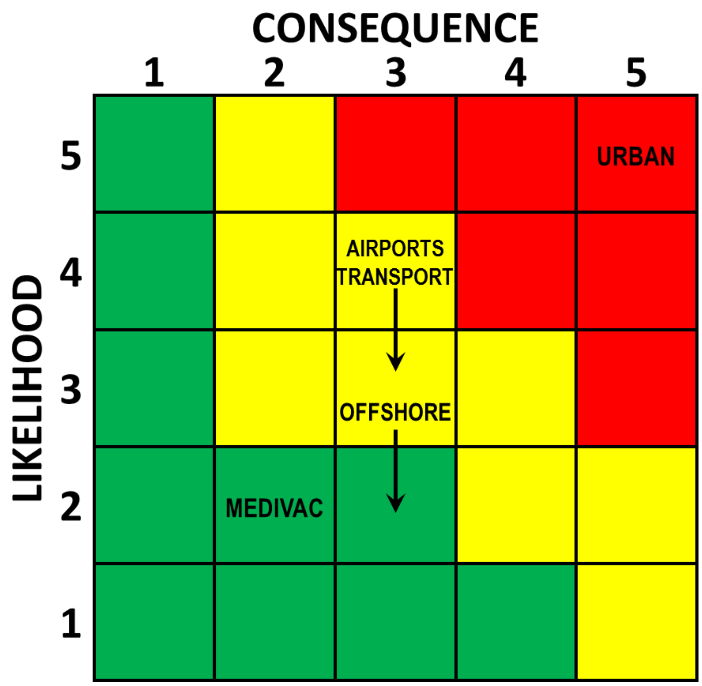

Figure 14: Risk Assessment of Potential Civil Tiltrotor Missions

As two of the shuttle missions (Airports, Transport) remain as YELLOW (moderate) performance risk, they are excluded from further analysis in this paper. The remaining mission with mitigated performance risk, Shuttle from Remote Vertiport to Remote Sea Platform (hereafter referred to as the "Sea Platform Mission"), is therefore used for further analysis in this paper.

The next assessment is for the Cost Risks for the six potential Civil Tiltrotor configurations (shown in Table 1) in accomplishing the Sea Platform mission. There are two types of cost risk to be analyzed: (1) Aircraft Purchase Cost, and (2) Aircraft Operational Cost. One study [29] estimated the cost-to-build for 300 units in comparison to a baseline "commercialized" V-22 (CTR-22A/B), as shown in Table 3. A U.S. Government study [35] estimated the purchase cost of a "commercialized" V-22 (CTR-22A/B) to be $14,000,000 in 2011 dollars, based on the anticipated Bell/Agusta AW609 civil tiltrotor cost (note that this price includes the noise certification cost of $588,000 in 2013 dollars amortized over 300 aircraft.) Given the U.S. Government Consumer Price Index (CPI) increase from 2011 to 2016 (cumulative 7.5%) [36], this allows calculation of the purchase cost for the present year (2016). A personally-estimated design cost uncertainty is shown, based on qualitative cost-to-build uncertainties described in two studies [29][30]. This allows a "realistic" purchase budget estimate to include the cost uncertainty factors, as none of the comparison vehicles have yet been designed and built. Assuming a 30% salvage value (estimated from helicopter resale values) for properly-maintained aircraft in 10 years with the U.S. Government standard interest rate of 7% compounded annually, the salvage net present value (NPV) for each comparison vehicle is calculated from the realistic budget estimate, along with the estimated investment value at the present time.

Table 3: Estimated Comparison Civil Tiltrotor Aircraft Purchase Costs.

Vehicle	Cost-to-Build	Purchase Cost (2011)	Purchase Cost (2016)	Design Cost Uncertainty	Budget Estimate	NPV * Salvage (2026->2016)	Estimated 2016 Investment $
CTR-800	-32%	9,520,000	10,234,000	10%	11,257,400	1,716,807	9,540,593
CTR-1900	-17%	11,620,000	12,491,500	10%	13,740,650	2,095,515	11,645,135
CTR-22A/B	0%	14,000,000	15,050,000	0%	15,050,000	2,295,197	12,754,803
CTR-22C	26%	17,640,000	18,963,000	10%	20,859,300	3,181,143	17,678,157
CTR-22D*	50%	21,000,000	22,575,000	25%	28,218,750	4,303,494	23,915,256
CTR-7500	147%	34,580,000	37,173,500	50%	55,760,250	8,503,705	47,256,545
** estimated*			*cumulative CPI of 7.5% for 2011-2016*		*Realistic: includes cost uncertainty*	** 7% interest rate, 30% salvage value,* $P = F[1/(1+i)^N]$	*Budget minus NPV Salvage*

Strictly for comparison purposes, Table 4 shows the resulting cost per passenger seat (or cost per kilogram of payload, e.g. cargo) for each of the comparison civil tiltrotor aircraft and for the AgustaWestland AW101 [17], a comparable civilian helicopter. Note that these figure present an incomplete picture, as they do not factor in differences in operating cost, maintenance cost, etc.

