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Adventures in Low Disk Loading VTOL Design

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Table of Contents

Table of Contents (cont.)

Adventures in Low Disc Loading VTOL Design

Dr. Mike Scully, Emeritus Engineer

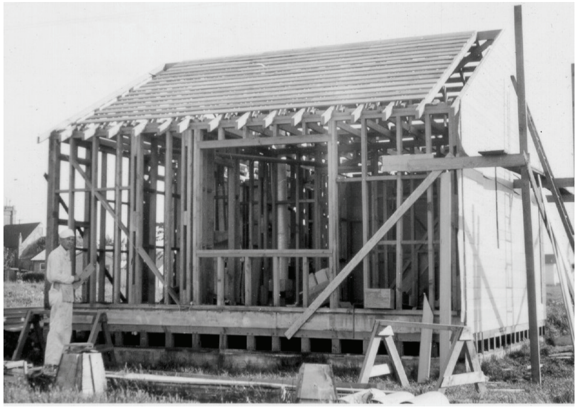
Ames Research Center

Introduction

This memoir covers the first 8 years of my 37-year career in vertical takeoff and landing (VTOL) aircraft design. It starts with family and how I came to be an engineer with a passion for aviation and a desire to make a difference. At the Massachusetts Institute of Technology (MIT) I acquired a solid understanding of basic physics, learned the basics of the various engineering disciplines, and gained design experience. After over a decade on the East Coast, I was homesick for Northern California. I decided to take a chance on working for the government instead of industry in order to return home. I was hired by Dr. Richard M. Carlson in March 1975 and joined a wonderful Army/NASA technical environment. The Interservice Helicopter Commonality Study (HELCOM) was an important introduction to Joint Service aircraft design. The Advanced Attack Helicopter (AAH) Source Selection Evaluation Board (SSEB) was an opportunity to learn acquisition system fundamentals and to lead a small team in a major technical evaluation. The Advanced Scout Helicopter (ASH) Concept Formulation was an opportunity to learn how an aircraft development program is created, and it formed a partnership between Dr. Carlson's Labs and Charlie Crawford's Development and Qualification (D&Q) Directorate. The Army was executive service for the first year (1982) of the Joint Services Advanced Vertical Lift Aircraft (JVX) program. The JVX Joint Technology Assessment (JTA) concluded that there was at least one design configuration, the tilt rotor, that could satisfy all JVX mission requirements with a high degree of interservice commonality. The Navy became executive service at the end of the year and promptly released a JVX request for proposal (RFP) to industry. This RFP resulted in the V-22 Osprey tilt rotor as the third type of VTOL aircraft to enter production and service. I was very lucky to have a useful role early in this program.

Getting Started

Late in 1945, when I was 3, Mom and Dad bought a 3-acre pear orchard in Contra Costa County some 15 miles east of Berkeley, California. The orchard sloped up from a row of walnut trees along the county road to three eucalyptus trees at the back. Dad had just returned from the war in Europe. He still had shrapnel in his leg from a Luftwaffe bomb on D+2 off Normandy. Before the war Dad had built a tiny redwood house for Mom in San Pablo, California. It was sold when Dad was drafted for World War II; Mom lived with her parents in Berkeley while Dad served in the Army. Now Mom, Dad, my brother Tim, and I moved to the pear orchard and camped while Dad built our family home under the eucalyptus trees. Good lumber was unaffordable after the war, so Dad built what was intended to be a temporary house using war surplus lumber—mostly unfinished 3- x 12-inch boards that had been used to make barges for the war. Tim and I grew up in the temporary house with room to play and chores to do. Mom and Dad raised chickens and rabbits, sold pears and walnuts, grew fruits and vegetables for food, and worked their day jobs.



Tiny house, San Pablo.

Temporary house, under smaller eucalyptus trees.

Dad in Belgium, 1945.

Grandmother, Mom, Mike, Berkeley.

Tim, Mike, big eucalyptus.

The area developed and our pear orchard became part of Pleasant Hill. Dad expanded the temporary house and made it more comfortable. The house was becoming less temporary and the new additions had concrete foundations. From 1953–55 we lived in a redwood lumber mill town (Scotia, California), but Pleasant Hill remained our real home. In 1959 a new development went up on the 17 acres behind our house, and we bought one of the new houses. Mom and Dad sold the last of the original 3 acres in 1966 when Dad was dying of cancer. Dad watched with some pride as the new owners struggled to demolish the "temporary house" with a bulldozer. In 1974 Mom retired from her medical technician career, sold the "new house" in Pleasant Hill and moved to Albion, California, on the north coast, 8 miles south of the town of Mendocino. Albion became home in my mind.

Mom near Mendocino. **Great Aunt Ethel, Berkeley.** **Uncle Carl, Naval Aviator.**

We were a family of readers. Mom and Dad encouraged us to explore the world and discover our passions through the magic of books. Mom frequently took us to the basement of the county library where they had tables of children's books for each grade level. We started at grade level but soon explored more challenging books, reading about both real and imaginary people, places, and things. In addition to our own reading, Mom, Dad, and Great Aunt Ethel read special books to us including *Little Men*, *Swiss Family Robinson*, and *Born Free*. When we lived in Scotia, it was 27 miles to the county library in Eureka. The librarian allowed us to check out more books for a longer time because of the long drive. When we returned to Pleasant Hill there was a new branch library. It had a good collection of science fiction (Asimov, Clarke, Heinlein, etc.). The dream of humanity spreading beyond Earth to the planets, and eventually to the stars, became an exciting possibility. I became interested in both aeronautics and astronautics.

Education was important in our family. Mom's family supported her college education. She graduated from the University of California, Berkeley, and through internships became a licensed medical technician. Licensing was new and she was proud of her 3-digit California license number. Dad studied chemical engineering for 2 years, but then Grandfather Scully decided it was time for his oldest son to quit school and help support the family. Dad had a variety of jobs including some years at a Union Oil refinery. In 1950 he became a firefighter for the Army, eventually becoming an assistant chief. Tim and I were encouraged to study hard and go to college. We were also encouraged make our own decisions about what to study. Medical technicians take turns being on call, and Mom would take Tim and me to the lab with her when there was a medical emergency. This exposure certainly increased our interest in science. My first real job was as an assistant in a medical lab. Tim built a cyclotron for the high school science fair. After 3 years of high school, Tim became a U.C. Berkeley student with a part-time job at the Radiation Lab on the hill above campus.

Army L-20A, military version of the civil DHC-2 Beaver short takeoff and landing (STOL) transport.

I became fascinated with airplanes and flight at an early age. Uncle Carl was a Naval Aviator who had many aeronautical adventures. I also remember listening to accounts of Korean War battles over MiG Alley on the radio. A bookstore on Union Square in San Francisco had a wonderful airplane book, *The Aircraft of the World,* [1] and I saved up the money to buy it. I studied this book night and day until I knew every airplane. I still have my original copy, worn but readable. Pacific Lumber Company owned the town of Scotia, and the redwood lumber mill. They had a de Havilland of Canada DHC-2 Beaver as their corporate aircraft. During 7th grade Mom got me a ride in the Beaver from Rohnerville airport near Scotia to Buchanan Field in Concord, California. That 210-mile trip was my first airplane ride, and I was convinced that aviation was what I wanted to do in the future. I took a drafting class in high school and designed a VTOL flying saucer with a circumferential fan driven by the exhaust of two Bristol Olympus turbojet engines.

On to MIT

Uncle Carl said that with my grades and College Board scores he could get me an appointment to the Naval Academy at Annapolis. This sounded great at first, but then I discovered that my eyesight was not good enough to be a Naval Aviator. Becoming an airplane designer sounded better to me than a non-flying career in the Navy. We applied to three engineering schools: Harvey Mudd College (first choice), the University of California, Berkeley, Engineering (fallback school), and the Massachusetts Institute of Technology (MIT) (the best). My transcript got lost in the mail, so I did not get admitted to Harvey Mudd. I did not really expect to get into MIT and failed to apply for regular financial aid. The choices were U.C. Berkeley Engineering with a California State Scholarship or MIT with only emergency financial aid. The family dug deep, including $1,000 from Great Aunt Ethel, and came up with enough money for my freshman year at MIT. Mom and Dad were concerned that working during school would hurt my studies, so I did not work freshman year. After my freshman year, I applied for financial aid. MIT prepared a budget of estimated income and expenses for each applicant. This budget included an expected family contribution and typical student earnings. MIT then offered financial aid (scholarships and loans) to balance the budget. I was able to earn more and spend less than the MIT budget, so very little family contribution was needed.

I was very shy and Mom was worried about a big school like MIT. It was not a problem. The dorm grouped freshmen together so there was a group of instant friends, and the MIT Libraries were a dream come true. The Aero Library had a complete set of *Jane's All the World's Aircraft* and the Engineering Library had a complete set of *Jane's Fighting Ships*. I spent many happy hours exploring the libraries. I worked part-time in the MIT Aero Library during sophomore and junior years for minimum wage ($1.25 per hour). One of my duties was "reading the shelves" (putting books in order). This was great fun and I became very familiar with the whole collection. During holidays I worked extra hours in the other MIT libraries. This was an opportunity to discover additional technical materials and to explore history, economics, political science, etc. The Aeronautics and Astronautics department had a cooperative education (co-op) program with industry, and this became part of the financial plan. I worked as a co-op student at Boeing Plant 2 in Seattle on the X-20 Dyna-Soar spaceplane. The co-op experience convinced me that I wanted to be an engineer doing creative work, but I would need an advanced degree. It motivated me to work harder, get better grades, and get into graduate school.

Professor Rene H. Miller was in charge of the co-op program, and in my senior year he offered me a job working on helicopter harmonic airloads at $1.75 per hour. Professor Norman D. Ham had an office next to Professor Miller and a desk was added to his office for me. Professor Miller had many interests. He developed several courses including VTOL Aircraft, Flight Vehicle Engineering, and Space Systems Engineering. He also researched helicopter harmonic airloads [2], spent 1 day a week as a consultant to Boeing Vertol, and founded the MIT Flight Transportation Lab (FTL). I applied to MIT for the Engineer in Aeronautics and Astronautics (EAA) program. The EAA included twice the course work of a Master of Science (SM) degree and was intended for designers. In addition to traditional aeronautical engineering courses, I studied Flight Transportation and Operations Research. Field trips were part of these courses, and a trip to the New York Airways helicopter airline operation included a flight to Wall Street heliport in a Vertol 107 helicopter. Under Civil Aeronautics Board (CAB) economic regulations airline ticket prices were fixed, so transcontinental passengers were offered extras like discounted flights on San Francisco and Oakland Helicopter Airlines, also known as SFO Helicopter Airlines. I used this several times on visits to home from MIT. This exposure to aircraft operations and operators greatly improved my abilities as an aircraft designer.

New York Airways Vertol 107.

SFO Helicopter Airlines Sikorsky S-61L.

The EAA degree was not very well known and, before I finished, Dad suggested that I consider going for a Ph.D. The written doctoral qualifying exam consisted of six questions that you choose to answer from about a dozen total questions. These questions required a solid understanding of basic physics. A typical question was: “A rotor blade breaks away from helicopter rotor on a whirl stand; where does it go?” I was surprised to learn that most students failed the written doctoral qualifying exam and had to take the oral version. Three of Miller and Ham’s students passed the written exam that year, and other professors asked why were so many smart students going into VTOL.

I was a full-time Research Assistant in graduate school, and Professor Miller was my advisor and my boss. He convinced Civil and Mechanical Engineering to give a small part of the Department of Commerce Northeast Corridor Transportation Study on high-speed rail to FTL [3]. I worked for FTL writing helicopter and tilt wing design codes, and designing VTOL transports to compete with high-speed rail. I worked on both VTOL design [4] [5] [6] and airloads for several years [7]. Lockheed California worked on a stopped, folded, and stowed rotor concept from 1965–70 [8]. Professor Miller sent me to Lockheed California to learn more about the stowed rotor concept. My point of contact at Lockheed was Dr. Richard M. Carlson, Division Engineer for Rotary-Wing Research and Advanced Design. The funding for VTOL design studies eventually dried up, but the Office of Naval Research (ONR) funding for airloads work [9] continued. My work followed the money and went back to airloads. My original Ph.D. thesis involved operational analysis and design studies for the Light Intra-Theater Transport (LIT). LIT was an Air Force program that sponsored three short takeoff and landing (STOL) and six vertical/short takeoff and landing (V/STOL) design studies with industry. The Air Force did not fund LIT work by MIT, so I continued the funded airloads work in addition to my thesis. This dual effort did not work well, and ultimately the airloads research became my Ph.D. thesis [10]. The various jobs I had as an MIT student were both financially necessary and essential to my education as an engineer. I earned SB (6/64), SM (6/67), EAA (6/67), and Ph.D. (2/75) degrees in Aeronautics and Astronautics.

I moved from a desk in Norm Ham’s office to various offices shared with other grad students including John Shaw and Wayne Johnson. Another student (Tom Imrich) was looking for partners to buy N72284, a 1946 Model Cessna 140, from his father. Tom had learned to fly in N72284 and wanted to keep it. He was a Certified Flight Instructor and offered to teach me how to fly as part of the deal. Wayne Johnson, who already had a Private Pilot’s License, became the third partner. We put up $1,000 each (in my case, borrowed from Mom) and became aircraft owners. When Wayne graduated and went to work at Ames he bought N72284 from Tom and me. Wayne drove his Corvair to California so I used my new Private Pilot’s License to ferry N72284 for him. It was November, so the plan was to avoid the high Sierra Nevada mountains by flying to Los Angeles and then up the coast to the Bay Area. N72284 was loaded with survival gear and a spare magneto. The idea was to fly from dawn to dusk and sleep under the wing at night. Small airports are very friendly, so I was always invited to sleep on the floor of a hangar or the Federal Aviation Administration (FAA) Flight Service Station. I had issues with a magneto in Kansas, so I diverted north to Dodge City where a shop was available to install the spare magneto. On arrival in Los Angeles, I tied N72284 down at Van Nuys airport and stayed with the Ham’s (Professor Ham was on sabbatical at RAND in Santa Monica). The next day the weather was very windy and N72284 was jumping against the tie-downs. It was not a good day to fly a light plane. I double-checked the tie-downs and called Wayne to request that he fly to Van Nuys to get N72284 when the weather improved. I then flew from Los Angeles to San Francisco on PSA ($11.43 on a DC-6) to visit home before returning to MIT.

N72284, 1946 Model Cessna 140.

Finding My Place

Boeing knew me through my co-op experience at Boeing Seattle and Professor Miller's consulting with Boeing Vertol. They offered me a job in Philadelphia where John Shaw was working. To my surprise I found that I wanted to return home to Northern California, and the only VTOL aircraft career option in the area was Ames Research Center. Norm Ham knew Professor Hank Velkoff who consulted for the Army Air Mobility Research and Development Laboratory (AMRDL) Headquarters (HQ) at NASA Ames Research Center. AMRDL was established in 1970 under the U.S. Army Aviation Systems Command (AVSCOM) in St. Louis, Missouri, and comprised four subordinate directorates. The Ames, Langley, and Lewis Directorates were named after, and co-located with, their respective NASA research centers. The Eustis Directorate was the former U.S. Army Aviation Materiel Laboratories (AVLABS) located at Ft. Eustis, Virginia. The Ames Directorate was the former U.S. Army Aeronautical Research Laboratory (AARL) that pioneered the unique Army-NASA collaborative relationship at Ames Research Center in February 1965.

The Army was looking for an experienced designer to work in preliminary design. Norm Ham and Hank Velkoff convinced Dr. Richard M. Carlson, now Chief of the Advanced Systems Research Office (ASRO), to offer me a job in preliminary design on the AMRDL HQ technical staff in ASRO. It was a GS 12 Step 1 (newly minted Ph.D.) with promotion potential to GS-13/14. Wayne Johnson had joined the Ames Directorate in 1970 as an Army employee working in the NASA Ames 40- by 80-Foot Wind Tunnel, and he told me that the Ames-Army Lab "has a good technical environment." I had dreamed of designing aircraft in industry because I knew that government aircraft designs would never go into production. Thinking about military aircraft history, I realized that government aircraft specifications needed improvement because they frequently resulted in unsuccessful designs from industry. I decided that government designs resulting in better government aircraft specifications could improve the chances of developing successful military aircraft. While Boeing offered me 10 percent more to work in Philadelphia, California represented mountains, ocean, and family, so it won out and I accepted the job at Ames.

Joining the Army Labs (AMRDL)

I joined AMRDL on March 3, 1975. The Army-NASA technical environment included world-class facilities and researchers plus senior engineers from industry who had developed actual aircraft and engines. I was blessed with an early opportunity to work with John Wheatley and learn from his adventures with the National Advisory Committee for Aeronautics (NACA), and the aircraft and engine industries. Dr. Carlson and Andy Kerr brought a wealth of industry experience including the development of the Lockheed AH-56A Cheyenne compound attack helicopter.

Dr. Carlson had hired a young engineer (Ron Shinn) to conduct Preliminary Systems Design Engineering (PSDE) studies under the mentorship of John Wheatley, a senior engineer and the ASRO Propulsion Specialist. They completed the first two PSDE studies in 1974 [11] [12]. I joined Ron Shinn at AMRDL HQ in ASRO Preliminary Design. Ron was starting on a tilt rotor PSDE study when I arrived, mostly adapting and improving design tools. John Wheatley asked me to do an analysis of the Napier Nomad, a turbo-compounded, two-stroke Diesel aircraft engine developed in the United Kingdom after WWII [13]. This subject was of great interest to me and an opportunity to use the Hewlett Packard HP35 pocket calculator the Lab had just provided. My analysis was based on *The Internal-Combustion Engine* by Taylor [14].

John Wheatley was well known in the rotary-wing world for his early NACA autogiro work at Langley before WWII. He left NACA to work for Northrop Corporation, which became the Douglas El Segundo Division in 1937. John worked on flight testing of the DC-5 at El Segundo. During WWII he designed engine installations for the Martin B-26 and the Eastern Aircraft P-75. When Eastern Aircraft was shut down at the end of WWII, John joined Allison and compared turbo-compound spark ignition engines with turboprops [15]. Turboprops won and Allison developed the T38 and T40 on the way to the very successful T56 [16] (C-130, Electra, P-3). John was T56 Project Engineer and Assistant Chief of Preliminary Design for the T63 [17] (OH-6, OH-58, Jet Ranger, etc.). After Allison, John worked for Dr. Carlson at Lockheed designing the AH-56 drive system. When Dr. Carlson was building ASRO he hired John Wheatley as the Propulsion Specialist. My technical discussions with John rapidly moved beyond the Napier Nomad and became a great learning experience.

John retired at the end 1975 with his 3 high salary years at the Army Labs added to 7 years at NACA. I was asked to be acting propulsion staffer until a permanent replacement was hired. Dr. Carlson defined the ASRO staff job as unloading burdens from the Labs so they could focus on research. We were expected to be familiar enough with the research to be able to explain and defend it to the Department of the Army (DA) in the Pentagon so that they could respond to Congress. The propulsion area included substantial research at both the Eustis and Lewis Directorates. John Wheatley had presented a unified propulsion program at previous major reviews. The two directorates viewed an acting staffer as an opportunity to present two competing programs and try to get a bigger piece of the pie. It was necessary to explain that either they would present a unified propulsion program or “the kid” would do the propulsion review. This was good experience because I became very familiar with the propulsion community and the DA staff. I also learned where funding comes from and how it is defended.

I came to Ames with my paper brains—a very large amount of professional books and papers. They included discarded library materials (NACA/NASA reports, aircraft engine specifications), material from Professor Miller (AVLABS reports, early McDonnell Aircraft engineering manuals), and some

16,000 pages of technical material copied from MIT libraries. These materials were useful during discussions with John Wheatley. Much of this material has since been digitized. *Jane's All the World's Aircraft* is a fundamental reference for aircraft designers. The NASA library had a good collection, but the design team only had two annual editions. Since 1975 we have purchased every annual *Jane's All the World's Aircraft* and appropriate other books for the design team. Boxes of AVLABS reports were stored in the AMRDL HQ public affairs office. I suggested that AVLABS reports and Army/NASA reports were the net output of AMRDL and they needed to be accessible on shelves. An AMRDL HQ Technical Information Center was eventually created.