Table 4: Comparison of Civil Tiltrotor Aircraft and Large Civilian Helicopter Costs.

Vehicle	Passengers	Estimated 2016 Investment $	Max Payload Weight (kg)	$ Cost per Seat	$ Cost/kg Payload
CTR-800	8	9,540,593	2,866	$1,192,574	$3,329
CTR-1900	19	11,645,135	6,807	$612,902	$1,711
CTR-22A/B	31	12,754,803	11,106	$411,445	$1,148
CTR-22C	39	17,678,157	13,972	$453,286	$1,265
CTR-22D	39	23,915,256	15,346	$613,212	$1,558
CTR-7500	75	47,256,545	26,869	$630,087	$1,759
Helicopter	30	18,200,000	5,300	$606,667	$3,434

Aircraft Operational Cost factors include direct costs for airframe and engine maintenance (plus 50% burden), fuel consumed, flight crew pay, and other indirect operating costs (e.g. insurance). An industry study in 1987 [29] estimated maintenance costs in terms of dollars per flight hour for the comparison civil tiltrotor aircraft, along with equivalent-sized turboprop fixed-wing aircraft and helicopters, as shown in Table 5. A follow-on study in 1989 [30] estimated cost of fuel consumed, flight crew pay, and other indirect operating costs and is also shown in Table 5. Given the U.S. Government Consumer Price Index (CPI) increase from 1987 to 2016 (cumulative 112.8%) and from 1989 to 2016 (cumulative 94.9%) [36], this allows calculation of the estimated total operating cost per flight hour for the present year (2016).

Table 5: Estimated Civil Tiltrotor Aircraft, Equivalent Turboprop, and Large Civilian Helicopter Operational Costs.

Vehicle	Passengers	(1987) Maint. $/ Flight Hour	(2016) Maint. $/ Flight Hour	(1989) Other $/ Flight Hour	(2016) Other $/ Flight Hour	(2016) Total Operational $/ Flight Hour
Turboprop	31	$180	$380	$479	$1,004	$1,385
CTR-800	8	$430	$909	$593	$1,242	$2,151
CTR-1900	19	$534	$1,128	$607	$1,271	$2,399
CTR-22A/B	31	$835	$1,764	$674	$1,412	$3,176
CTR-22C	39	$849	$1,794	$741	$1,553	$3,347
CTR-22D	39	$900	$1,902	$741	$1,553	$3,454
CTR-7500	75	$1,502	$3,173	$876	$1,835	$5,009
Helicopter	30	$1,567	$3,311	$926	$1,940	$5,250
			cumulative CPI of 112.8% for 1987-2016		*cumulative CPI of 94.9% for 1989-2016*	

As the turboprop fixed-wing aircraft cannot be used in the Sea Platform Mission, it is useful only for operating cost comparison and cost credibility purposes.

Future sales (or leases) of civil tiltrotor aircraft for use in the Sea Platform Mission are subject to uncertainty. Table 6 shows the estimated 10-year sales quantity based on potential services to the 1,472 world-wide oil platforms according to public statistics for 2015 [37]. This assumes that the current helicopter fleets are replaced with newly-purchased aircraft over the 10-year period, and that the market share for U.S. aircraft (based on personally-estimated sale penetration %) is dependent on the sea platform location. Furthermore, it assumes a probability distribution of growth in the number of sea platforms to the year 2026, based on personally-estimated growth probabilities derived from various news reports that the number of sea platforms may actually shrink, especially for the European North Sea area.

Table 6: Estimated Civil Tiltrotor Aircraft and Large Civilian Helicopter Platforms needing US Aircraft over 10 Years.