My education in military helicopter preliminary design and existing tools continued in parallel with the John Wheatley discussions and propulsion staff work. There were two other AMRDL preliminary design activities: 1) the Systems Research Integration Office (SRIO) located at AVSCOM in St. Louis, and 2) a group at the Eustis Directorate. SRIO focused on the early, more conceptual phase of preliminary design and developed design and performance codes SSP-1 and SSP-2 based on momentum theory [18]. The Eustis Directorate group focused on the later phase of preliminary design when rotor definition is detailed enough to allow the use of blade element theory. Ron Shinn had combined SSP-1 and SSP-2 into a single helicopter sizing and performance code called PSDE, and he was adapting the PSDE code to approximate tilt rotors [19]. Weight estimation is central to preliminary design, and Ron Shinn had written a multiple linear regression analysis code to develop better statistical weight equations. These tools were the foundation for the continued development of improved helicopter preliminary design capability. I came out of MIT with a dream of designing advanced VTOL aircraft for military and civil applications and developing associated design codes. At MIT we developed civil VTOL design codes that calculated direct operating cost (DOC) vs. stage length but could not fly military mission profiles. The PSDE code was developed to size military helicopters, including mission analysis, and it became the basis for further code development.

HELCOM—My First Joint Service Preliminary Design Study

In June 1975 the Interservice Helicopter Commonality Study (HELCOM) [20] [21] started. It addressed the question, "Can greater use of common helicopter designs cover existing Department of Defense (DoD) missions more affordability." A Joint Study Group was assembled by Colonel Joseph Rutkowski (Ft. Rucker) with operational and technical membership from the Army, Air Force, Navy, and Marines. I was the Army technical member of the study group, joining Dave Norman (Air Force) and Dudley Cate (Navy). In June 1975 the study started with a meeting at Ft. Belvoir, Virginia, and I visited Hal Johnson (Eustis Directorate Preliminary Design) for advice, and met his technical staff including Jim O'Malley and Bill Pleasants.

Traditionally, military helicopters were developed by one service to satisfy their requirements. These single-service helicopter designs were often adapted to satisfy the needs of other services after initial development. The HELCOM plan was to develop a limited number of helicopter designs to address all service primary helicopter missions. Primary missions were defined as those that could justify a separate development program. The study identified 22 primary service helicopter missions (7 Army, 5 Air Force, 5 Navy, 4 Marine Corps, and self-deployment) plus their mission requirements. The service primary missions were then assigned to a limited number of logical groups of similar capabilities (Capability Groups).

No attempt was made to reconcile differences in service requirements. Instead point designs were sized for the service primary missions to quantify their difficulty, and a baseline helicopter (BLH) preliminary design was defined for each Capability Group. Individual service versions of each BLH had mission-specific equipment, fuel capacity, inlet air particle separation, and infrared (IR) suppression. Most BLH designs included provisions for powered blade fold, flotation, and aerial refueling kits. These BLH designs were then adapted to satisfy the needs of all missions in their Capability Group. The goal was to satisfy all missions in each Capability Group with a common helicopter dynamics system.

Significant changes to BLH airframe or dynamic systems became a variant. The most important variant was an attack fuselage (tandem seating) version of the utility helicopter with common dynamics. Two other variants were generated by severe shortfalls, Air Force search and rescue (SAR) and Navy vertical replenishment (VERTREP). The 22 service helicopter missions were performed by the 9 helicopter types and 6 variants in DoD inventory. HELCOM showed that a commonality program of five baseline helicopter types and three variants could perform the same missions. Our HELCOM experience eventually proved useful for the Joint Services Advanced Vertical Lift Aircraft (JVX) [22], which developed into the V-22 Osprey, and the Overarching Rotorcraft Commonality Assessment (ORCA) study [23] for the Joint Staff (J-8).

The Naval Air Systems Command (NAVAIR) used the HESCOMP code (originally developed by Boeing Vertol) for helicopter preliminary design. The Army and NAVAIR did a detailed (source-code level) technical comparison between PSDE and HESCOMP. Ron Shinn and I changed PSDE to print out much more detail and generate comparable answers for HELCOM. We concluded that our design tools needed a lot of work. This started us on a long path of design code developments. The final pure Army design code was called RC. NASA used RC in their Heavy Lift Rotorcraft Systems Investigation [24]. This experience convinced Wayne Johnson that RC was very capable, but poorly documented and coded. He offered to create a new design code based on RC if the Army design team would provide the essential design experience and technical support. The result was the NASA Design and Analysis of Rotorcraft (NDARC) code, with an Army version used by Army Concept Design and Analysis (CD&A).

Advanced Attack Helicopter (AAH) Source Selection

Helping the Army be a "smart buyer" of new aviation systems was an important part of AMRDL's mission. Charlie Crawford's Flight Standards and Qualification Directorate (FS&QD) and AMRDL were the major sources of Source Selection Evaluation Board (SSEB) technical leadership and expertise.

The Army Utility Tactical Transport Aircraft System (UTTAS) and Advanced Attack Helicopter (AAH) were two-phase helicopter development programs. The Phase I paper competitions selected two UTTAS designs in 1972 and two AAH designs in 1973 for the Phase II Competitive Fly-Offs in 1976. The resulting U.S. Army Aviation Engineering Flight Activity (AEFA) flight test reports [25] [26] [27] [28] became the foundation of technical evaluations by the UTTAS and AAH SSEBs. Finding experienced government technical staff for two simultaneous SSEBs was a challenge. Andy Kerr was a GS-14 and had been technical lead on the Lockheed Phase I AAH proposal, but his work was essential to AMRDL HQ. Although a GS-12 at the time, I was assigned as AAH SSEB Performance Factor Chief and made an acting GS-13 for the SSEB. Suspending my work as half of

ASRO Preliminary Design to spend 5 months in Granite City, Illinois, was not attractive, especially since I thought that AEFA flight test data would make performance easy to evaluate. I was wrong.

Five offerors submitted proposals in the Phase I AAH competition, and in June 1973 Bell and Hughes were selected to design, build, and fly AAH prototypes. “Fly Before You Buy” was still an affordable step in the acquisition process. Bell and Hughes submitted Phase II proposals for the Bell YAH-63 and the Hughes YAH-64 based on the prototypes tested by AEFA. The proposals included design modifications to overcome shortfalls. Thus, we entered a technical debate about the sources of performance shortfalls and the effectiveness of proposed design changes. Dr. Carlson offered complete support, and through him I could call on the technical resources of the Army-NASA team as needed. A job that I did not want turned out to be technically challenging, important to Army Aviation, and a great learning experience.

In June and July 1976 there were two Factor Chief training sessions in St. Louis. This was important because I had not served on an SSEB before. The job of an SSEB is evaluation (technical evaluation in the case of the technical area). Selection is the job of the Source Selection Advisory Council and the Source Selection Authority. The Contracting Officer (KO) is the person with a warrant to sign contracts that obligate the government. The KO and his/her staff are the experts on all of the legal and contractual requirements of an SSEB. Failure to follow the rules could result in a formal protest by the losing offeror. In extreme cases, this could require a new competition and years of delay. KO staff reviewed all written communication with the offerors and supervised all oral communication. My first few meetings with offerors were preceded by a training session, to be sure that I understood the rules, and were followed by a critique and lessons learned. The training diminished as I gained experience, but we always had an after-action discussion. Notes were taken during all meetings, and in some cases more formal documentation was prepared. Security was critical as any leakage of Competition Sensitive Information could compromise the Source Selection. We had clean desks with all material locked up when we were not working on it.

The AAH SSEB started at the beginning of August 1976. I reported for duty in Granite City, Illinois, a day late because my 1966 VW Squareback broke down in Utah and again in Kansas City. Not a good start. The senior SSEB leadership was Brigadier General Joseph Jaggers, Jr. (Chairman) and Dick Lewis (Deputy Chairman). The Performance Factor was under the Tech Approach Element Chief (LeRoy Ludi), who reported to the Tech Area Chief (Ron Gormont). LeRoy Ludi was extremely helpful with formal SSEB processes and paperwork. All of our technical expertise would have been useless if it did not get into the system. Ron Gormont had been Performance Factor Chief for the Phase I AAH SSEB, so he was a historical and technical resource. Charlie Crawford was on the Source Selection Advisory Council along with Dr. Carlson. The story was that the Tech Area on a previous SSEB had floundered without technical leadership, and Charlie had been brought in to save the day. Charlie provided the Tech Area Chiefs (Bob Wolfe for UTTAS and Ron Gormont for AAH) and many of the engineers for the Phase II SSEBs from his FS&QD.

AAH SSEB Performance Factor

Teams of evaluators were assigned to the factors being evaluated. The Performance Factor consisted of four evaluators: Roger Smith (SRIO), Jim O’Malley (Eustis Directorate), Major Mike Summers (RD&E), and myself. Our initial task was to read the proposals looking for Errors, Omissions, and Clarifications (EOCs). These were documented by us and submitted to the offerors by the government KOs. Proposals are evaluated against requirements in the government System

Specification, not against each other. However, it was useful to compare similar numbers in the proposals and ask ourselves why they were different to identify areas for deeper investigation. One proposal included some modifications to overcome what were expected to be small performance shortfalls. The other proposal included no modifications expected to impact performance. Naturally we devoted extra effort to studying the proposed modifications.

Jim O'Malley brought a set of tools for calculating isolated main rotor performance. The Landgrebe Prescribed Wake program was used for hover. The rotor performance analysis module (ROTOR) from the Eustis Directorate Preliminary Design Program (PDP) was used for forward flight. Unlike the very fast momentum theory used in PSDE, SSP-1, and SSP-2, the ROTOR code used prescribed inflow strip theory with 2D airfoil data tables. This allowed us to estimate the impact of rotor design changes on performance. ROTOR was in an early stage of development, and trim capabilities were limited, requiring plotting to get what we needed. ROTOR included a compressibility tip relief correction by LeNard [29] that was new to me. I took advantage of the Army-NASA technical support offered by Dr. Carlson. Wayne Johnson was not a member of the SSEB, but it was okay to ask him to evaluate a public technical report. He said that LeNard was about as good as we could do until computational fluid dynamics (CFD) research by Frank Caradonna got to a practical state. He also provided a simple physical explanation of the LeNard model. This was very helpful when Bell became confused about the LeNard model. Thanks to Wayne, I was able to simply explain how it worked.

Our job was to evaluate performance specification compliance. This included both vertical flight (hover and vertical climb) and forward flight requirements. Level flight airspeed at Maximum Continuous Power (MCP) became the dominant performance issue for the SSEB. The MCP speed requirement was at mission gross weight (MGW), 4,000 feet pressure altitude, and 35 degrees C (95 degrees F). MGW included primary mission fuel. Major Mike Summers calculated primary mission fuel as a function of MGW, and the Weights Engineers (Doyle Hixson and Ken Hutchinson) provided the rest of MGW. Mission fuel calculations were based on our estimates of power required vs. airspeed for various gross weights, and engine fuel flow vs. power required from the Propulsion Factor (Vern Edwards). Power required equals power available for maximum airspeed level flight. The Propulsion Factor provided power available vs. airspeed, and we calculated power required vs. airspeed and gross weight. Power required included transmission losses from the Propulsion Factor and accessory losses from the Secondary Systems Factor (Eugene Birocco).

We prepared our methodology to use preliminary AEFA Government Competitive Test (GCT) data for aircraft power required (measured by engine torque meters) vs. gross weight and airspeed. The AEFA data included nondimensional curve fits (C_P vs. C_W for various μ). The nondimensional form corrects for density altitude but not tip Mach number (outside air temperature). The AEFA curve fits were substantiated by flight test data points plotted as engine power required vs. true airspeed and compared with a line calculated from the nondimensional curve fits. Each plot was for a specific flight with a given configuration and average values of flight gross weight, center of gravity (CG) location, density altitude, outside air temperature, and rotor speed. We used the AEFA curve fits to calculate GCT power required vs. airspeed and gross weight for other density altitudes. GCT main rotor power required was calculated by subtracting measured tail rotor power and estimated losses (transmission and accessory) from measured engine shaft power. GCT main rotor lift was calculated by subtracting airframe lift from gross weight. The resulting GCT main rotor data in nondimensional form (C_Q vs. C_L for various μ) could be used to calibrate the ROTOR code. When an offeror proposed design changes for their Phase II (P2) AAH proposal, we could model main rotor modifications with the ROTOR code and then build back up to P2 total aircraft power required vs. gross weight and airspeed. The ROTOR code was used to calculate the effects of changes in outside air temperature, airframe drag, rotor blade airfoils, and tip speed on main rotor power required vs. main rotor lift for various airspeeds.

This was before the advent of electronic spreadsheets (VisiCalc, Lotus 123, etc.), and there was no time to write new computer codes. We used pocket calculators like the HP35 in conjunction with the ROTOR code to implement our performance evaluation methodology. Roger Smith did the majority of the hand calculations, but we all contributed to this labor-intensive bottleneck in our analysis process. Our calculations were documented in writing and carefully checked; we checked each other's work because fresh eyes were important. The result of this care and teamwork was that we made fewer mistakes than the much bigger engineering teams of the offerors.

AAH SSEB Flight Test and Wind Tunnel Test Data

The preliminary AEFA GCT data arrived about a month into the SSEB. It included performance flight test data, but it left the evaluation of performance specification compliance to the SSEB. Flight test outside air temperatures were a maximum of 24 degrees C and an average of 15 degrees C, significantly lower than the 35 degrees C ambient temperature required for the most critical performance specifications. Our initial evaluation used flight test data for power required without any correction for outside air temperature. The calculation of primary mission fuel, MGW, and power available was labor intensive as described above. The results of these calculations are included as Table 2 (YAH-63) and Table 3 (YAH-64) in the AEFA final reports [27] [28]. The specification requirement for cruise speed (level flight airspeed at MCP) was 145 to 175 KTAS. The GCT cruise speed for YAH-64 was 141 KTAS; see Table 3 in the AEFA final report [28]. The YAH-64 Phase II proposal included some modifications to overcome small performance shortfalls so 145 KTAS seemed possible. The GCT cruise speed for YAH-63 was 122 KTAS; see Table 2 in the AEFA final report [27]. The original YAH-63 Phase II (P2) proposal included no performance modifications. We now anticipated a modified YAH-63 P2 proposal with major changes to overcome such a large performance shortfall. This shortfall was a surprise to the SSEB. Jim O'Malley did the original calculations for YAH-63 and triple checked them. I checked the calculations, Ron Gormont (Tech Area Chief) checked the calculations, and Dick Lewis (Deputy Chairman) checked the calculations.

While we continued to work on the YAH-64 evaluation and other YAH-63 performance issues, YAH-63 cruise speed now consumed most of our effort. A modified Bell YAH-63 P2 proposal soon arrived, and it included rotor airfoil changes intended to improve high Mach airfoil performance at the expense of stall margin. We needed help. Dr. Carlson put me in touch with Gene Bingham at the Langley Directorate. A famous fixed-wing airfoil designer, Dr. F. X. Wortmann, had developed custom rotor airfoils for the YAH-63. One of the goals was profile drag reduction due to laminar flow. These 2D airfoil sections were tested at low Reynolds number (3.0 to 5.7 million) in the United Aircraft Research Labs (UARL) 8-Foot Large Subsonic Wind Tunnel using the 2D channel insert [30] [31] [32]. Gene Bingham had worked with the 2D channel insert when he was at UARL. He later joined AMRDL and developed an improved Army-NASA airfoil test facility—the Langley 6- by 28-Inch Transonic Wind Tunnel [33]. The Army-NASA facility is pressurized and can test airfoils at full-scale Reynolds number (6.0 to 13.6 million), eliminating the need for theoretical Reynolds number corrections. The Army-NASA facility is also properly slotted for transonic testing, eliminating the need for theoretical transonic corrections. Starting with a request in September, the

Army-NASA team was able to change priorities and test the two (GCT and P2) outboard rotor airfoils during October. The test results [34] and complementary analytical work [35] were presented to the SSEB on 29 October 1976. We provided this airfoil data to Bell the same day.

Airframe aerodynamics (both lift and drag) was the area with the largest potential YAH-63 cruise power reduction between GCT and P2. A series of 1/6th-scale low-speed wind tunnel tests [36] [37] [38] was the basis for this important change. Bob Stroub, an Army engineer at the NASA Ames 40- by 80-Foot Wind Tunnel, had worked interesting aircraft programs around the industry doing airframe aerodynamics wind tunnel testing before coming to Ames. His wide and varied experience made him the ideal engineer to witness the Bell YAH-63 low-speed wind tunnel testing. Dr. Carlson was able to make this happen for the SSEB. The result was a good understanding of the wind tunnel data. The SSEB assessed about 10 percent less drag reduction between GCT and P2 than Bell. The main airframe lift difference between Bell and the SSEB was the change in pitch trim between GCT and P2 (discussed below).

The GCT AAH prototypes carried the eight BGM-71 Tube-launched, Optically-tracked, Wire-guided (TOW) anti-tank missiles in streamlined four-tube launchers designed by the AAH offerors. The Army was developing a larger diameter, longer range anti-tank missile for the Phase 2 AAH, the AGM-114 Hellfire. The Hellfire engineering development competition was decided during the AAH SSEB, and details of the selected design only became available late in the SSEB. Unlike TOW, the Hellfire is rail-launched, and platforms are required to use the launcher provided by the missile developers. Low cost and ease of maintenance were priorities for the launcher, but aerodynamic drag was clearly not considered important.

The AAH offerors argued that they had no control over, and therefore no responsibility for, the drag increase due to replacing eight TOW with eight Hellfire missiles. Dr. Carlson agreed that Army-NASA wind tunnel tests to measure the drag increase made sense. Bob Stroub coordinated the effort for the AAH SSEB. The NASA Langley V/STOL wind tunnel was made available on very short notice for full-scale semispan tests of TOW and Hellfire systems mounted on the two AAH wings. Full-scale hardware was obtained from both AAH offerors and the Hellfire contractor. The reduced wind tunnel test data was delivered to the SSEB on 18 November 1976. This data was used for the final evaluation. The Army-NASA wind tunnel test was ultimately documented in a published report, reference [39].

Hellfire Missile Launcher.

The test effort included evaluation of fairings to reduce Hellfire system drag. Minor modifications reduced the Hellfire system drag increase over TOW by about 35 percent and major modifications had greater potential. The missile developers were not interested in modifying their just awarded contract to reduce armed AAH system drag and nothing changed.

AAH SSEB Rotor Performance

We needed to calculate YAH-63 main rotor performance both to correct the AEFA GCT aircraft power-required data for outside air temperature and to evaluate the proposed P2 airfoil changes. GCT flight test outside air temperatures were an average of 15 degrees C, significantly lower than the 35 degrees C required for the most critical performance specifications. The ROTOR code was used to correct the AEFA aircraft power-required curve fits from 15 to 35 degrees C. This reduced power required because the higher speed of sound at 35 degrees C reduced compressibility power. YAH-63 rotor power required calculated from GCT aircraft power required showed a very steep slope for main rotor power required vs. main rotor lift at constant airspeed. This was a clear indication of poor rotor performance (as opposed to airframe drag). However, the test data did not indicate how much of this power-required increase was due to advancing blade problems (drag divergence) vs. how much was due to retreating blade problems (stall). Bell concluded that drag divergence on the advancing blade was the principle problem. Bell conducted a high-speed wind tunnel test to evaluate the effect of 3D airfoil surface conditions on profile drag [40]. The results showed no laminar flow drag reduction for normal field airfoil surface conditions. Bell proposed a P2 rotor airfoil section that traded laminar flow airfoil design for better transonic properties to delay drag divergence. Unfortunately, this P2 rotor airfoil had poorer static stall characteristics than the GCT rotor airfoil.

The net effect of the P2 airfoil change was a combination of benefit on the advancing blade and penalty on the retreating blade. We used the ROTOR code to predict the effect of the P2 airfoil on main rotor power required. Initially we used the 2D airfoil data from the UARL wind tunnel. This data was replaced with 2D airfoil data from the Army-NASA airfoil test facility when it became available. The static airfoil data was modified for dynamic lift-stall delay. The lift-stall delay was 3 degrees up to Mach 0.3 and was reduced linearly to 0 degrees between Mach 0.3 and Mach 0.75. We used no drag-stall modification for the evaluated performance.

Correlation of calculated forward flight aircraft power required with AEFA GCT flight test data was important to validate our performance analysis methodology. Our goal was correlation of forward flight power required at all airspeeds and all gross weights. This was important not only to validate the analysis but to accurately calculate primary mission fuel and to assess compliance with the entire set of performance specifications. We found that by varying parasite drag area with gross weight we could get good correlation of power required vs. airspeed at all gross weights. Unfortunately this required that parasite drag area increase with gross weight, which is not physically realistic. This correlation problem was not surprising given the state of the art for rotor performance analysis at the time. Our solution was to calculate the delta between GCT power required and P2 power required. This approach meant that errors in the total P2 power required cancelled out and only the delta power required was important. This delta power-required technique was used for the final SSEB performance evaluation. Efforts to explore the impact of various improvements in rotor modeling on performance continued as time permitted. The most interesting are discussed below.

Strip-theory computations were made using ROTOR with detailed output of angle of attack, lift, drag, and profile power as functions of azimuth and radius. These showed that advancing blade drag divergence and retreating blade drag stall are both significant in forward flight. We then experimented with changes to airfoil drag characteristics to help understand the reasons for poor GCT forward flight rotor performance. The changes tried were earlier (lower angle of attack) drag stall and earlier (less negative angle of attack) drag divergence. These changes were simulated in ROTOR by looking up the airfoil data at an increased angle of attack. The early drag divergence trials all resulted in poor correlation. The early drag-stall trials resulted in improved correlation, with 2.75 degrees early being the best. Good correlation of power required vs. airspeed was obtained at all gross weights using a realistic parasite drag area decrease with gross weight. A 2.75-degree error in the static airfoil data was not believable; there had to be dynamic effects or some other unknown effect. Combined with up to 3 degrees of dynamic lift-stall delay, this implied an up to a 5.75-degree difference between drag stall and lift stall. ONERA had reported in 1972 [41] dynamic measurements of lift, drag, and moment on a NACA 0012. At Mach 0.3 there was typical dynamic lift-stall delay and 2 or 3 degrees of early drag stall. This showed that the combination of dynamic lift-stall delay and early drag stall was possible in one specific case. Unfortunately the airfoil and test conditions were so different from the GCT that they did not apply directly to the case being evaluated by the SSEB.

The early drag-stall trials demonstrated good correlation of power required vs. airspeed at all gross weights using a realistic parasite drag area decrease with gross weight. Because no other method of obtaining such correlation was found by either the SSEB or the offeror, early drag stall was a probable explanation for the poor GCT rotor performance. Because of the poorer static stall characteristics of the P2 airfoil compared to the GCT airfoil, a 2.75-degree early drag-stall trial resulted in a 7-knot P2 cruise speed penalty. We used no drag-stall modification for the SSEB evaluated rotor performance. However we evaluated the risk of failing to achieve the SSEB evaluated cruise speed because of rotor performance as high.

Performance meetings with Bell were typically with an engineering manager, sometimes overseen by the Director of Technology. Eventually this escalated to the Vice President of Engineering. His subject was the correlation of performance analysis with GCT data. Bell carefully tuned their analysis to match GCT power-required data at the gross weight and airspeed corresponding to the level flight airspeed at MCP requirement. We responded that correlation was indeed important to validate performance analysis methodology. By varying parasite drag area with gross weight, we had been able to get good correlation of power required vs. airspeed at all gross weights. However this required an unrealistic parasite drag area trend with gross weight. We had chosen the parasite drag area corresponding to the gross weight for the level flight airspeed at MCP requirement. This resulted in good correlation of power required vs. airspeed at that gross weight, which was much better than their correlation at a single airspeed. We described how our early drag-stall trials had demonstrated good correlation of power required vs. airspeed at all gross weights using a realistic parasite drag area decrease with gross weight. We stated that the substantial early drag stall required for correlation was not well supported by available experimental evidence. We observed that, if they were okay with early drag stall, then good correlation would only cost them a 7-knot reduction of P2 cruise speed. Bell dropped the correlation discussion at that point.

Both our ROTOR code and the Bell strip-theory code F35 [42] normally used uniform inflow but allowed input of a nonuniform inflow distribution. Bell tried both an empirical, prescribed inflow distribution and a calculated one. Their calculated inflow was based on a very simplified vortex wake model consisting of a single, constant circulation tip vortex line from each blade. Bell's calculations showed a significant influence of nonuniform inflow on high-speed (0.32-advance-ratio) performance. This seemed surprising, so we decided to investigate. The SSEB used a published nonuniform inflow computer program LDS-73 [10]. A rigid wake model was used consisting of a tip vortex line, a tip vortex sheet, an inboard vortex line, and a series of shed vortex lines. Bound circulation was calculated every 15 degrees in azimuth, and the circulation of each wake vortex element was calculated by conservation of circulation. The circulation in the tip vortex sheet rolled up into the vortex line in the first 180 degrees of wake. A very large vortex core was used for the inboard vortex line and shed vortex lines to simulate the distributed nature of these portions of the wake. A realistic tip vortex core size was used. This realistic wake model produced a very different inflow distribution than either tried by Bell. The SSEB used LDS-73 to calculate a nondimensional inflow distribution at 0.32 advance ratio and then input it into ROTOR to calculate a performance point. The result was a modest increase in P2 high-speed power required. We did not have time to do a complete performance analysis using this procedure, so evaluated performance was based on uniform inflow.

AAH SSEB Comprehensive Analysis (C81)

The C81 Rotorcraft Flight Simulation [43] [44] was a large and complex computer program (developed by Bell under an AVLABS contract) containing a variety of different math models for the same phenomena. These math models included a large amount of empiricism to supplement fundamental physics. Empirical models can only be used to analyze rotorcraft configurations for which correlation has been demonstrated. For the SSEB, this meant first developing a set of C81 input data (physical parameters, correlation parameters, and math models) to get correlation with GCT test data. The same correlation parameters and math models could then be used to analyze the effect of changing physical parameters to represent the P2 configuration. The offeror concluded that rotor blade torsional oscillations had a significant effect on flight performance and used C81 to estimate the effect. The number of C81 runs required to fully investigate this problem was beyond the ability of the SSEB to complete and analyze in the available time. The fallback plan was to use offeror-supplied C81 data, checked and supplemented by board-generated C81 data. Guidelines for C81 runs used by the offeror to substantiate their proposal were formalized in a KO letter to the offeror [45]. Standard input data sets were to be established and substantiated for both GCT and P2 aircraft. Correlation with GCT flight test data was to be demonstrated using the GCT standard input data set with appropriate changes to operating state variable inputs for each data point. All C81 runs submitted to the SSEB had to include a complete listing of all inputs and outputs. They also had to identify, explain, and substantiate differences between the input data used and the appropriate standard input data set.

Bell submitted a number of other C81 runs to the SSEB during the evaluation. However, Bell was unable to substantiate their C81 standard input data sets. The SSEB found so many errors in the input data for these C81 runs that the results were useless. Bell ultimately admitted that they were unable to assemble and substantiate a complete, consistent, and accurate set of C81 input data in the time available.

The calculation of aircraft pitch attitude vs. airspeed, and hence airframe lift vs. airspeed, is complex. In theory this would be a great application for C81. It was vital that C81 input data accurately represent the aircraft including airframe aerodynamics as measured in wind tunnel tests. The SSEB concluded that this complex task was not practical in the time available. Bell had more engineers and attempted to use C81. Bell also eventually concluded that this was not practical in the time available. Bell then created a simplified manual computation analysis based on wind tunnel test data and GCT flight test data. The SSEB corrected the manual analysis to include the movable elevator proposed for P2 and fixed various minor errors.

Air Vehicle Technical Description Data is intended to provide enough detail to allow the government to analyze the proposed design. A 1975 Aeronautical Design Standard (ADS-10) [46] defined the data required as that identified in section 2 of USAAMRDL-TR-74-10B, the C81 User's Manual [44]. ADS-10 data included both a description of the design and various aerodynamic, dynamic, structural, and control system properties of the design. The description of the design included only enough detail to support the level of analysis available in C81. The government needs enough detail to support any state-of-the-art analysis tool likely to be needed. The air vehicle properties inputs to C81 are those required to approximate actual air vehicle properties with the math models in C81. The government needs the best possible data on actual air vehicle properties so that it can model them with the best available math models. The properties data are based on a mixture of test data and engineering analysis. ADS-10 data would be much more useful if the basis for this type of data was documented. This documentation could be formal or informal copies of test reports and other engineering work done to prepare the data.

AAH SSEB Technical Reviews and Issues

When Dr. Carlson came to St. Louis for a meeting of the Source Selection Advisory Council, he asked me to meet him and review the technical details of the performance evaluation. It was a rigorous review with lots of tough questions and some good suggestions. My confidence in our work was significantly bolstered by this review. Charlie Crawford eventually asked the SSEB for a similar review. Dick Lewis was worried about this and asked if I wanted support. I said it was not necessary. Dr. Carlson had given me confidence that we were on solid technical ground. I had heard a lot of stories about Charlie, but never met him. Our meeting was in a small room at the SSEB. The technical review was excellent with plenty of good questions. Charlie was the professional engineer doing his job. It was a relief and a reminder not to worry about myth and rumor.

During the meeting with Charlie, the issue of the YAH-63 inlet air temperature rise came up. Engine power available is a function of the temperature of the air entering the engine, which was measured during the GCT. Bell had decided that hot air from around the transmission was leaking into the engine inlets and significantly reducing engine power available. They wanted to very carefully seal the engine inlets from the transmission compartment and measure the inlet air temperature rise again. I used simple thermodynamics to calculate the inlet air temperature rise for the worst case of all of the transmission power losses entering the engine inlets as heat. The result was a modest increase in inlet air temperature. I showed the calculation to Charlie and asked if it was worth spending money on additional government flight testing. He said that it was not just a technical issue—Bell was becoming concerned that the government was out to get them, and he believed that this was a way to reassure them. This was a new insight for me into the complexities of management and perception.

Bell expressed their concern about the government to the SSEB Chairman, Brigadier General Jaggers. This resulted in a very large performance meeting between Bell and the SSEB. The Bell team was headed by their president and the SSEB team was headed by Brigadier General Jaggers and Dick Lewis. I was allowed to attend but told to keep quiet. The most technical part of the meeting was Bell insisting that the inlet air temperature rise measured in the planned additional government flight test be accepted without question. I could not resist stating that if the measured inlet air temperature rise was less than the ideal (adiabatic) temperature rise, I would charge them an accessory loss for a refrigerator. The engineers in the room understood my point, and I did not get in trouble. When the additional government flight test data became available, the hoped-for reduction in inlet air temperature rise was not there, and the whole issue quietly went away.

Bell eventually proposed a swept tip P2 tail rotor design for the YAH-63. They had tested this on a High Accuracy Tail Rotor Test Stand, and the data showed a useful reduction in power required. I asked about the aerodynamics behind the modification, and the answer did not make sense. I asked for the complete set of raw test data including zeros and calibrations. When Roger Smith dug into the data, he found that the High Accuracy Tail Rotor Test Stand was anything but accurate. The zeros and calibrations wandered all over the place. You could get any answer you wanted by choosing from the various zeros and calibrations. The addition of senior watchers at engineering meetings had abated, and I called the engineering manager (under KO supervision) and said that he really needed to review the zeros and calibrations of the tail rotor test data. Shortly afterward he called back to ask if we were going to charge them a performance penalty for the swept tip tail rotor design. I said no; the test data was worthless so we would just call it a wash.

Accessory losses were a much more serious issue. We had noticed a big difference in accessory losses between the two offerors and asked Secondary Systems Factor for an explanation. They investigated and said that it seemed to be in the electrical load. The state of the art for rotor blade deicing was electrical resistance heating. This was a very large load, and it was expected to size the capacity of the electrical system. However running the deicing system on a 35 degree C (95 degree F) hot day did not make sense. We repeatedly requested a detailed electrical load breakdown from both offerors. Bell had decided that we were only looking for data to reduce their performance and ignored our requests. We were concerned that if we suggested their electrical load was too high, they would agree and create data designed to support improved performance. We were unable to come up with another explanation for the very high electrical load. Finally I called Bell to ask if they were running deicing on a hot day. This quickly resulted in a detailed electrical load breakdown from Bell. The change in accessory losses did not have a big impact on cruise speed, however Vertical Rate of Climb (VROC) is very sensitive to power changes. The result was that Bell now met the VROC requirement. Dick Lewis was not pleased, but I believed that it was my call and the right thing to do.

Bell made significant changes to the P2 YAH-63 design in their best and final offer. They were under great time pressure, and their technical substantiation was incomplete and inconsistent. We were no longer allowed to communicate with the offerors, so we interpreted the new data in light of their previous practice. We were under a deadline to submit our final evaluation, and there was not enough time to update all of our calculations. Our final cruise speed evaluation was 140 knots, compared to the requirement of 145 to 175 knots. We estimated that if we had been able to update everything, it would have been 3 knots lower. This showed the need for a comprehensive and flexible analysis code. We needed to be able to calibrate the code to available data and then quickly analyze last-minute design changes under schedule deadlines.

AAH SSEB Wrap-up and Aftermath

The SSEB ended and the members were sent home in time for Christmas. I drove my VW Squareback home to California. Dick Lewis was kind enough to offer the use of his heated garage to prepare for the journey. I was very grateful. Dick asked about my long-term career goals. It was not something I had thought about. I just talked about doing hands-on technical work, designing next-generation VTOL aircraft, and making a difference. It was clear that for many years he had been on a path to eventually running a helicopter company. In future interactions he treated me as a useful technical resource rather than a potential rival.

Some Factor Chiefs were required to return for 2 weeks in January 1977 to prepare for a possible protest. Since Roger Smith was stationed in St. Louis, he was able to help. He had gotten married during the Christmas break and was fresh off his honeymoon. We produced a 46-page document on forward flight performance. Roger signed the final typed version for me and sent me a copy. This document was a great help in correcting my memory of events some 40 years ago. In the end there was no protest, but the possibility had caused us to carefully document and substantiate everything we did.

In December 1976, Hughes was announced the winner of the AAH competition. The AH-64 Apache went on to an illustrious career. AMRDL (SRIO, Eustis Directorate, and ASRO) made notable contributions and greatly benefited from the Army-NASA collaboration.

After losing the AAH competition, Bell decided to strengthen its engineering capability by hiring Franklin D. Harris from Boeing Vertol. Frank was very well known and respected in the rotorcraft technical community. I first met Frank when I was a grad student through Professor Miller's consulting for Boeing Vertol. He called and said he had talked to many Bell people about what happened during the AAH Source Selection, and he wanted to get input from people in the government. Part of the AMRDL mission is to help our industry strengthen its technical capability. It was agreed that I could talk freely to Frank about Bell, so we talked at length one evening. We got deep into the various technical challenges, the limitations of current analysis tools, the different types of correlation, the importance of technical substantiation, and the apparent lack of quality control on technical data submitted to the government. Over the next several years Bell invested in improving and correlating their performance methodology. They contributed to the technical community by publishing some of the results [47] [48] including plots of correlation with test data.

I returned to work at Ames in mid-January 1977 and resumed my duties as acting ASRO Propulsion Specialist and with ASRO Preliminary Design. I shared my concerns about C81 and comprehensive analysis with Andy Kerr and Dr. Carlson who had initiated an Army effort at the Eustis Directorate to develop an improved comprehensive analysis code called the Second Generation Comprehensive Helicopter Analysis System (2GCHAS). I was asked to attend some 2GCHAS meetings. Eventually the 2GCHAS project was moved to the Ames Directorate with John Davis and Art Ragosta as the technical core. I visited John and Art to follow 2GCHAS development progress until they left the project.

In July 1977 I got the opportunity to observe exercise Brave Shield XVI at the National Training Center in the Mojave Desert. This included 2 days of riding in Army helicopters, 8 hours in a CH-54B, and 6 hours in a CH-47C. It was a great opportunity to observe real-world Army helicopter operations.

Preliminary Design Team Consolidation and Design Tool Development

The research and development (R&D) functions of AVSCOM were established as a separate command, the Aviation Research and Development Command (AVRADCOM), in 1977. At the same time, AMRDL became the U.S. Army Research and Technology Laboratories (RTL). The four AMRDL directorates became laboratories; the Ames Directorate became the Aeromechanics Laboratory (AL) and the Eustis Directorate became the Applied Technology Laboratory (ATL). AVRADCOM directed that Army Aviation preliminary design activity be consolidated in two locations in July 1977. The Preliminary Design Team (PDT) in ASRO at Ames was responsible for preliminary design methods development, correlation, and conceptual design of emerging aircraft systems including layout, weights analysis, and systems integration. The Design Analysis Team in St. Louis was responsible for maintenance of a performance datum on each current Army Aviation system, for assessing the impact of product improvements and Engineering Change Proposals and providing data for cost effectiveness and other comparative analysis. Systems and Cost Analysis in St. Louis would provide cost data in support of both groups.

The preliminary design consolidation resulted in three SRIO engineers (Milton Schwartzberg, Dr. Roger Smith, and David Chappell) moving from St. Louis, Missouri, to Ames to join the ASRO PDT. Meanwhile Charlie Crawford got the St. Louis design responsibility transferred to his Development and Qualification (D&Q) Directorate (formerly FS&QD) and hired Jim O'Malley from ATL. Jim's great performance on the AAH SSEB got Charlie's attention. Charlie offered Jim a well-deserved double promotion to move. The GS-12 happened right away, but the GS-13 took a little longer. Jim brought the Preliminary Design Program (PDP) code to D&Q, and a tradition of collaboration between Jim and the PDT on appropriate projects developed over time. Bill Pleasants and the other Eustis preliminary design engineers were reassigned within ATL.

The addition of three experienced engineers and new responsibilities significantly changed the PDT. Dave Chappell assumed responsibility for layout design and structural analysis. He also provided substantial structural analysis and evaluation support to the NASA/Army XV-15 Tilt Rotor Research Aircraft. Milt Schwartzberg started development of a new tilt rotor design code. He also supported and encouraged the preparation of PDT Memoranda for Record (MFR) documenting design tool methodology. Roger Smith and Milt Schwartzberg worked on aerodynamic performance methodology and provided design support to the Advanced System Technology Integration Office (ASTIO) in St. Louis. In 1977, the new AVRADCOM Commanding General (Major General Story C. Stevens) decided SRIO should become ASTIO and work directly for him. Dean C. Borgman, who had been the Army Deputy Program Manager (PM) for the XV-15 Tilt Rotor Research Aircraft project at Ames, had moved to St. Louis in 1975 to lead SRIO. Two years later he was working directly for the AVRADCOM Commanding General.

A series of MFR were prepared to document design tool methodology. Roger Smith covered helicopter ground effect in hover (ASRO-PDT-79-1) [49]. Ron Shinn covered statistical group weight equations developed using multiple regression in ASRO-PDT-79-2 [50] and ASRO-PDT-79-3 (public version without proprietary data). Ron also developed linear equations for turboshaft engine fuel flow vs. power (ASRO-PDT-79-5) [51] and equations for turboshaft engine power available lapse rate (ASRO-PDT-79-6) [52]. I covered autorotation calculations where main rotor inertia was increased by adding tip weights to satisfy autorotation requirements (ASRO-PDT-80-1a) [53] and vertical flight power required including hover, lifting tail rotor, and VROC (ASRO-PDT-80-2) [54]. A missing MFR numbered ASRO-PDT-79-4 was intended to document the TR code but

Milt Schwartzberg became ill before it could be completed. Milt left his professional books and papers to the PDT. I had the opportunity to sort and file this wonderful legacy for the AFDD library. The variety and depth of his technical contributions are amazing.

After the HELCOM experience, Ron Shinn and I concluded that both PSDE and HESCOMP needed substantial development, including better math models and better technical substantiation, and that PSDE was a better starting point for future code development. The top priority was better math models and better technical substantiation. More flexible mission analysis was needed to address Joint Service mission profiles, and improved productivity for batch runs of design and off-design cases was essential.