Sea Platform Location	2015 Quantity	10 Years Estimated Sale Penetration %	Very Pessimistic Growth (-50%)	Pessimistic Growth (-25%)	Slightly Pessimistic Growth (-10%)	No Growth (0%)	Slightly Optimistic Growth (+10%)	Optimistic Growth (+25%)	Very Optimistic Growth (+50%)	2026 Expected Platforms Sales Quantity
North America	368	50%	92	138	166	184	202	230	276	176
South America	174	50%	44	65	78	87	96	109	131	83
Western Europe	210	50%	53	79	95	105	116	131	158	100
Asia	389	20%	39	58	70	78	86	97	117	74
Africa	99	10%	5	7	9	10	11	12	15	9
Middle East	160	5%	4	6	7	8	9	10	12	8
Australia	17	5%	0	1	1	1	1	1	1	1
Other	55	2%	1	1	1	1	1	1	2	1
Total:	1472		237	355	426	474	521	592	710	453
		Probability:	*5%*	*15%*	*33%*	*25%*	*10%*	*7%*	*5%*	*100%*

Table 7 shows the expected 10-year sales for the various aircraft. The 10-year aircraft sales are based on the 2026 expected platforms sales quantities shown in Table 6, then adjusted for sales changes due to differences in price and performance relative to a large civilian helicopter, with a probability distribution ranging from very pessimistic to very optimistic sales change percentages. A sales change of minus 100% for a vehicle indicates that *none* of that aircraft would be purchased over the next 10 years to replace the current helicopters, whereas a sales change of 0% indicates that *all* of the current helicopters would be replaced *one*-for-one with that aircraft over the next 10 years. A sales change of plus 100% for a vehicle indicates that *all* of the current helicopters would be replaced *two*-for-one with that aircraft over the next 10 years, i.e. it would require twice as many of that vehicle to replace each current helicopter. Note that this analysis results in a homogeneous (and not a mixed) fleet in 10 years in order to accomplish a decision matrix of which single vehicle type to design and produce for this mission—the expected sales quantities are exclusive of each other.

Table 7: Expected Civil Tiltrotor Aircraft and Large Civilian Helicopter Sales over 10 Years

Vehicle	Very Pessimistic Sales Change	Pessimistic Sales Change	Slightly Pessimistic Sales Change	Neutral Sales Change	Slightly Optimistic Sales Change	Optimistic Sales Change	Very Optimistic Sales Change	Expected Sales Change %	Expected 10-Year Exclusive Sales Quantity
CTR-800	-100%	0%	30%	60%	70%	80%	100%	55%	**703**
CTR-1900	-100%	0%	10%	25%	33%	40%	50%	23%	**558**
CTR-22A/B	-10%	-5%	0%	0%	5%	15%	25%	4%	**471**
CTR-22C	-25%	-15%	-10%	-5%	0%	0%	0%	-5%	**432**
CTR-22D	-100%	-50%	-33%	-25%	-15%	-10%	-5%	-25%	**342**
CTR-7500	-100%	-90%	-75%	-60%	-50%	-25%	-10%	-55%	**204**
Helicopter	0%	0%	0%	0%	0%	0%	0%	0%	**453**
Probability:	*3%*	*7%*	*10%*	*40%*	*20%*	*15%*	*5%*	*100%*	

Table 8 shows the resulting decision matrix with expected future market cost of ownership for the Sea Platform Mission for 2016 through 2026 for civil tiltrotor comparison aircraft and a large civilian helicopter, assuming a 7% interest rate and given the previously-estimated exclusive (homogeneous fleet) sales quantities and costs for each type of aircraft. This shows that from a Sea Platform Mission perspective, the "best value" is 471 of the CTR-22A/B aircraft—the civilian derivative of the current military V-22. The "worst value" is the current fleet of large helicopters—costing about 70% more than the CTR-22A/B. Note CTR-22A/B is also the lowest risk of the civil tiltrotor aircraft alternatives, and has roughly the same seating/cargo capacity of a large 30-seat helicopter.