The new design code included improvements in flight performance modeling, output depth, mission analysis, parametric weight estimation, design sensitivity studies, off-design cases, and coding style. Flight performance modeling improvements included better math models and generalizing the equations so that alternate math models could be chosen by input. Math model development included better non-ideal induced power, basic profile power, compressibility power, and stall modeling. It also included pitch trim to model airframe lift and parasite drag vs. operating condition in forward flight. In vertical flight, it included induced power and download as a function of vertical rate of climb. Flight performance output was improved to provide detailed power required vs. airspeed and maximum gross weight vs. takeoff condition outputs. This was driven by the need to sanity-check the results and to compare them with other design and analysis codes.

Mission analysis was generalized to model Joint Service missions that included substantial altitude changes. This required more complex climb, descent, loiter, dash, and reserve mission segment models. It also required a better atmosphere model and a more flexible engine model. PSDE had only calculated atmospheric properties and engine performance once for a limited number of operating conditions. The design code was restructured to calculate atmospheric properties and engine performance every time they were needed. This cost more run time, but it provided essential mission and performance analysis flexibility.

Ron Shinn had coded a multiple linear regression algorithm for the development of weight equations. We used this code to develop and substantiate new parametric weight equations including the development and validation of a database of actual component weights and design parameters for real aircraft.

Design parameter sensitivity studies were important to identify a minimum weight or cost design. Typical helicopter design parameters were rotor size (input disc loading or rotor radius), blade area (input blade loading, solidity, or chord), tip speed, and number of blades per rotor. The goal was to input several values of a design parameter and get a realistic aircraft design for each value without any other input changes. Rotor size was the most challenging because it forced other parts of the helicopter to change (e.g., tail boom length, tail rotor size, airframe wetted area, parasite drag, and download). This required developing formulas to scale these other parts of the helicopter as a function of rotor radius and some empirical inputs to the design code.

The ability to run a series of off-design missions and performance analysis points with an aircraft sized by a design mission was essential for the HELCOM study. This was done manually with repeated PSDE runs. The ability to combine multiple cases into one run was developed as a first step. This worked well for simple missions. More complex mission capability has been a continuing part of design code development.

These design codes are written in various generations of FORTRAN. PSDE contained legacy FORTRAN II code with arithmetic IF statements. A policy of converting to the logical IF statements of FORTRAN IV was established to improve the ability to understand and modify the code. The code was gradually converted from FORMATED to NAMELIST input to make the input files easier to read and for quality control. Input data and code modifications were printed as part of the output to fully document design runs. This made it possible to make a design run with one input change and know that it was comparable with a previous design.

At this stage it was simpler to split the design code development into parallel efforts to develop two specialized codes rather than a single generalized code. The two codes were Helo (originally called PDPAC) and TR. Helo involved a major cleanup that was only applicable to single-main-rotor helicopters; the ability to design compound helicopters with a wing and/or auxiliary propulsion was eventually added. Airframe lift (L/q) and drag (D/q) remained a function of airframe angle of attack. A wing was simply modeled as part of the airframe. A controllable horizontal stabilizer allowed airframe pitch attitude vs. airspeed to be controlled. The pitch trim was typically chosen for minimum power required at all airspeeds. Helo was used for projects like ASH that created urgent needs for new capabilities. Urgent code mods were replaced with better solutions as time permitted.

The second code, TR, was only applicable to tiltrotor configurations. A self-imposed requirement to provide detailed level flight power required vs. airspeed, at all airspeeds including conversion, resulted in considerable aerodynamic performance methodology development. The wing including flaps was modeled separately, not as part of the airframe. Tilting the rotor shafts was a new control and a new pitch trim strategy was needed. The trim goal remained minimum power required at all airspeeds. This goal was approximated by transferring lift from the rotors to the wing as rapidly as possible. The difference between power available and power required vs. airspeed gave power that could be used for energy method calculations of rate of climb, acceleration, and normal load factor vs. airspeed. We did not develop the ability to trim and fly the aircraft for maneuvers until later developments made the need urgent.

Development of the improved design code was far from complete in August 1976 when I was assigned to the AAH SSEB for 5 months. The SSEB experience demonstrated the need for a better Air Vehicle Technical Description (ADS-10) to provide accurate design data for analysis, better analysis configuration control, and much better analysis codes. This did not directly impact the development of conceptual design codes, but it indicated the need for the PDT to collaborate with applied aeromechanics researchers who would develop and apply what became known as comprehensive analysis codes.

Advanced Scout Helicopter (ASH)—My First Concept Formulation

The Advanced Scout Helicopter (ASH) was intended to replace the Army's existing Light Observation Helicopter (LOH) designs, the Bell OH-58 Kiowa and the Hughes OH-6 Cayuse. The Army had studied an ASH off and on for some years. In 1977 the ASH requirement became more serious, and Charlie Crawford was now lead for the technical effort. Dr. Carlson assigned the PDT to work with Charlie on ASH; I was skeptical at first, but it turned out to be a very good partnership.

The Army Aviation Rationalization, Standardization, and Interoperability (RSI) review early in 1978 focused on the ASH requirement. The RSI review included a congressionally mandated contractual study effort with the North Atlantic Treaty Organization (NATO) helicopter industry. This resulted in design studies by the French, German, and Italian helicopter companies (the British did not respond). Jim O'Malley and I were co-authors of the Statement of Work (SOW) for these NATO ASH design studies and co-technical monitors. The design studies were modifications of existing baseline designs so they included detailed descriptions of those baseline designs. There was a midpoint review of the NATO ASH design studies in May 1979 at the Abrams Complex in Frankfurt, West Germany. Charlie Crawford brought Colonel Walter Rundgren, Jim, and me to the review. We were impressed with the emerging results and stressed the importance following the specified data formats, such as MIL-STD-1374 weight reports. This standard bookkeeping was essential when comparing NATO data with other aircraft and design studies.

The ASH Special Study Group (SSG) was established in August 1978 as part of the ASH Concept Formulation. The user-defined ASH Required Operational Capability (ROC) [55] was the foundation for the ASH SSG effort. The ASH was intended to replace the LOH. The most fundamental requirement was Target Acquisition and Designation capability similar to AAH but in a Mast Mounted Sight (MMS). Several MMS flight demonstrations had shown greatly improved survivability against ground-based air defense. This MMS background, and scout helicopter history in general, are well documented in the first part of the OH-58D paper [56] by Frank Harris. Flight performance, maneuverability, crashworthiness, ice protection, and ballistic protection similar to AAH were required. Mission performance included a 2-hour ASH mission with 30 minutes reserve. Maximum integral signature suppression against visual, infrared, aural, electro-optic, and radar-directed threats was required. A twin-engine configuration with One Engine Inoperative (OEI) performance equivalent to AAH and UTTAS was desired. Wheel landing gear and a Pilots' Night Vision system were required. Armament hard points and 600 lb of external stores were required.

The developer (Army Materiel Command (AMC)) prepared the Trade-Off Determinations (TODs) that defined materiel solutions (new development and existing aircraft) to address the ROC. The user (Army Training and Doctrine Command (TRADOC)) prepared the Trade-Off Analysis (TOA), the Best Technical Approach (BTA), and the Cost and Operational Effectiveness Analysis (COEA). The TOA was a user analysis of the TOD defined solutions. COEA cost analysis and effectiveness modeling of the TOD defined solutions that informed and supported the BTA. This elaborate process was essential to get support from Army and DoD senior leadership, not to mention funding from Congress.

Charlie was developer lead for the ASH SSG effort and pulled together work from the entire technical community. Our ASRO PDT (Mike Scully, Ron Shinn, Roger Smith, and Dave Chappell) was responsible for design of new development alternatives, and the D&Q design analysis team (Jim O'Malley, Harold Sell, and Gene Heacock) was responsible for design of modifications to existing aircraft (e.g., OH-6 and OH-58). We helped each other by reviewing designs and suggesting improvements. Air vehicle designers need lots of input data including space, weight, and power for Mission Equipment Package (MEP) and Air Vehicle Equipment; armor density vs. capability; Advanced Composites Factors (ACFs); Technology Factors (TFs); and engine characteristics (dimensions, weight, power available, and fuel consumption). Much of this data came to us through D&Q, but air vehicle and engine advanced technology came from the RTL Labs.

Engine data is essential for air vehicle design. Turboshaft engine performance for standard engines is normally defined by a computer program called an engine deck. D&Q propulsion ran the available engine decks for us so we could model standard engines in our design codes. Applied Technology Laboratory (ATL) prepared an 800-shp-class Advanced Technology Engine (ATE) technology projection for the ASH SSG. ATE technology was supported by the completed Small Turbine Advanced Gas Generator (STAGG) program [57] [58] and the ongoing Advanced Technology Demonstrator Engine (ATDE) program [59] [60] [61]. The ATE was scalable from 700 shp to 1,000 shp and required an engine development program.

Weights are fundamental to evaluating the impact of design and requirements trades on air vehicle size, weight, and cost. Major ASH design trades included single vs. twin engine, side-by-side vs. tandem crew seating, and armor protection levels. These trades required improved statistical weight equations and the use Calibration Factors (CF) to capture the impact of crashworthiness and survivability requirements. Weight statements are the data needed for the development of statistical weight equations. The PDT had a good collection of weight statements, and Charlie allowed me to copy D&Q weight statements as part of our ASH partnership. Ron Shinn and I developed improved statistical weight equations and the Advanced Technology Factor (ATF) technique. Statistical weight equations predict trend weights representative of the aircraft in the weights data. The ATF modifies these trend component weights to account for crashworthiness and survivability requirements (CF), advanced composite structure (ACF), and other (rotor, drive system, flight control) technology (TF). Ron published a detailed technical paper [62] on all of this in 1981.

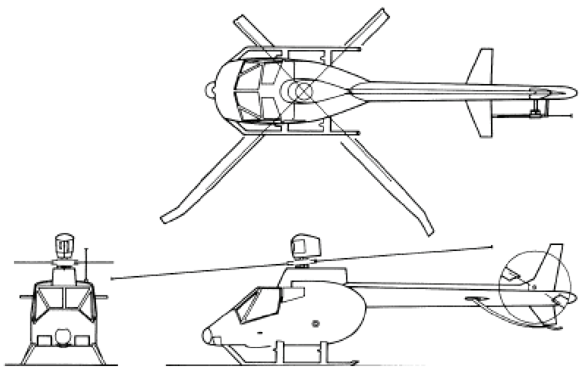
The ASH TOD included technology meetings at St. Louis, Missouri, and Ft. Eustis, Virginia. The results were a set of documented government technology projections for the TOD. The PDT was working hard on Helo design code development, especially better weight estimation. From December 1978 through April 1979 the air vehicle design effort included several meetings with D&Q in St. Louis to develop a briefing that was then taken to Ft. Rucker to present emerging results. These briefings included design trades quantifying the impact of various requirements on new development ASH designs. Charlie was the briefer, and he energized detailed discussions with the user community that guided our design work. The user became convinced to accept skid landing gear with wire strike protection and to move both the external stores and some MEP from MGW to structural design gross weight (reduced performance allowed).

The design meetings in St. Louis used PDT design runs for new development alternatives. They also included 3-view drawings by Roger Smith. Sometimes it was necessary to get additional PDT design runs as new issues emerged during development of the briefing in St. Louis. These extra PDT design runs were made by Ron Shinn in California, and the results were read to me over the phone. Verbal transmission of design numbers was a lengthy process with lots of double- and triple-checking to catch errors. We did not get a better system until the Kermit file transfer protocol was developed by Columbia University in the early 1980s.

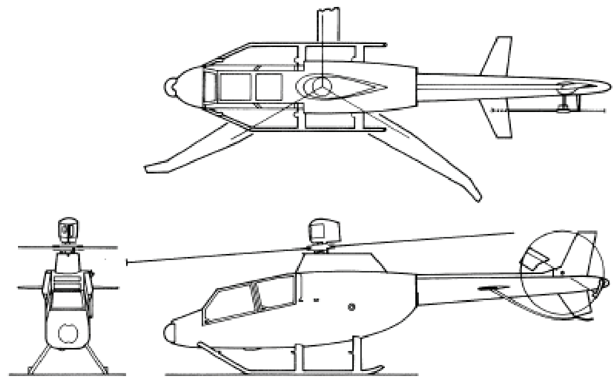
The ASH COEA included CARMONETTE, a stochastic battle simulation developed by the TRADOC Systems Analysis Activity (TRASANA) at White Sands, New Mexico, and AVWAR, a computer-assisted manual war game developed at Ft. Rucker, Alabama. I visited both White Sands and Ft. Rucker to better understand the inputs to these effectiveness analyses. The important inputs were mission performance (payload, range, and endurance for Mid-East VTOL and European VTOL), target acquisition and designation capability (range and probability), and survivability. Survivability was primarily characterized by single hit vulnerable areas for various threats. Single hit means that redundant systems (e.g., twin engines, two crew) are best protected by separation or armor between the systems so that a single hit cannot kill both systems. ASH twin-engine designs had armor between the engines, while single-engine designs required armor around the engine. Tandem seating ASH designs had armor between the crew to protect against high-explosive incendiary (HEI) rounds hitting the canopy. No practical design was developed for armor between the crew with side-by-side (SBS) seating. In practice, we also provided crew protection armor even though it got no credit in the effectiveness analyses. An attempt was made to model the MMS survivability advantage, but it was difficult in the time available.

Vulnerable areas were analyzed by the Ballistic Research Lab (BRL) at Aberdeen, Maryland. We worked with BRL to define new development ASH design constrains for survivability. These included a minimum rotor blade chord of 18 inches, a tail boom diameter not less than AH-64, and autorotation capability at least equal to AH-1 for single-engine and UH-60 for twin-engine designs. Failure modes and effects are an important part of vulnerability analysis. Loss of an engine in cruise would be a mission kill, not a forced landing, because you could still fly home. Loss of an engine during a 4k/95 Hover Out of Ground Effect (HOGE) would be a forced landing unless you could Hover In Ground Effect (HIGE) with OEI and transition to forward flight to fly home. The ATE technology projection included an OEI emergency engine rating 30 percent above intermediate rated power (IRP) (30-minute rating) to enable this capability. Thus, engine technology would allow a new development ASH with twin ATE to be more survivable than the twin T700-powered UH-60 and AH-64.

Ron Shinn and I wrote a 1980 AHS paper [63] describing rotor trade-offs for the new development ASH baseline designs and some 365 variations. Ron's 1981 Society of Allied Weight Engineers (SAWE) paper [62] includes a lot more detail on weights and technology. All designs included the 822-lb ASH Best Technical Approach (BTA) MEP and ASH mission fuel required in MGW. ASH performance at MGW included 500 fpm VROC at 4k/95 using 95 percent IRP and AAH maneuverability. Rotor diameter was minimized for nap of the earth (NOE) agility with a maximum disc loading of 8.0 psf. Main and tail rotor tip speeds were 700 fps and 600 fps, respectively, to reduce acoustic signature. The five new development ASH baseline designs were BTA1 (SBS, 1xATE), and BTA2 (Tandem, 2xATE), (SBS, 2xATE), (SBS, 1xT700), and (Tandem, 1xT700). BTA1 was a lightweight, "no frills design," less survivable (7.62-mm armor-piercing (AP) protection), single-engine vehicle, while BTA2 was the other end of the spectrum—fully survivable (12.7-mm AP protection plus 23-mm high-explosive incendiary (HEI) survivable rotor), twin-engine vehicle. BTA1 had a 22-percent-lower MGW than BTA2 (5,108 lb vs. 6,567 lb), 36 percent less fuel burned (577 lb vs. 902 lb), greater vulnerable area (1.6 times, 4.7 times, and 3.9 times for various threats), and lower cruise speed (143 knots vs. 167 knots). BTA1 had a 32.9-foot rotor with four 12.4-inch-chord blades, a 6-psf disc loading, and one 991-shp ATE engine. BTA2 had a 32.3-foot rotor with three 21.6-inch-chord blades, an 8-psf disc loading, and two 893-shp ATE engines.



BTA1 (SBS, 1xATE), R. Smith.



BTA2 (Tandem, 2xATE), R. Smith.

Work on mod designs continued in parallel with the new development effort. In March 1979 Charlie led technical meetings at Bell to review OH-58, UH-1, and AH-1 mods. These were large meetings with a team of Army technical experts from D&Q and RTL. Airframe structural mods needed to operate the OH-58 at higher weights were covered in depth. An ATL-sponsored effort to fly an MMS on OH-58C was reviewed. This work was eventually documented in a technical report [64] and a flight test report [65]. In June 1979 we evaluated the results of the NATO ASH studies at St. Louis and Ft. Rucker. The Agusta A129 required the least modification and became the best NATO alternative. Hughes 500 MD and Sikorsky S-76 mods were also evaluated. All of this work became part of the TOD.

The Army Systems Acquisition Review Council (ASARC) was the top-level Army review body for major acquisition programs. ASARC met on 30 November 1979 to review ASH. The Technical Alternatives ASARC briefing included Near Term Alternatives (OH-58D, 500 MD, OUH-1, AAH/TADS, and OAH-1) and Long Term Alternatives (New Developments, Mod Approaches, and AAH with MMS). New Developments were BTA1 and BTA2 while Mod Approaches were Mod NATO (A129 mod) and Mod U.S. Commercial (S-76 mod). ASARC decided that only the Near Term Alternatives were affordable and could meet a Congressional Initial Operational Capability date (31 December 1984). The Near Term Scout Helicopter (NTSH) was approved and soon became the Army Helicopter Improvement Program (AHIP).

Charlie organized an AHIP Request for Proposal (RFP) preparation effort led by Dan Schrage (D&Q). I made two trips to St. Louis to help Jim O'Malley support the AHIP RFP work. The AHIP competition was between a four-blade OH-58 modification and an OH-6 modification. The AHIP SSEB started in April 1981 and Jim O'Malley was Performance Factor Chief. I spent 2 weeks in Granite City, Illinois, as a consultant, but Jim had the situation well in hand and I was not needed again. The Bell proposal led by Frank Harris was a professional effort and won the AHIP competition to become the Army OH-58D. The Hughes proposal effort struggled. It is human nature for the winners of a competition, in this case Hughes and the AAH, to become over-confident and not work as hard for the next competition. Meanwhile the losers of a competition (Bell) learn from their mistakes and work all-out on the next competition.

The ASH experience developed a partnership of the PDT and the D&Q design analysis team for Concept Formulation. Led by Charlie Crawford, we carried new development and mod aircraft alternatives to an ASRAC decision. The mod alternative was carried through RFP preparation and source selection. This experience laid the foundation for the JVX Concept Formulation.

Team Building and Tool Building

In October 1978 we hired Henry Lee from Harry Diamond Lab were he had done wind tunnel testing on fuses. Aerodynamics was not his strength, and he became the PDT turboshaft engine model engineer. We needed better engine models. Dave Woodley (Boeing Vertol) suggested referred parameters would be a good way to model gas turbine engine performance. I put together a Turboshaft Engine Math Model that used referred parameters to model power, jet thrust, mass flow, and fuel flow as functions of operating condition. This math model eventually became the Referred Parameter Turboshaft Engine Model in the present-day NASA Design and Analysis of Rotorcraft (NDARC) conceptual design tool [66]. Aircraft gas turbine engine performance capabilities are formally specified by computer programs known as engine decks, which are developed by engine manufacturers in an industry-standard format. Henry obtained engine decks and ran them to develop data for referred parameter curve fits for a wide variety of turboshaft engines.

In the summer of 1978 we recruited Tex Jones from the Structures Lab (formerly Langley Directorate) to work on aerodynamics and performance for the PDT. Tex was a member of the NTSH SSEB in 1981 with Jim O'Malley. Later he helped set up the Army Centers of Excellence for Helicopter Technology (Georgia Tech, Maryland, and RPI initially). Tex also supported 2GCHAS in the beginning and did some PDT testing of the original NASA Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD) software. The need for an improved ADS-10 defining Air Vehicle Technical Description data was an important lesson learned from the AAH SSEB. D&Q were officially responsible for ADS-10, but it normally got updated in a hurry as part of an RFP development. I believed that development of a draft ADS-10 under less schedule pressure would result in a much better product. Tex got the job as his long-term background task. This proved to be much more challenging than I expected, but the results provided a solid foundation for the eventual development of ADS-10 for JVX. California real estate prices caused Tex and his wife, Lori, to return to Langley in the summer of 1987, where he continued to be a valued member of our Army-NASA rotorcraft technical community for many years.

I became a GS-14 Team Leader in June 1979. The new responsibility was a learning experience. We had access to various internship programs through NASA. Tex Jones set up a co-op program with Cal Poly, San Luis Obispo, and Mac Dinning joined the PDT as a summer co-op in 1979 and 1980. He became a full-time member of the PDT after he graduated in 1981. Mac was very willing to experiment with computer technology. When the PDT got its first VAX-11/780, he was able to help boot it when the official Digital Equipment Corporation (DEC) people failed. Mac left the PDT in August 1984 for the Directorate for Advanced Systems (DAS) in St. Louis. He had an adventuresome career including industry (McDonnell Douglas Helicopter Company (MDHC), Mesa, Arizona), D&Q in St. Louis, the Aviation Applied Technology Directorate (AATD) (formerly the Eustis Directorate), and the DA in the Pentagon. Mac became the survivability expert for Army Aviation Science and Technology (S&T). During the Joint Future Theater Lift (JFTL) Technology Study effort we had a detailed survivability review with a team of U.S. Air Force (USAF) survivability specialists. Mac was a one-man team for the Army and, from my point of view, was more knowledgeable than the entire USAF team. After retiring from federal service he has returned to Ames to work for the Concept Design and Analysis (CD&A) Focus Area as a contractor.

Charlie Ingalls joined the PDT in August 1982. He initially worked with Dave Chappell on wing fold design for the JVX Tilt Rotor. After Ron Shinn left for St. Louis, Charlie took responsibility for PDT weights data and statistical weight equations. He served on the LHX SSEB in Granite City. He eventually moved from the PDT to technical staff work on survivability, crashworthiness, logistics and an Unmanned Aerial Vehicle (UAV) project. Charlie had a love of flying and joined the 129th Rescue Wing of the California Air National Guard as a second job. He became a C-130 navigator and had many adventures on deployments around the world. He retired as an O-6 after 30 years of commissioned service. Today he is Administrative Officer and Security and Emergency Manager for the Aeroflightdynamics Directorate (AFDD).

ASTIO in St. Louis eventually became the Directorate for Advanced Systems (DAS). After the ASH ASARC selected the NTSH alternative for the AHIP, the next new development system became the Long Term ASH assigned to DAS. Roger Smith moved back to St. Louis in December 1979 to design Long Term ASH alternatives for DAS. This effort evolved into what would eventually become the Light Helicopter Family (LHX). Ron Shinn joined Roger at DAS in 1981 and they both came out to Ames to support the JVX Joint Technology Assessment (JTA) in early 1982. After JVX contract award in early 1983, both DAS and the PDT supported LHX. Roger and Ron were responsible for helicopter and compound helicopter designs while the PDT (with NASA support) developed tilt rotor designs.

In September 1985 Roger and Ron left St. Louis to work for Dean Borgman at MDHC in Mesa, Arizona. Ron became a full-time Weights Engineer and eventually moved to McDonnell Douglas in St. Louis to be closer to family. Roger stayed in Mesa working aerodynamics and performance. He became their expert on tip drive rotors among other things. MDHC had lost much of the early Hughes Tool Company work on tip driven rotors, and we were able scan some paper files from Hank Velkoff and John Wheatley to share with Roger.

Dave Chappell took over TR code development after Milt Schwartzberg became ill. Tilt rotor wing structure is sized by a combination of jump takeoff loads from rotors at the wing tips and stiffness requirements for aeroelastic stability. This is very different from conventional wings so statistical wing weight equations are not useful. Dave developed a dimensional analysis to size tilt rotor wing torque box structure and simple approximations for the rest of the wing weight. This methodology was eventually documented for JVX [67]. Dave was also responsible for PDT layout design and structural analysis plus substantial technical support to the NASA/Army XV-15 Tilt Rotor Research Aircraft program.

Because of our increasing programs and the impending emergence of the JVX, we needed reinforcements. Dr. Carlson turned to NASA Ames and borrowed Rick Peyran who was doing mechanical design for the space program. Dave trained him in aircraft layout design and structural analysis. Rick quickly became invaluable, and we eventually hired him as an Army employee. When Dave retired some years later, Rick replaced him. Jeff Bowles came from NASA systems analysis and took over TR code development from Dave, continuing to develop and run it through JVX. Jeff eventually returned to NASA to work on the National Aero-Space Plane (NASP). While NASA was creating a facility for NASP, we let Jeff use our Army secure facility.

Vertical Takeoff and Landing (VTOL) Aircraft

The helicopter is the original VTOL aircraft. It is wonderful for hover and low-speed flight, however its cruise speed and aerodynamic efficiency are much less than airplanes. This has resulted in the development of a great many VTOL concepts that attempt to combine airplane cruise speed and aerodynamic efficiency with VTOL capability. Campbell [68] gives an excellent technical overview and categorization of VTOL aircraft up to 1962. Rogers [69] carries the VTOL story up to 1988. By the early 1980s, the only VTOL aircraft other than the helicopter to enter production and service was the Hawker Siddeley Harrier—a single-turbofan-engine jet lift design with rotating nozzles to deflect the jet thrust [70]. The Harrier was in service with the Royal Air Force, Royal Navy, and U.S. Marine Corps (AV-8A).

AMRDL's contribution to Army interest in the tilt rotor VTOL really began when an agreement between NASA and the Army was signed on 1 November 1971. The agreement called for Joint Development and Operation of a Tilt Rotor Proof-of-Concept Research Vehicle at Ames. This NASA/Army agreement provided resources (engineers and funding) to lay the technology foundation for the XV-15 Tilt Rotor Research Aircraft (TRRA). The XV-15, in turn, laid the foundation [71] for development of the Marines/Air Force V-22 Osprey tilt rotor as the third type of VTOL aircraft to enter production and service.

The technology foundation for the XV-15 program included the design and testing of two full-scale rotors mounted on cantilever semispan wings in the Ames 40- by 80-Foot Wind Tunnel. Two competitors (Bell and Boeing Vertol) were selected for development of this groundbreaking VTOL aircraft. The Bell Model 300 had 25-foot-diameter, gimballed, stiff-inplane rotors and engines that tilt with the rotors [72]. The Boeing Vertol Model 222 had 26-foot-diameter, hingeless, soft-inplane rotors and engines that did not tilt [73]. Wayne Johnson developed and correlated with wind tunnel test data an analytical model for the dynamics of both proprotor designs [74] [75]. The NASA/Army program conducted a competition between these two technically viable tilt rotor solutions and selected the refined Bell Model 301 to become the XV-15.

The NASA/Army XV-15 was very successful technically and as a concept demonstrator. A five-volume flight test data report [76] was published in June 1985. In June 1981, the XV-15 got the attention of the aeronautical world at the Paris Air Show with a carefully choreographed daily flight demonstration. In his excellent book, *The Dream Machine*, Richard Whittle [77] quotes the New York Times "…the Bell XV-15...the hit of the show." Secretary of the Navy John Lehman and Senator Barry Goldwater were both very impressed by the flight demonstration and tilt rotor technology [77].

The XV-15 also impressed the pilots who flew it. The first Navy evaluation flown in May–June 1980 and reported in December 1980 [78] was very favorable and recommended additional evaluations as the envelope was expanded. In October 1981 Senator Barry Goldwater became the first non–test pilot to fly the XV-15 as part of the Bell guest pilot program. He said, "The tilt rotor is the biggest advance in aviation in a quarter of a century" [71]. A January 1982 Aviation Week Pilot Report [79] and a March 1982 flight by Secretary of the Navy John Lehman were also significant.

XV-15 hovers at Paris Air Show, *Aviation Week & Space Technology* cover, June 29, 1981.

Joint Services Advanced Vertical Lift Aircraft (JVX)

The Army-NASA collaboration at Ames that produced the XV-15 demonstrated how effective combining funding and engineers can be when technology needs to be advanced in one giant step. The XV-15 provided enough confidence for the DoD to launch the Joint Services Advanced Vertical Lift Aircraft (JVX) as the first step towards the Marines/Air Force V-22 Osprey. Less well known is the important role that the Army-NASA team played in the early stages of the JVX program. I count myself as very lucky to have been a part of this major development program at the beginning.

Dick Ballard was Chief of Technology for Aviation Systems in the Weapons Directorate of the Army Deputy Chief of Staff for Research, Development, and Acquisition. In October 1981 Dick Ballard called Dr. Carlson to discuss a memo from the Under Secretary of Defense for Research and Engineering, Dr. Richard DeLauer, to the Navy and the Air Force about consolidating V/STOL and helicopter development programs into a single joint rotary-wing development program. Army leadership was considering entering the debate. Dr. Carlson and I suggested that the Army should be responsible for subsonic VTOL / V/STOL aircraft with 50-psf-or-less disc loading. The 50-psf disc loading was chosen to include tilt wing aircraft such as the XC-142.

Whittle [77] describes a 24 September 1980 meeting of Marine General P. X. Kelley and Vice Admiral Richard Seymour with the Secretary of the Navy, John Lehman. The subject was a CH-46 replacement for the Marines. Lehman said, "I am not going to spend 2 billion dollars of non-recurring cost to evaluate a new helicopter." Lehman continued, "I want to bring the Marine Corps into the twenty-first century on the leading edge of technology and that leading edge is tilt rotor." This background was unknown to us at Ames.

During the last week of 1981, Dick Ballard called Dr. Carlson to report that the Deputy Secretary of Defense was about to send a memo to the service secretaries announcing the formation of a new joint rotary-wing development program. There was a strong indication that the new aircraft should be an advanced VTOL aircraft such as a tilt rotor and that the Army would be named as the executive service. This program was to address the Marine Corps assault transport helicopter (HXM) requirement and several others. HXM was intended to replace the Marine CH-46 performing the Medium Assault mission. The relevant Capability Group 3 of the 1975 HELCOM study included Navy and Marine CH-46s and Navy and Air Force H-3s, but no Army helicopters (the Army UH-60s, AH-64s, and CH-47s were in Groups 2 and 4). This implied to us that the Army was named executive service because of its technical background and experience, rather than a need for aircraft of this CH-46 size.

The HXM was expected to be based on, and operate from, U.S. Navy Landing Helicopter Assault (LHA) ships. Only the Navy had qualified aircraft to operate from Navy ships. Any effort to shipboard-qualify a new joint rotary-wing aircraft would need partnership with Navy qualification authorities. This central challenge meant that Charlie Crawford, as the Army's development and qualification authority, was the best Army technical leader for the program. Dr. Carlson and I called Charlie at home to discuss the challenge and the opportunity. Charlie agreed to lead the effort starting with a JTA at Ames followed by an RFP Task Force at AVRADCOM. He agreed to spend at least 2 days a week on the effort, and he rightly said that the JTA would need to convince him of the best VTOL aircraft configuration for the program.

The next step was to get support from the AVRADCOM Commander. Major General Story C. Stevens and the AVRADCOM Technical Director, Dick Lewis, were scheduled to visit Ames the first week of January 1982. Charlie flew out to Ames for the visit. Dr. Carlson and Charlie met with Major General Stevens to discuss the opportunity and the proposed approach. He agreed with the proposal and JVX was launched.

Charlie led the developer side of JVX. The user side of JVX, the Joint Services Operational Requirements (JSOR) working group, was headed by Navy Captain Jim Magee. Charlie was effectively the PM for several months before the official PM was appointed. His responsibilities included planning JVX program schedules, engine alternatives, and risk reduction activities (wind tunnel and simulation programs) in addition to the JTA and RFP preparation. Charlie also started working with NAVAIR to develop a plan for JVX shipboard qualification.

JVX Joint Technology Assessment (JTA)

The JVX Joint Technology Assessment (JTA) was intended to assess the technical feasibility of developing a common family of VTOL aircraft capable of performing all of the DoD JVX missions, propose trade-offs and trade-ups to the JSOR designed to maximize commonality between the various members of the family, and prepare the technical foundation for an RFP for Engineering Development of a JVX Aircraft System. The JTA was specifically not intended to set requirements, select a design configuration, or define a program management plan. Part of the JTA team continued working on JVX after the completion of the formal JTA study to provide technical support to AVRADCOM for JVX RFP preparation.

The JTA was an approximately 3-month technical effort held at NASA Ames from February to May 1982. The JTA involved many studies encompassing requirements, cost, mission equipment, and all of the key aeronautical technology disciplines and vehicle configurations. Specialists were assigned from all of the services and NASA. Charlie was the Director, I was Deputy Director Technical, and Marine Lieutenant Colonel Greg McAdams was Deputy Director Requirements. Andy Morse handled both Admin and Tech Support and was critical to our success. Requirements and Cost (Lieutenant Colonel Greg McAdams) included User Requirements (Major King), Mission

Equipment (Lieutenant Colonel Bob Yeend), and Cost (Ralph Tate). Tech Support (Andy Morse) included Tech Factors and Weights (Ray Foye), Propulsion (Dennis Enders), Layout Design (Dave Chappell), Rotor/Aero (Wayne Johnson), and Fly-by-Wire (FBW) (Bill Stevens). Configurations (Dennis Earley) included Helo (Jim O'Malley), Compound and Advancing Blade Concept (ABC) (Roger Smith), Tilt Rotor (John Magee), and Lift/Cruise Fan (Sam Wilson). A total of 65 people (some part-time) were assigned to the JTA (35 Army, 12 Navy, 3 Air Force, 4 Marines, and 11 NASA). Technical people were especially motivated by the idea that JVX could become the third type of VTOL to reach production (after the helicopter and the Harrier). Dennis Earley from D&Q was Charlie's "official spy," which was great because he took care of reporting to Charlie.

JVX Joint Service Missions

JVX was intended to address Army, Navy, Marine Corps, and Air Force mission needs. The Army Special Electronic Mission Aircraft (SEMA) included a high-altitude (30,000-feet) Corps Signals Intelligence (SIGINT) mission and a lower altitude (7,000-feet) Division SEMA mission. The Marine Corps HXM included Amphibious Assault and Land Assault missions for both Troop Lift and External Cargo. There were both Navy and Air Force Combat Search and Rescue (CSAR) missions. The 700-nm-radius Air Force Long Range Special Operations Forces (LR SOF) mission was very challenging.

In April 1980 a very complex mission using RH-53D helicopters and C-130 transports was mounted to resolve the Iran hostage crisis by rescuing 52 embassy staff. The mission failed and became known as Desert One after the first staging area where the mission was aborted. The potential for an advanced VTOL to perform a mission like Desert One without staging was obvious to the technical community. While nothing was said, we assumed that the LR SOF mission was intended to address that need.

JVX was required to self-deploy worldwide without refueling. The longest over-water leg was west coast (Travis Air Force Base (AFB), California) to Hawaii (Hickam AFB, Hawaii). The nominal ground distance is 2,100 nm. The Air Force uses 2,400 nm air distance for subsonic jets (typical cruise Mach 0.8 at 36,000 feet). The JTA was comparing VTOL designs with very different cruise speeds and altitudes, so we needed wind vs. altitude data. The Air Force provided 85th percentile, winter-quarter headwinds vs. altitude from Travis AFB to Hickam AFB.

The altitude and temperature at a VTOL performance point are critical. The Army used 4,000 feet and 95 degrees F. The Navy and Marines used the MIL-C-005011B [80] hot day at sea level (103 degrees F) for ship-based VTOL and at 3,000 feet (91.5 degrees F) for land-based VTOL. The Air Force used sea level (103 degrees F) for ship-based VTOL and at 4,000 feet (95 degrees F) for land-based VTOL, but higher altitudes for mid-mission VTOL. Charlie rationalized all of this by saying that the Navy and Marines land-based VTOL points were within 50 nm of the ocean and the Air Force mid-mission VTOL points were high in the mountains.

The Army developed the UTTAS maneuver [81] for terrain avoidance at cruise speed. It included a 3-second 1.75-g pull-up starting at 150 knots and ending at no less than 120 knots. This sized the blade area for rotor-borne flight. The Marines required at least 180 knots cruise speed at 3,000 feet (91.5 degrees F) so Charlie required a 3-second 1.75-g pull-up starting at 180 knots. This resulted in a high-solidity rotor for the 180-knot pure helicopter design. We convinced Charlie to allow a small maneuver wing on the helicopter, which resulted in a lower solidity rotor and reduced MGW by about 3,000 lb (Table 9.9 of reference [22]). Tilt rotor designs are only rotor-borne in low-speed flight. Low-speed maneuver margin (Section 6.6.3.2 of reference [22]) includes jump takeoff and low-speed forward flight. A low-speed transient maneuver was defined where loss of airspeed or altitude is used to provide power. We suggested a 1.75-g pull-up starting at 60 knots with airspeed loss allowed. This eventually became a 1.75-g pull-up at 60 knots with altitude loss allowed.

JVX JTA Technical Foundations

The JTA effort was divided into three phases, which partially overlapped: 1) laying the technical foundations (technology review and synthesis model refinement), 2) a first-cut assessment of the missions (point design studies), and 3) development of a common design for all missions (commonality design studies). Layout design started at the beginning and continued through all three phases.

The technology review established and documented a realistic and consistent level of technology. The consistent technology rule was relaxed during the study to allow higher risk technology for configurations that proved to be least suitable for the JVX missions. This ensured that these configurations were not limited by possibly conservative technology inputs. The tools used for assessing the impact of Joint Service mission requirements on JVX designs were aircraft design synthesis computer models and layout design studies. The design synthesis models were modified and calibrated as necessary for use in the JVX JTA.

The VTOL configurations studied were single-main-rotor helicopters (with and without auxiliary wings), auxiliary propulsion compounds (winged and ABC versions), tilt rotors, and lift/cruise fan aircraft. All of the VTOL configurations that had flown would have been about five times as many, which was clearly not practical. The single-main-rotor helicopter represented conventional helicopters, since the differences between single and tandem rotor helicopters (e.g. CH-53 and CH-47) are detailed source selection evaluation questions and not relevant to a broad technical feasibility assessment. Tilt rotor designs optimized at the upper boundary of allowable disc loading (constrained by shipboard compatibility to about 17 psf). The higher disc loading (typically 50 psf) tilt wing was not studied. The very high disc loading (500 psf) lift/cruise fan concept was included by management direction rather than on technical grounds.

JVX JTA Weight and Cost Impact of Technology and Special Requirements

Preliminary design involves the estimation of size, weight, cost, and performance using various methods. These methods were calibrated against data from a suitable existing baseline aircraft. This calibration point was then shifted to reflect the impact of advanced technology and any special requirements not included in the baseline and not modeled by the estimation method used. The advanced technology considered included rotor aerodynamic improvements, advanced composite materials, FBW flight controls, and drive train components. Advanced technology engines were considered separately. The types of special requirements considered included crashworthiness; pressurization; ballistic tolerance; nuclear, biological, and chemical (NBC) protection; bird strike; signature reduction; flotation; and folding.

Ray Foye was lead author of “Cost and Weight Impact of Applications of Advanced Composite Materials” (Appendix B of reference [22]). The study breaks up the airframe into 16 different weight groups. For each weight group, a survey was made of the results of previous composite designs. In most cases, a sufficient number of designs were available to give some confidence in the average weight savings obtained. In cases where many designs had been built, tested, and flown, paper studies were not included in the weight-saving averages. Design studies atypical of VTOL aircraft structural concepts were also dismissed. The cost impact estimates were less reliable than the weight impact estimates because of a smaller data base and less accurate data.

Fly-by-Wire/Fly-by-Light Flight Controls (led by Bill Stevens) concluded that fiber-optic control technology was not mature enough for JVX. They compared FBW with a redundant mechanical control system, with both systems designed to tolerate a 23-mm HEI single hit (Table 4.3 of reference [22]). The resulting technology factors were applied to normal weight trends for redundant mechanical flight control systems. ABC rotor controls were assumed to fall on the helicopter trend line because XH-59 controls were well above the trend line (the result of experimental features that were no longer required). Tilt rotor controls were calibrated using the dual mechanical estimates from Table 4.3 of reference [22] (FBW components) or XV-I5 (close to helicopter trend line).