Table 8: Expected Future Market Value of Civil Tiltrotor Aircraft and Large Civilian Helicopter Sales over 10 Years

Vehicle	Expected Sales Quantity	Estimated 2016 Annual Cost of Ownership	Future Market Cost of Ownership (2016-2026)	Rank Order	
CTR-800	**703**	**$8,734,316,807**	**$120,677,233,644**	**3**	
CTR-1900	**558**	**$8,297,031,692**	**$114,635,506,604**	**2**	
CTR-22A/B	**471**	**$8,013,635,252**	**$110,719,974,443**	**1**	(best)
CTR-22C	**432**	**$9,569,749,386**	**$132,219,944,401**	**4**	
CTR-22D	**342**	**$9,767,062,150**	**$134,946,105,930**	**5**	
CTR-7500	**204**	**$11,000,276,361**	**$151,984,745,908**	**6**	
Helicopter	**453**	**$13,882,673,071**	**$191,809,230,053**	**7**	(worst)
		** 1/10th purchased in 2016, plus all yearly ops costs*	** 7% interest rate,* $F = A([(1+i)^N-1]/i)$		

The "Future Market Cost of Ownership (2016-2026)" values are extremely sensitive to the "Sales Change Percentages" shown above in Table 7. For the purposes of sensitivity analysis, Table 9 shows the equivalent of Table 8 but with *optimistic* aircraft quantities, rather than the *expected* sales quantities. The same aircraft (the CTR-22A/B) is still the "best value".

Table 9: Optimistic Future Market Value of Civil Tiltrotor Aircraft and Large Civilian Helicopter Sales over 10 Years

Vehicle	Optomistic Sales Quantity	Estimated 2016 Annual Cost of Ownership	Future Market Cost of Ownership (2016-2026)	Rank Order	
CTR-800	816	$10,143,077,583	$140,141,303,587	4	
CTR-1900	635	$9,436,104,280	$130,373,443,741	2	
CTR-22A/B	521	$8,874,030,371	$122,607,578,825	1	(best)
CTR-22C	453	$10,052,257,759	$138,886,496,219	3	
CTR-22D	408	$11,650,571,153	$160,969,510,055	5	
CTR-7500	340	$18,354,187,477	$253,589,676,154	7	(worst)
Helicopter	453	$13,882,673,071	$191,809,230,053	6	
		* 1/10th purchased in 2016, plus all yearly ops costs	* 7% interest rate, $F = A([(1+i)^N-1]/i)$		

For purposes of comparison of the aircraft for the Sea Platform Mission, Figure 15 shows the values as percentages of large, 30-seat civilian helicopter.

Figure 15: Comparison Aircraft for Sea Platform Mission: % of Large 30-Seat Civilian Helicopter

VI. SUMMARY OBSERVATIONS

The V-22 architecture is a logical evolution of tiltrotor technology derived from experience and lessons-learned from the XV-1, XV-3, and XV-15 experimental aircraft and flight test programs. The architecting process described included both a quantitative and qualitative evaluation of the technical characteristics, benefits, and limitations of the resulting military V-22 system, including several design heuristics. The development of a V-22 variant for civil aviation holds much promise, but must overcome significant problems of organized complexity and system-level constraints [1] (such as noise abatement requirements) before use at urban vertiports is accepted by the public. The most viable civilian mission for tiltrotor aircraft is shown to be regular shuttle services of personnel and supplies to off-shore oil platforms (the Sea Platform Mission). Other missions were considered but not analyzed in this paper, either because of the risk of unacceptable noise level in densely-populated areas, or because the mission required only the capabilities of the smallest civilian tiltrotor aircraft. Several tiltrotor aircraft sizes and a larger civilian helicopter were compared. Economic analysis of these aircraft performing the Sea Platform Mission shows that the “best value” aircraft for that mission is a civilian version of the U.S. military V-22 “Osprey” Tiltrotor, designated as the CTR-22A/B. This tiltrotor aircraft has the same exterior dimensions and similar performance as the V-22, but with less expensive materials and “commercialized” passenger seating and other accommodations.

Given the analysis of potential Sea Platforms which could require a U.S. manufactured civilian tiltrotor aircraft replacement of current helicopters over the next 10 years, it appears that the potential market is 471 CTR-22A/B aircraft for the Sea Platform Mission. That quantity is just sufficiently high to justify design and manufacturing of that model, which may be useful for other missions that do not require late-off and landing in densely-populated areas (e.g. major city urban areas). If those other missions justify the design and manufacture of larger or smaller tiltrotor aircraft, then those tiltrotor aircraft could be candidates for the Sea Platform Mission as well as the CTR-22A/B tiltrotor aircraft.

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Appendix: Calculated Tables and Figures

Spreadsheet used to generate tables: (double-click to open, tables on separate tabs)

civil-v-22.xlsx

PowerPoint file used to generate Risk Matrix: (double-click to open)

Final-Paper-Figures
.pptx