Advanced Drive System Technology (led by Dennis Enders) concluded that the 20-percent goal for total drive system weight reduction from ongoing research would not be mature in time for JVX. However technology already demonstrated supported an 11-percent total drive system weight reduction. Table 4.4 of reference [22] showed a typical breakdown of this weight saving by component.

Special Requirements weight impact was accounted for by factors multiplying the weight trends or delta weight added to them (Section 4.6 of reference [22]). Table 4.5 of reference [22] summarized these factors and deltas as a function of aircraft type (configuration).

JVX JTA Turboshaft Engine Technology

The JVX JTA design studies used three different turboshaft engines: the Modern Technology Engine (MTE), the T64-GE-416, and the T64-GE-418. The MTE was a new development engine in the 5000-shp class, with both turboprop and turboshaft versions. The T64-GE-416 was a production turboshaft engine in the 4,000-shp class, with application in the CH-53E helicopter. The T64-GE-418 was a potential growth version of the T64-GE-416 in the 5,000-shp class. These engines were used to represent current technology (T64) and advanced technology (MTE). They were scaled up and down in size as required.

The Turboshaft Engine Math Model (Section 7.2 and Appendix H of reference [22]) was used to model power available, mass flow, fuel flow, and gross jet thrust as functions of operating condition. This math model eventually became the NDARC Referred Parameter Turboshaft Engine Model as documented in chapter 20 of the NDARC Theory Manual [66]. Henry Lee obtained official engine math models for the three engines and ran them to develop data for referred parameter curve fits (Appendix H of reference [22]).

Turboshaft engine installation losses were carefully modeled (Section 7.3 of reference [22]). Inlet losses included duct losses (1.25 percent power loss) and inlet particle separator (IPS) losses. MTE had an integral IPS so MTE performance data included IPS losses. T64 did not have an IPS, so a 3-percent IPS power loss was applied to T64 performance. Exhaust losses consisted of IR suppressor installation power loss plus the momentum drag associated with IR suppression. These losses were significant at airplane mode cruise speeds, so JVX had an IR suppressor inlet air diffuser to recover ram air pressure and a variable area IR suppressor nozzle. The nozzle allowed modulation of the IR suppressor mass flow in the same way that cowl flaps modulate cooling air flow on air-cooled piston engines. IR suppressor installation power loss was 2 percent suppressed and 0.4 percent hot exhaust. IR suppressor mass flow was equal to 100 percent of engine mass flow suppressed and 20 percent of engine mass flow hot exhaust. The combination of an inlet air diffuser to recover ram air pressure and a variable area exhaust nozzle was assumed to be 40 percent efficient in recovering IR suppressor momentum drag.

JVX JTA Rotor Aeromechanics Technology

Rotor Technology (led by Wayne Johnson, Section 4.2 and Appendix A of reference [22]) used both test data (small- and large-scale wind tunnel tests plus flight tests of advanced rotors or technology demonstration aircraft) and CAMRAD [82] [83] calculations to develop advanced technology rotor performance data. This data was used to calibrate the simplified performance estimation trends used in the rotorcraft design synthesis computer programs. Rotor Performance Estimation Methodology Calibration Data (Appendix C of reference [22]) documents the simplified performance estimation trends calibration to CAMRAD data. CAMRAD was the state-of-the-art rotorcraft analysis code that was not available for the AAH SSEB back in 1976.

The High-Speed Helicopter rotor technology assessment used production helicopter (Sikorsky S-76) full-scale wind tunnel test data [84] for CAMRAD calibration. Small-scale, high-speed (above 0.4 advance ratio) wind tunnel data [85] was used to extend CAMRAD correlation beyond the limit of available full-scale test data. CAMRAD was used to change the full-scale data from production airfoils to advanced airfoils, and to predict the effects of changes in solidity, twist, and propulsive force on rotor equivalent lift-to-drag (L/D) ratio. Negative propulsive force was used for the auxiliary propulsion compound case. CAMRAD was also used to change airfoils and predict the effects of changes in solidity and twist on rotor figure of merit. Compound helicopter lift and propulsive force trim was based on Lockheed AH-56A Cheyenne data [86] [87].

Calibration of Helicopter and Compound Helicopter simplified performance estimation trends to CAMRAD data was documented in Section C.2, Appendix C of reference [22]. This section also included calibration to current technology rotor test data (UH-60A) to increase confidence in the ability of simplified performance estimation trends to model a wide range of rotor operating conditions.

The Advancing Blade Concept (ABC) rotor technology assessment [88] used data from the XH-59 ABC Technology Demonstrator program [89]. The XH-59 demonstrated developing lift primarily on the advancing blades of a rotor system to improve lift at high speed and maintain airspeed at altitude. The inability to slow rotor rpm, because of trim and hub stress problems, prevented the XH-59 from meeting its full-speed potential. Limited XH-59 level flight performance data was available [89] [90] up to about 230 knots, but it was not at the desired advance ratio (μ) and tip Mach number (M_T). Full-scale rotor wind tunnel tests [91] [92] provided data for high μ conditions but at lower M_T than would be encountered in flight. For an advanced rotor, it was necessary to calculate the effect of different operating conditions (μ and M_T) as well as the effects of planform, twist, taper, and airfoils. The approach was to correlate the analysis with existing flight and wind tunnel test data and then to predict the performance of a given advanced design.

Bill Pleasants (ATL) modified CAMRAD to model the ABC rotor [88]. CAMRAD could model a coaxial rotor realistically, including rotor-rotor interference. Previous analysis of the ABC represented the rotor as a single rotor with all blades in a plane and trimmed with a lift offset. CAMRAD was used to represent two rotors in close proximity with full wake interaction. This rotor-rotor interference caused significant shifts in calculated rotor angle of attack (Figure 1 of reference [88]). Rotor effective lift-to-drag ratio (L/De) calculated using uniform inflow was significantly more optimistic than nonuniform inflow results. CAMRAD was correlated with ABC flight test data [89] [90] using model-scale [93] and full-scale [94] wind tunnel data for the XH-59 airframe aerodynamics. Full-scale rotor wind tunnel test data [91] [92] was used to gain insight into the ability of CAMRAD to predict the effects of high μ and to calculate rotor lift offset.

A Sikorsky HMX rotor design [95] [96] was selected as the basic configuration for an advanced ABC design. These references predicted very large improvements in rotor L/De compared to those demonstrated by the flight test program. Performance estimates for the JVX advanced ABC design were based on both demonstrated capability achieved in flight test, and assumed solutions to problems encountered by the XH-59. The design goals and the operating conditions for the JVX rotor were nearly identical to the HMX rotor, and significant changes in the performance trends due to major rotor design variables (twist, taper, airfoils) were not expected. General requirements for the advanced ABC design were a maximum speed of 250 knots at altitudes up to 10,000 feet, with hover performance at the design point approximately equal to the XH-59 [97]. Overall trends of the maximum blade loading and the flight envelope would be similar to the XH-59. Advanced ABC rotor cruise blade loading was chosen to fall within the capability demonstrated by the XH-59. The advanced ABC rotor did not have the ability to hold performance up to 30,000 feet as desired for some JVX missions. Significantly increased rotor solidity or a wing would be required at such a high altitude.

Much of the predicted performance improvement of the advanced ABC design was due to the more optimum operating conditions. Rotor hub and aircraft stress problems prevented the XH-59 from reducing rotor RPM to attain the desired conditions. It was assumed that an adequate mechanism for RPM control would be available for the advanced ABC design. Airfoils were selected to allow operation at tip Mach numbers up to 0.85. Advance ratio ranged from 0.47 at maximum range speed to 0.85 at maximum cruise speed.

CAMRAD performance calculations generally substantiated that greatly improved ABC rotor performance was obtainable, although not as great as projected for the HXM [95] [96]. The calculated improvement in L/De between the XH-59 rotor and the JVX advanced rotor design was due to optimum operating conditions, planform, and twist improvements. The rotor-rotor interference had a significant impact for all cases investigated. Design blade loading was chosen to provide maximum L/De at normal cruise conditions. Rotor twist was significantly reduced for improved high-speed performance. Lift offset had a strong impact on the structural design of the ABC rotor, and a lift offset of 32 percent was assumed. A dimensional analysis developed by Dave Chappell was used to size ABC rotor blades, hubs, and upper rotor shaft weights [98].

An ABC version of the Helo design code was developed for JVX by Steve Zalesch (NAVAIR). This task was very challenging given the time constraints. Vertical flight rotor performance was successfully modeled using helicopter momentum theory with empirical correction factors. An initial attempt to use forward flight momentum theory was not successful in modeling the CAMRAD rotor performance data for the advanced ABC design. Instead, ABC rotor power required was represented by three empirical equations (Section 6.2.2 of reference [22]). Calibration of these simplified ABC performance estimation trends to CAMRAD data was documented in Section C.3, Appendix C of reference [22].

The Tilt Rotor Aircraft rotor technology assessment used XV-15 Tilt Rotor Research Aircraft (TRRA) full-scale wind tunnel test [72] and flight test [76] data for CAMRAD calibration (Section A.3, Appendix A of reference [22]). CAMRAD was used to change XV-15 airfoils to advanced helicopter rotor airfoils (VRI2/VRl5) and to predict the effects of changes in solidity on rotor figure of merit and propeller efficiency. Specialized tilt rotor airfoils were being developed, but adequate test data was not available.

Tilt Rotor Aeroelastic Stability was analyzed using CAMRAD. The JVX rotor system was assumed to be a gimballed, stiff in-plane design like that of the XV-15. The critical flight condition for aeroelastic stability for this type of rotor system is a high-speed dive, in autorotation, and at low altitude (high air density). The stability boundary was calculated for an autorotation dive, at sea level, for both standard temperature (59 degrees F) and –25 degrees F. The JVX requirement was a maximum dive airspeed (VDIVE) of 360 knots with a 25-percent safety margin (Section 4.2.3.2 of reference [22]), which yields a stability boundary of 450 knots. Aeroelastic stability boundaries were calculated for the XV-l5 and for 10 possible JVX tilt rotor designs (Section A.3.3 and Figure A.41 of reference [22]). These calculations defined the wing stiffness required for aeroelastic stability.

A dimensional analysis developed by Dave Chappell was used for the JVX tilt rotor wing weight estimation (Section 5.3.1 of reference [22] and reference [67]). The predominant critical design criteria were the wing stiffness required for aeroelastic stability and the vertical bending strength for a 2-g jump takeoff.

JVX JTA Airframe Aerodynamics Technology

Airframe drag was an engineering culture issue for JVX. We were moving from helicopters cruising at fixed-landing-gear biplane speeds to advanced VTOL configurations cruising at retractable-landing-gear monoplane speeds. Parasite drag varies as airspeed squared, and parasite power varies as airspeed cubed. Thus, the engineering trade of drag vs. weight, complexity, and cost changes dramatically. Jim O’Malley led a comprehensive JTA parasite drag effort (Section 6.4 and Appendices D, E, and F of reference [22]). Wing drag including interference was carefully modeled (Appendix D.1.2 of reference [22]). Interference drag was also modeled for empennage, engine nacelles, rotor pylons, and fairings. Momentum drag for low-mass-flow items (oil cooling and air conditioning) was modeled as parasite drag in the conventional manner. IR suppressor momentum drag was modeled correctly (proportional to mass flow times airspeed instead of dynamic pressure) in the propulsion model because of high mass flow. Helicopter and rotor hub and mast parasite drag trends with gross weight were used as a methodology sanity check (Figures 6.1 and 6.2 of reference [22]). Airplane parasite drag trends with gross weight and wetted area were used as a tilt rotor and lift/cruise fan sanity check (Figures 6.5, 6.6, and 6.2 of reference [22]).

Induced drag for rotor-borne concepts (helicopter, compound helicopter, and ABC) was modeled by a delta parasite drag area vs. fuselage angle-of-attack trend for similar size fuselages (Section 6.4.1.e and Figure 6.4 of reference [22]). Wing-induced drag for wing-borne concepts (tilt rotor and lift/cruise fan) was modeled by conventional fixed-wing Oswald span efficiency. Fixed-wing extensions could be added to tilt rotor designs outboard of the engine nacelle, for those missions requiring long-range or high-altitude performance. These winglets increased the overall wing aspect ratio, reducing the wing-induced drag in airplane mode cruise.

Download in hover was estimated conventionally for helicopter, compound helicopter, and ABC. John Magee (NASA) led a careful study of tilt rotor download (Section 6.5.2 and Appendix G of reference [22]). A retracting leading edge slat was added to the main wing of the JVX tilt rotor. With wing flaps at 60 degrees, the slat reduced download from 0.18 * c/R to 0.12 * c/R, where c = wing chord and R = rotor radius. A similar formula was developed for download due to wing tip extensions.

JVX JTA Rotorcraft and V/STOL Design Codes

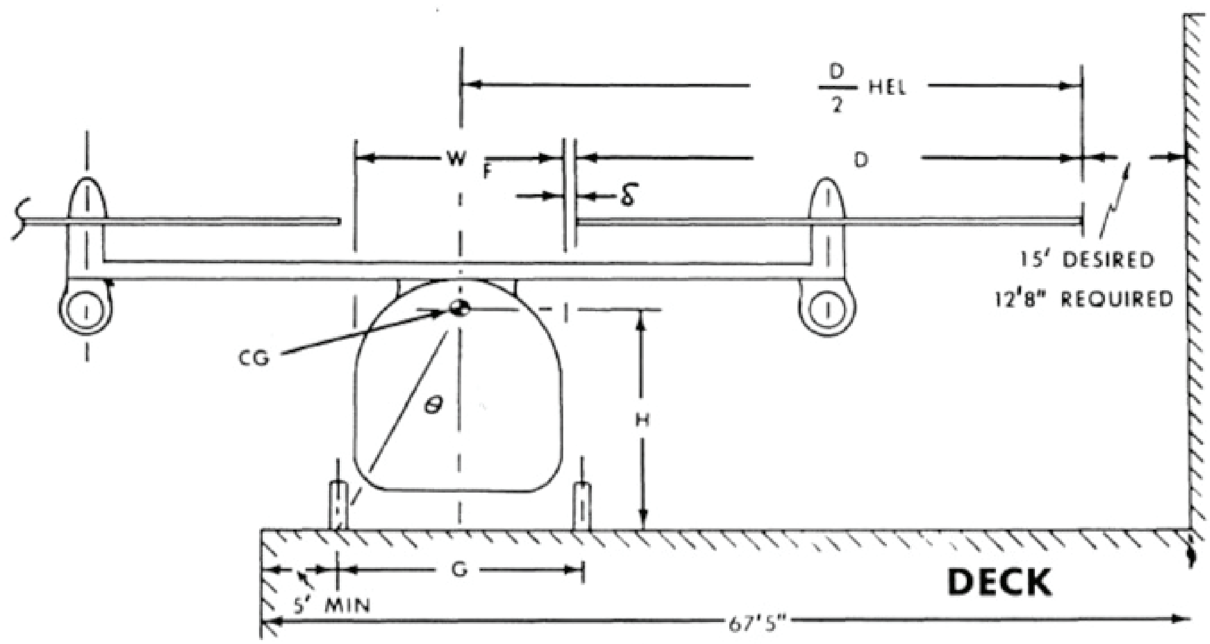
The rotorcraft design codes used for JVX were the result of a continuing in-house preliminary design methodology development effort by the Army and NASA. The JVX JTA required substantial modifications to these codes to accommodate the special requirements from the various services, to permit efficient development of service-specific variants from the baseline design, and to accurately represent the advanced technology projected for the JVX. The Helo code was used for helicopter and compound helicopter designs, a modified version of the Helo code was used for ABC designs, and the TR code was used for tilt rotor designs. Lift/cruise fan designs were based on VASCOMP (a code developed by Boeing Vertol for NASA).

The flight performance math models used in the rotorcraft design codes were generally based on simplified physical models of the aircraft, rather than curve fits or tables (Section 6 of reference [22]). Various calibration factors were used to match these simplified math models to test data or more detailed analysis tools. The disadvantage was that it did not match the calibration data as exactly as a simple curve fit or table. However, it was normally within the accuracy of the calibration data, and it had the great advantage of providing a physically realistic way of interpolating and extrapolating from limited available data. Interpolation and extrapolation was essential in JVX where a wide variety of design configurations were considered, including several with only limited test data.

JVX JTA Layout Design

Preliminary design requires both design synthesis computer codes and layout design. Design synthesis codes take a given set of mission requirements, engine characteristics, and design configuration decisions and determine the size (dimensions), component weights, and flight performance of the resulting aircraft design. Design codes are not able to evaluate practical operational concerns such as operating clearances, crew visibility, cargo handling, troop loading/unloading, fields of view/fire, and shipboard compatibility. Layout design is used to address these characteristics and to provide configuration and geometry inputs for the design codes. Since layout design drawings are based, in part, on dimensions determined by the design codes, preliminary design becomes an iterative process between design codes and layout design.

Shipboard compatibility with LHA and Landing Helicopter Dock (LHD) class ships drove JVX layout design, particularly the limitations on rotor diameter and wingspan. The design parameters for shipboard compatibility are shown in the figure on the next page. JVX had to be able to operate from spots abeam the LHA/LHD island superstructure with rotor-tip-to-obstruction clearance no less than 12 feet 8 inches (15 feet desired) and wheels 5 feet from the deck edge, and the rollover angle had to be 32 degrees (36 degrees desired). Powered folding/unfolding was required in 2 minutes with up to 45-knot winds from any direction. JVX folded/stowed size on LHA could not to exceed a spot factor of 1.2 times the CH-46E helicopter. JVX spot factor was defined by the maximum number of folded/stowed CH-46Es divided by the maximum number of folded/stowed JVXs.



JVX rotorcraft design implications of LHA flight deck width limits.

JVX is positioned with its outboard wheels 5 feet from the deck edge. Quad landing gear track (G) is set by the CG height (H) and the rollover angle. Tricycle landing gear track would be wider than quad gear track for the same CG height and rollover angle. Helicopter rotor radius (D/2) cannot be greater than the distance from the JVX CG to 12 feet 8 inches from the LHA island superstructure. Maximum rotor diameter (D) for tilt rotor designs is maximum helicopter rotor radius (D/2) minus rotor/fuselage clearance (δ) minus half the fuselage width (W_f). Tilt rotor wingspan is rotor diameter plus fuselage width (W_f) plus twice the rotor/fuselage clearance (δ).

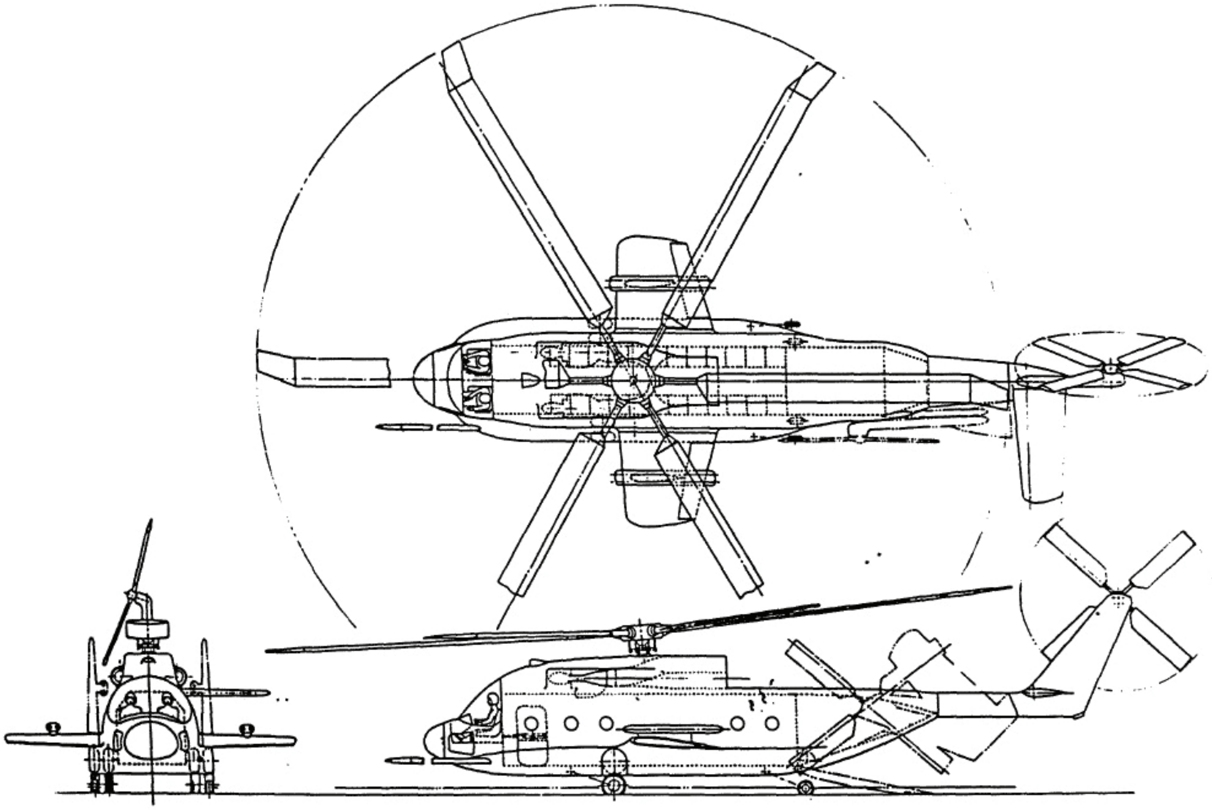
The JVX designs needed the largest possible rotor diameter and wingspan for aerodynamic efficiency. The landing gear track (G) was minimized by choosing a quad gear design and lowering the CG height (H) as much as possible. The Marines operate the CH-53E helicopter from spots abeam the LHA island superstructure. The CH-53E has tricycle landing gear and a 79-foot rotor. Thus, JVX designs with a single main rotor or co-axial rotors no larger than 79 feet and quad gear should be acceptable. The JVX fuselage was required to accommodate 24 troops for the Marine Assault missions. We minimized JVX fuselage width (W_f) by stretching the length of the 72-inch-wide CH-46E cabin to accommodate 24 troops. Rotor/fuselage clearance (δ) was chosen to be 18 inches for aerodynamics and acoustics. This sized the rotor diameter and wingspan for JVX tilt rotor designs.

NAVAIR had developed a formula to predict spot factor for helicopters from folded dimensions. A Navy facility in a converted airship hanger at Lakehurst Naval Air Station, New Jersey, used large-scale models of ship decks and folded aircraft planforms to evaluate the official spot factor. The procedure was to manually park as many folded aircraft models as possible on the ship flight and hanger decks, with appropriate clearances. The Marines wanted an early evaluation of the spot factor for the JVX tilt rotor, so we sent an initial design to Lakehurst based on the helicopter formula. The official spot factor from Lakehurst was too high, so the helicopter formula did not work for tilt rotor designs. The layout design team led by Dave Chappell went into emergency mode. A 12-foot-long drawing of the LHA flight deck, and a drawing of the hanger deck to the same scale, were created. Scale drawings of the JVX tilt rotor designs were duplicated in a copy machine and used to replicate the official spot factor evaluation procedure. After a very intense weekend, an improved JVX tilt rotor design was sent to Lakehurst. The folded width was set by the width of the quad landing gear, with everything else required to fold inside that dimension. The folded length was set by the wingspan, with the fuselage and folded tail constrained to fit inside the wing in folded configuration. To our great relief, the official spot factor came back as acceptable.

I got a phone call from Ken Wernicke, Project Engineer for the Bell JVX effort. He reported that they were having great difficulty with the official spot factor evaluation for their tilt rotor design and asked how we were doing. I said that we had just passed on our second try and shared our design strategy. When I reported this conversation to our design team, moral was over the top. The government team had come through while industry was struggling. In the end, Bell stayed with tricycle landing gear and decided that the tail folding added too much complexity to an already complex configuration. The Bell-Boeing team eventually convinced the Marines to accept a larger spot factor.

Layout design work continued and developed design solutions to a wide variety of problems for the four rotorcraft configurations (helicopter, auxiliary propulsion compound helicopter, auxiliary propulsion ABC, and tilt rotor). These included shipboard compatibility, operating clearances, crew visibility, troop loading/unloading, cargo handling, engine location, IR suppressor integration, drive system layout, auxiliary propulsion system integration, fuel location, in-flight refueling, landing gear layout, CG location (including tip-forward/back and turnover angles), and crashworthiness considerations. A large number of specialized drawings and working sketches were produced during this process. The final JTA layout products were the 3-view drawings of the basic rotorcraft configurations.

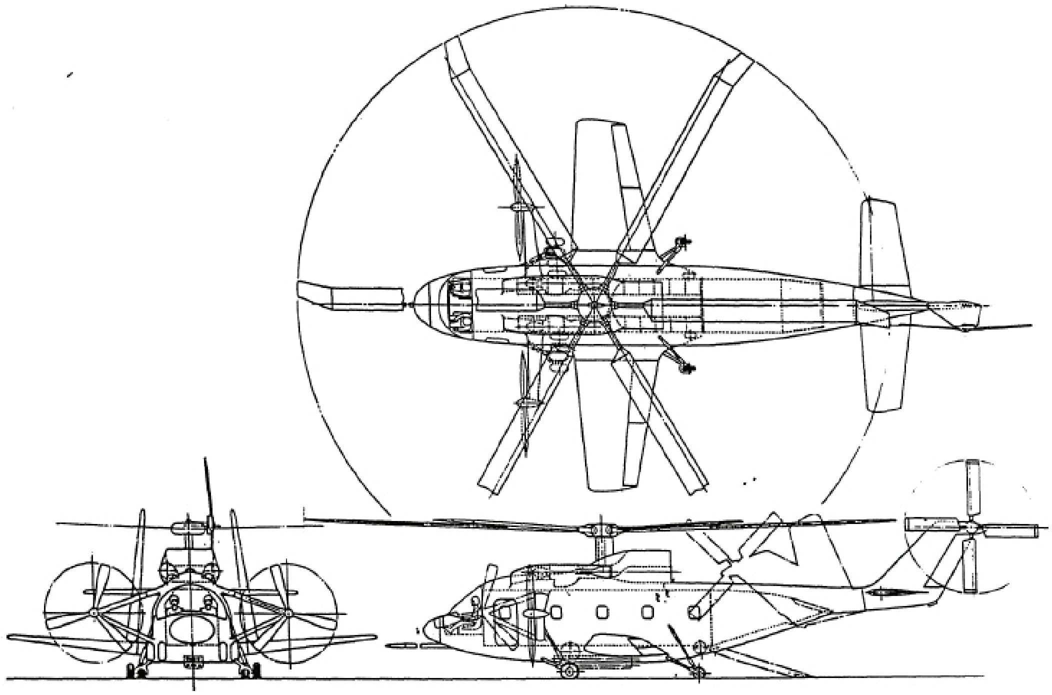
JVX JTA helicopter 3-view. Special features include a wing for high-speed maneuverability, quad landing gear for minimum folded width, canted tail rotor plus engines forward of the rotor to minimize folded length, and careful integration of the large IR suppressors to reduce drag. The width of the folded configuration is set by the width of the landing gear, with everything else folding inside that dimension. The wingspan is constrained to allow it to fold vertically under the folded main rotor. The in-flight refueling probe is retractable to minimize folded length. The floor depth is 10 inches (to lower the CG and allow a narrower landing gear), thus the fuel and landing gear are located in a pair of low-mounted sponsons.



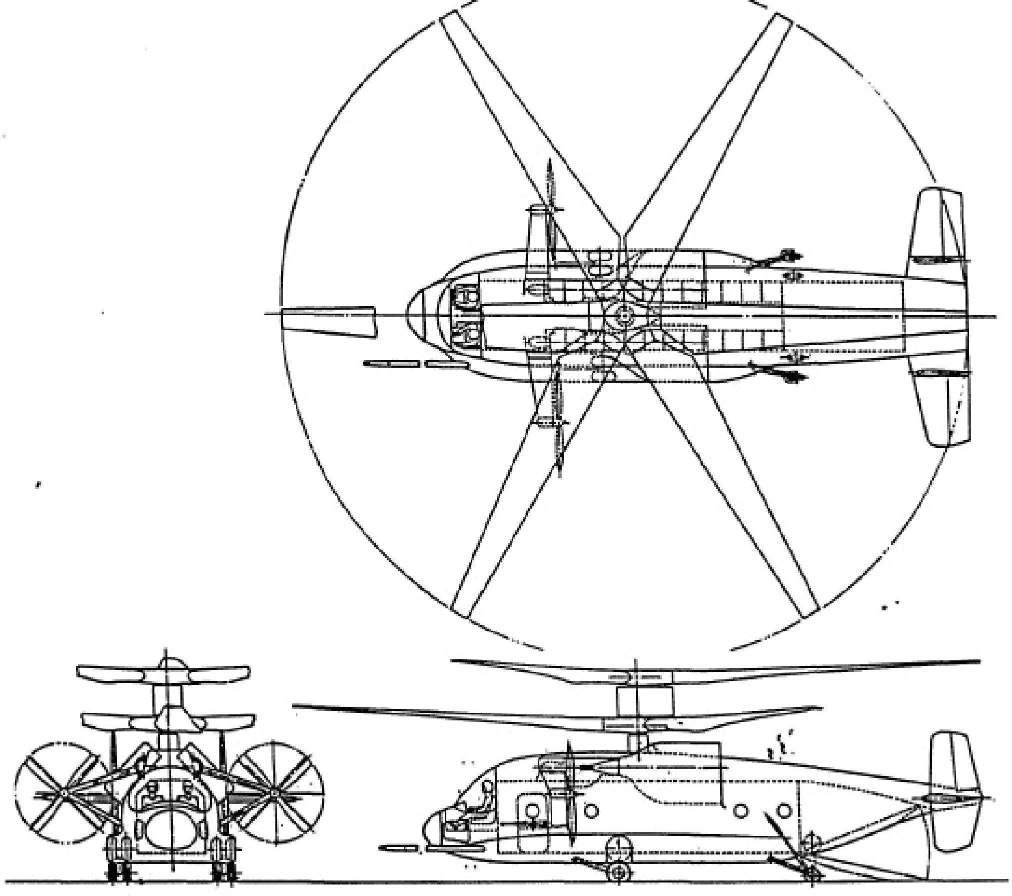
JVX JTA helicopter concept 3-view, Chappell/Peyran, 22 April 1982.

JVX JTA aux propulsion compound 3-view. This drawing is one generation older than the others, because the auxiliary propulsion ABC (which has similar capabilities) was given priority. An updated drawing would be lower and narrower, like the helicopter design. Twin propellers, mounted forward of the main rotor and folding forward along the nose, provide auxiliary propulsion. This layout was chosen to minimize the folded length. A propeller at the tail would lead to a longer nose (forward of the main rotor) to balance the prop and its drive train.

JVX JTA aux propulsion ABC 3-view. The rotors have three blades and are highly tapered for minimum weight, at some risk of increased vibration (compared to four blades). The fuselage is short enough to fit under the rotors, thus allowing a simple tail fold scheme. The aux propulsion system is similar to that of the compound, and the same reasons apply. The width of the folded configuration is set by the width of the landing gear, with everything else folding inside that dimension. The very stiff rotor blades allow the lower rotor to be closer to the fuselage than the helicopter. This is important, because the upper rotor raises the CG, which would require a wider landing gear if not compensated for by lowering the entire rotor system. The price of this low-mounted rotor is an IR suppressor design that is not as well integrated into the fuselage as that of the helicopter design. The ABC design is otherwise similar to the helicopter design.

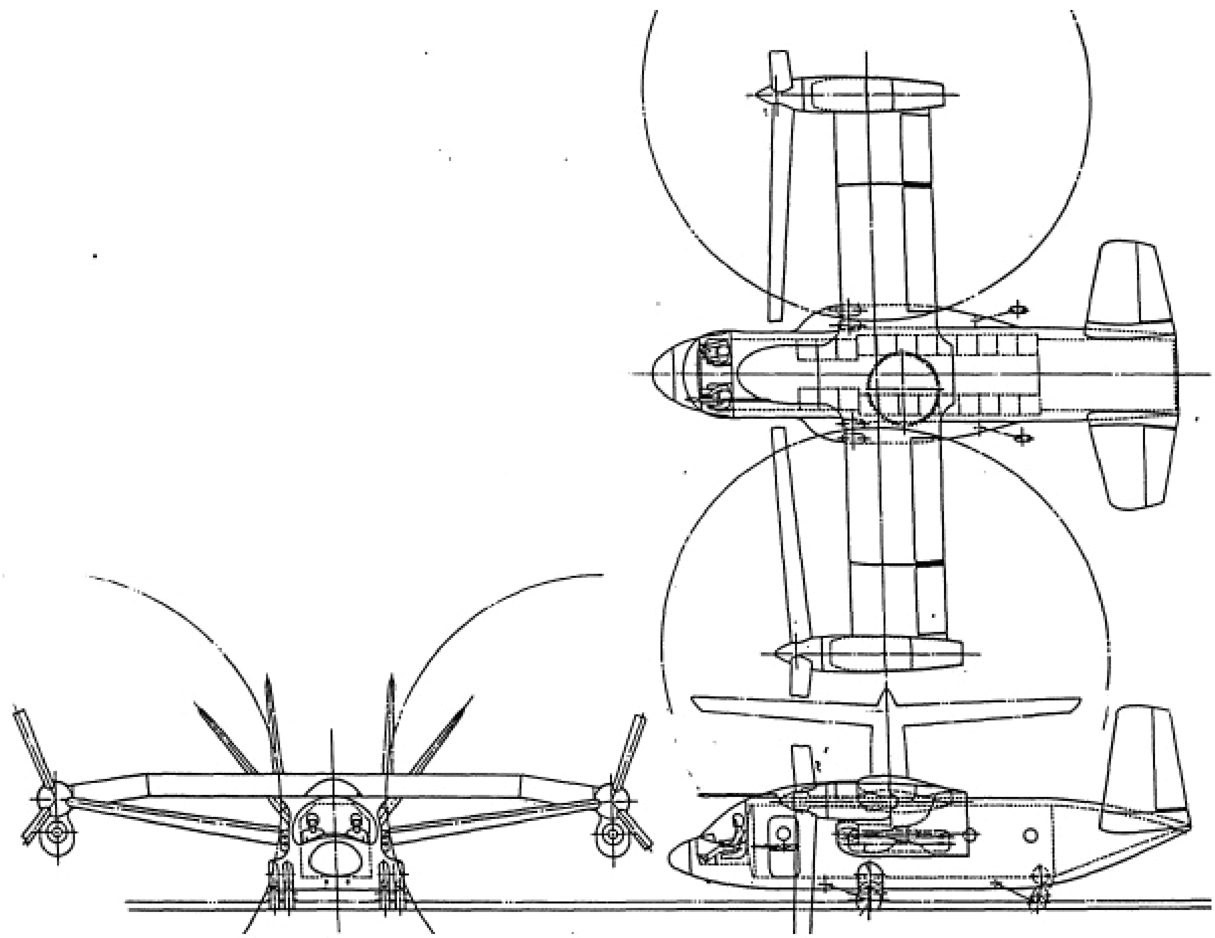


JVX JTA aux propulsion compound concept 3-view, Chappell/Peyran, 2 April 1982.

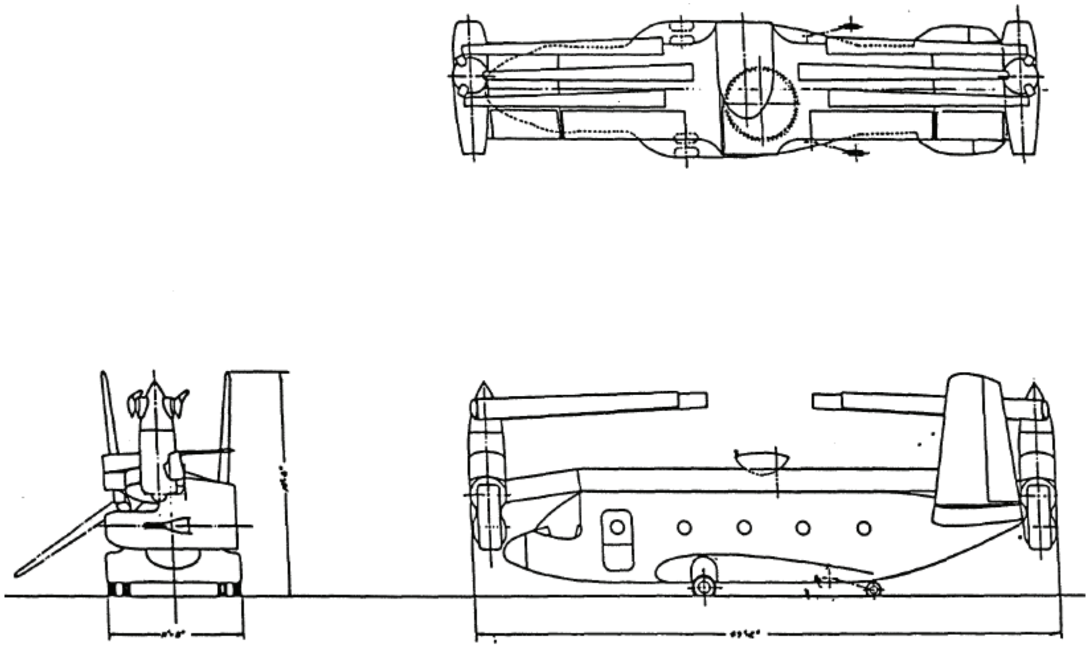


JVX JTA aux propulsion ABC concept 3-view, Chappell/Peyran, 3 May 1982.

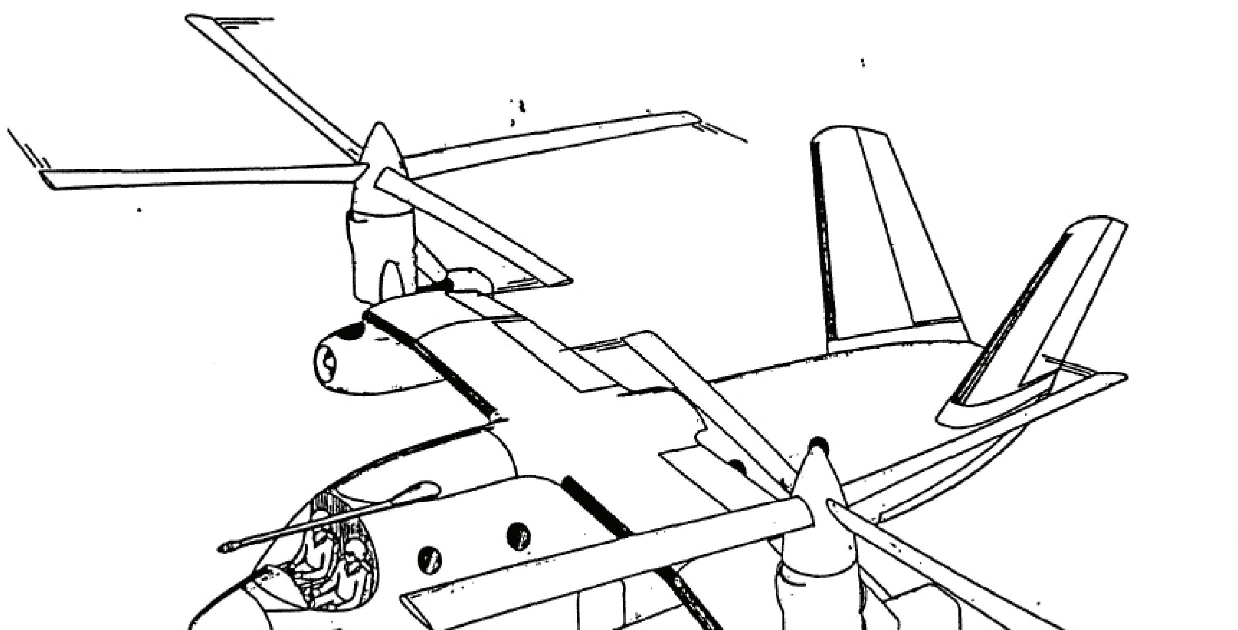
JVX JTA tilt rotor 3-view in cruise mode with a dashed-line version of the rotor and pylon in hover mode. This design is strongly driven by shipboard compatibility. The folded length is set by the wingspan, with the fuselage constrained to fit inside the wing in folded configuration. The folded width is set by the width of the landing gear, with everything else required to fold inside that dimension. This requires a very compact engine installation with a short, high-aspect-ratio (3:1) IR suppressor. The width of the landing gear is minimized by the use of quad gear and a very low CG. The CG is lowered by outer wing panel anhedral (thus lowering rotors, engines, and most of the drive system), fixed engines mounted below the wings, the location of most equipment in the sponsons or under the cockpit, and the use of a shallow (10-inch) floor. The fuel is carried in the wings, which tends to raise the CG but is safer in a crash and saves weight. The anhedral is limited by a straight rotor interconnect cross-shaft requirement (no extra gearboxes).



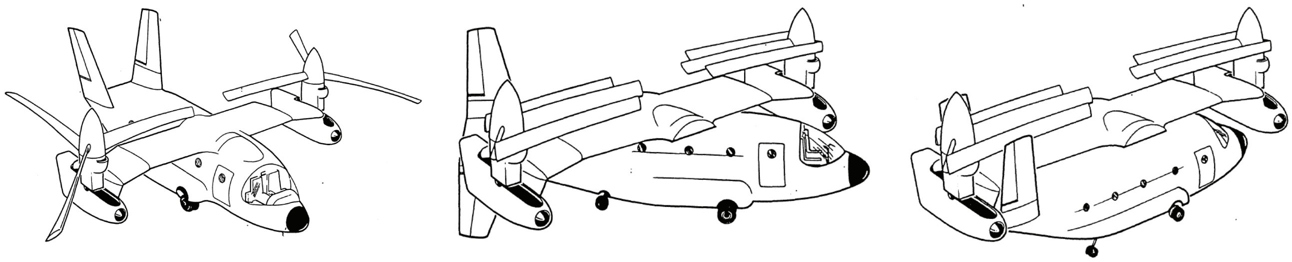
JVX JTA tilt rotor concept 3-view, Chappell/Peyran, 14 April 1982.



JVX JTA folded tilt rotor concept 3-view, Chappell/Peyran, 16 April 1982.



JVX JTA tilt rotor concept perspective view (hover mode), Peyran, 27 April 1982.



(a) **(b)** **(c)**

JVX JTA tilt rotor concept, three-position (a, b, c) folding process.

The basic folding scheme uses a pivoting wing concept (developed by NAVAIR) to eliminate the need to fold the drive shafts. The aircraft starts in landing configuration with the rotors stopped (a). The rotor blades are folded above the wings, and the wing/body fairing is folded over the top of the wing. Simultaneously, the wing flight load transfer system of lugs and pins is unlocked to allow the wing to pivot on its "lazy susan." One of the V tails folds down out of the way to allow the wing to pass (b). After the wing stops in its folded position, the V tails are folded up out of the way (c).

JVX JTA Point Designs

A vehicle designed to meet one specific set of mission requirements is referred to as a point design. A point design analysis was carried out for each of the nine service missions for each of the VTOL configurations selected as JVX candidate concepts. The nine service missions plus all services self-deployment were:

- 1D—Navy combat search and rescue (CSAR).
- 2A—Army Corps SIGNIT (SEMA).
- 3A—Army Division electronic warfare (EW) (SEMA).
- 4B—Air Force combat search and rescue (CSAR).
- 5B—Air Force long range special operations (LR SOF).
- 6C—Marine Corps amphibious assault (troop lift).
- 7C—Marine Corps amphibious assault (external cargo lift).
- 8C—Marine Corps land assault (troop lift).
- 9C—Marine Corps land assault (external cargo lift).
- 10—All services self-deployment.

Some missions required a 250-knot cruise speed. This was beyond the capability of some configurations (e.g., helicopter). These slower configurations cruised at MCP to establish fuel requirements. The fallout capability of each point design to perform self-deployment was evaluated. Several candidate engines were used during the initial point design phase. A final point design airframe and engine combination was then selected, based on minimum MGW, for each mission. Section 9.2 of reference [22] presents the final point designs with tabulated results for each mission and VTOL concept.

The helicopter point designs were carried out by Jim O'Malley and Ron Shinn, the aux propulsion compound helicopters were done by Roger Smith and Ron Shinn, the aux propulsion ABC designs by Roger Smith, Ron Shinn, and Steve Zalesch, and the tilt rotor designs by John Magee, Jeff Bowles, and Marty Maisel. The lift/cruise fan (LCF) designs were carried out by Sam Wilson, Paul Gelhausen, and Moise Devalier.

The JVX helicopter, aux propulsion compound, and aux propulsion ABC designs had engines sized by takeoff or mid-point hover requirements. Fall-out cruise speed was accepted, although this did not meet some or all mission requirements. Disc loading was chosen for minimum MGW. There were no solutions for Mission 2A (Corps SIGNIT), because rotor-borne designs could not conduct sustained operations at 25,000 to 30,000 feet at any airspeed, without prohibitive increases in rotor blade area. The helicopter blade area was sized for 1.75g at 150 knots, and a small wing was added for the high-speed (180-knot) maneuver requirement; helicopter maximum speed was limited by vibration rather than power. The rotor RPM of the compound and ABC designs was reduced in high-speed cruise to keep the advancing blade tip Mach number below 0.85. The compound and ABC designs had higher gross weights than the faster tilt rotor designs.

Faster ABC designs would have substantially increased technical risk, engine size, fuel weight, and gross weight. The Mission 8C ABC point design had a fall-out dash speed of 229 knots, installed power of 10,733 shp, and an MGW of 42,603 lb. An ABC design excursion with 250-knot dash speed required installed power of 13,297 shp and an MGW of 45,590 lb.

The JVX tilt rotor designs were sized by the same general mission and performance constraints as the various rotor-borne configurations. Two candidate engines were studied, the T64-GE-418 and the MTE. The designs were first sized by takeoff or mid-point hover requirements using "rubber engines." Fallout cruise speed exceeded mission requirements in all cases, although it did not meet the desired 300 knots in some cases. Point design performance was recomputed using the actual standard engine size, when this was sufficient to perform the mission. Rotor diameter for Navy and Marine designs was limited to 39.3 feet by shipboard compatibility. Larger rotors reduced MGW for Army and Air Force designs. Blade loading was determined by low-speed-maneuver requirements. Tilt rotor inner wingspan was rotor diameter plus fuselage width plus twice the rotor/fuselage clearance. Wing extensions were added outboard of the engine nacelle, for missions requiring long-range or high-altitude performance. The self-deployment mission used a rolling takeoff from a very long runway (Travis AFB). Self-deployment gross weight was limited by an OEI requirement for 100-fpm rate of climb (30 minute power). The impact of wing extensions on OEI gross weight was more important than the impact on cruise efficiency. Wing loading was selected to minimize gross weight for each point design mission. Hover mode rotor tip speed (775 fps) was selected based on figure of merit, weight, and acoustic signature. Airplane mode rotor tip speed (550 fps) was based on both proprotor cruise efficiency and wing torsional stiffness requirements.

JVX LCF designs studied two high-bypass turbofan engine cycles, CFM56 and QSCEE. LCF was not suitable for external load missions (7C and 9C) because of very high fuel consumption, high velocity downwash, and limited control power. The poor hover efficiency inherent in the very high disk loading of the LCF resulted in high mission design gross weights compared to more lightly loaded rotorcraft concepts. However, LCF did provide superior high-speed/high-altitude performance.

The LCF team decided that a crashworthy fuel system represented an unfair penalty for the LCF because of very high fuel consumption. I pointed out that over half of the lives saved by crashworthiness were due to the fuel system, and the Marines strongly supported the requirement. The LCF team observed that the Marine AV-8 Harrier did not have a crashworthy fuel system. I said that the AV-8 had an ejection seat for its pilot, and if providing ejection seats for everybody onboard (4 crew plus 24 troops) was a good trade for a crashworthy fuel system, then show me the numbers. That was the end of the debate.

JVX JTA summary of point designs.

Mission	1D	2A	3A	4B	5B	6-9C	Design Notes	Mission Notes
Helicopter								
Rotor Dia, ft	73		66	78	74	67.8	DL = 10-11 psf	**Navy**
Engine	T64-418		T64-416	T64-418	MTE	T64-416		1D Combat SAR
Engine Size, shp	5,115	No Solution	4,113	5,115	5,750	4,113	Vmax = 200 kt	
Mission Fuel, lb	16,019		9,166	14,653	22,821	6,612		**Army**
Mission GW, lb	48,074		36,674	46,382	58,236	38,390	Ferry = 1,100-1,840 nm	2A Corps SIGNIT
Compound								3A Division EW
Rotor Dia, ft	75		65	68	75	66	DL = 12-13 psf	
Engine (+ rubber)	T64-418+		MTE+	MTE+	MTE+	T64-418+		**Air Force**
Engine Size, shp	6,413	No Solution	5,859	5,914	7,596	5,653	Vmax = 220-230 kt	4B Combat SAR
Mission Fuel, lb	18,949		10,648	13,621	27,751	7,834		5B LR Spec Ops
Mission GW, lb	57,241		42,828	46,598	70,617	44,957	Ferry = 1,400-1,950 nm	
ABC								**Marines**
Rotor Dia, ft	70		64	58	66	58	DL = 15-19 psf	6C Ship Assault (troop)
Engine (+ rubber)	T64-418+		T64-418+	MTE+	MTE+	T64-418+		7C Ship Assault (cargo)
Engine Size, shp	7,596	No Solution	6,159	6,521	8,007	5,362	Vmax = 225-240 kt	8C Land Assault (troop)
Mission Fuel, lb	22,704		12,857	16,775	30,042	7,848		9C Land Assault (cargo)
Mission GW, lb	64,944		47,476	49,752	72,172	42,603	Ferry = 1,400-1,900 nm	
Tilt Rotor								
Rotor Dia, ft	39.3	44.4	46.6	47.5	49.2	39.3	DL = 12-17 psf	
Engine	T64-418	MTE	MTE	T64-418	MTE	T64-418		
Engine Size, shp	5,115	5,750	5,750	5,115	5,750	5,115	Vmax = 270-290 kt	
Mission Fuel, lb	12,409	8,122	9,472	11,325	17,240	5,930		
Mission GW, lb	41,423	41,525	42,298	42,512	53,150	39,770	Ferry > 2,100 nm	
Lift/Cruise Fan								
Engine (+ rubber)	CFM56+	QCSEE+	CFM56+	CFM56+	CFM56+	QCSEE+	DL = 500-700 psf	
Engine Size, lbst	39,608	29,178	43,047	38,939	38,848	25,218		
Mission Fuel, lb	27,435	14,623	25,274	23,354	30,677	9,181		
Mission GW, lb	71,726	49,484	73,096	66,121	79,557	42,713	Ferry > 2,100 nm	

The JVX JTA point designs for each mission are summarized in the table above. Data includes rotor diameter, engine designation (+ indicates a rubber growth version), engine size (power or thrust), mission fuel, and MGW. The Marine missions (6C–9C) are represented by the most difficult Marine mission (8C). The compound helicopter and ABC were somewhat optimistic compared to the helicopter and tilt rotor, because they used rubber engines instead of actual (fixed-size) engines.

Even with this advantage, the compound helicopter and the ABC were heavier and required larger engines than the helicopter and tilt rotor. The compound helicopter and the ABC were better than the helicopter in maximum speed and self-deployment (ferry), but still failed to meet the JSOR mission requirements. The ABC and the tilt rotor both had higher disc loadings (DL) than the helicopter or compound helicopter, a disadvantage in rough field and external load operations. The ABC disc loading was higher than the tilt rotor because the rotor system and inter-rotor shaft weights scale as radius times gross weight, which forces high disc loading on large designs. The ABC would be more attractive in a smaller size. The tilt rotor and the LCF easily exceeded the required ferry range. The tilt rotor exceeded maximum speed requirements but not the desired maximum speed (300 knots). The LCF easily exceeded the desired maximum speed; indeed it would be more efficient at 450 knots. The LCF was heavier than either the helicopter or the tilt rotor for all missions, and it was the heaviest of all the configurations for most missions. This was primarily because the LCF uses more fuel than any other configuration on every mission and typically uses about twice as much fuel as the tilt rotor. LCF downwash (500- to 700-psf disc loading) was prohibitive for rough field and external load operations. The helicopter, compound helicopter, and ABC were unable to perform the high-altitude (25,000- to 30,000-feet) Army SIGNIT mission.

JVX JTA Commonality Designs

For each VTOL configuration, the JTA studies attempted point designs for every JVX mission. As shown previously, some VTOL configurations were not able to meet all of the JSOR service mission requirements. The commonality design studies were intended to produce a single design that would satisfy the requirements of all of the JSOR service missions for each VTOL configuration.

Since the LCF configuration was not suited to the low-altitude, low-speed, and hover requirements of the JSOR service missions, the LCF was not considered for the commonality designs. The compound helicopter and the ABC, while better than the helicopter in some respects, could not meet all service mission requirements. They were heavier and required larger engines than the tilt rotor, which could meet all service mission requirements. Thus, the compound helicopter and the ABC configurations were not considered for the commonality designs. Although the helicopter could not meet all mission requirements, it was the lightest solution with the smallest engine for some missions, and it provided a benchmark of a conventional configuration to quantify the price of the extra capability provided by the tilt rotor. The tilt rotor was the only configuration that satisfied all service mission requirements and was the lightest solution for three of the missions. Therefore the configurations considered for commonality designs were the helicopter and the tilt rotor.

The helicopter and tilt rotor commonality designs started with the baseline point design for the Marine 8C mission (Land Assault Troop Lift), the most demanding shipboard compatible mission. The helicopter and tilt rotor designs were then modified to meet as many of the other mission requirements as possible. Fallout performance for the commonality designs was then computed for all the JVX missions using actual (not rubber) engine sizes. Three candidate engines were considered: T64-GE-416, T64-GE-418, and the MTE. Changes were made to the baseline design airframe equipment weight, mission equipment weight, fixed useful load, and payload, plus other changes as required for each mission. This included tilt rotor wing extension kits outboard of each engine nacelle for missions requiring long-range or high-altitude performance. Section 9.4 of reference [22] presents the commonality designs with tabulated results for each mission.

The helicopter could satisfy the Marine (6C–9C) mission requirements, except for dash speed and world-wide self-deployment, using any of the engines considered. The T64-GE-416 engine helicopter could not satisfy any of the other services' mission requirements. The T64-GE-418 could satisfy the Army low-altitude SEMA mission (3A) and the Air Force CSAR mission (4B) requirements, but it could only partially satisfy the Navy CSAR mission (1D) requirements because it could not reach the survivors fast enough. The MTE substantially improved helicopter performance on all missions, but it did not reduce the number of mission requirements that the helicopter could not perform: 1D (speed), 2A (altitude + speed), 5B (payload/radius), 6C (speed), 7C (speed), and 10 (payload/range). The tilt rotor could perform all of the Navy and Marine missions, including world-wide self-deployment, using the T64-GE-418 engine. The tilt rotor using the MTE could perform all of the JSOR missions, with substantial performance margins in most cases. The most difficult mission, the Air Force LR SOF (5B), had a 50-nm margin (750 nm available vs. 700 nm required).

The commonality studies showed that there was at least one design configuration, the tilt rotor, that could satisfy all of the JSOR mission requirements with a high degree of interservice commonality. The tilt rotor System Specification design demonstrated a representative design that met the JSOR mission requirements.

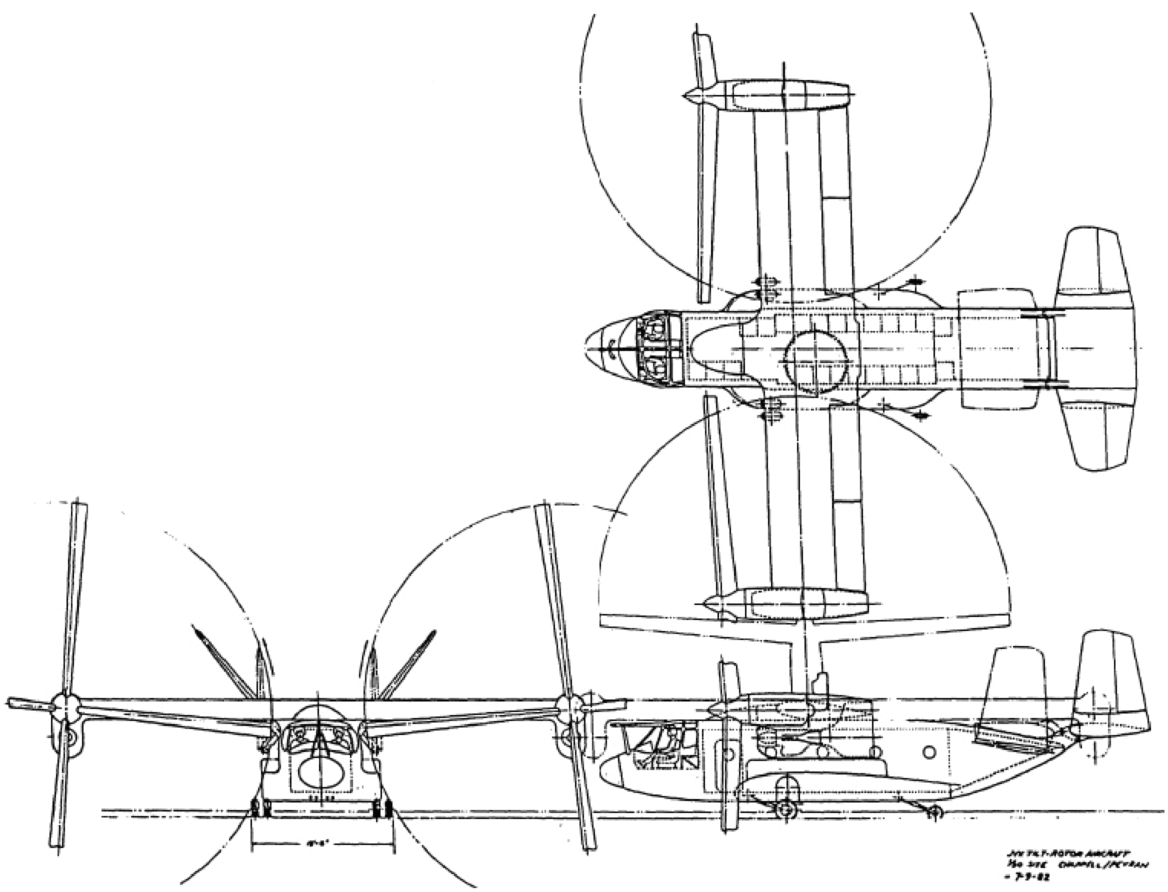
JVX System Specification Design

The development of the detailed System Specification for the JVX RFP and changes to the JSOR requirements necessitated an update of the JVX JTA tilt rotor commonality design. For example, the structural design load factor was reduced from 6.0 to 4.0, and the maximum gross weight was changed to reflect internal cargo load requirements, self-deployment mission changes, and internal fuel storage requirements. Long-range aux fuel tanks were changed from internal to external to make room for cargo. The update was an opportunity to refine the tilt rotor commonality design. The outer wing panel anhedral was removed, and the rotor diameter was increased from 39.3 to 39.4 feet. Dual wheel main landing gear increased both weight and track. The folded width increased, but the folded length remained the same. The JTA design had a short tail moment arm and a large tail area. A folding tail design was introduced to increase the tail moment arm. This decreased tail area, drag, and weight, but added folding mechanism weight.

The JVX System Specification tilt rotor design table below includes rotor figure of merit, download, and aircraft figure of merit. After the JVX JTA, the actual XV-15 rotor was tested on the Outdoor Aerodynamic Research Facility (OARF) at Ames [99]. This very-high-quality hover data showed much higher rotor figure of merit than expected. OARF data, plus XV-15 hover flight test data, implied much higher download than previous estimates of vertical drag from rotor downwash on the wing. The search for an explanation resulted in the idea that downwash from the two rotors turns inward along the wing and meets over the fuselage to form an upward fountain. A JVX tilt rotor download estimate including both vertical drag and the fountain would be about twice as large. The aircraft figure of merit would not change because the increased rotor figure of merit and download would cancel.

JVX System Specification tilt rotor design.

Rotors		Propulsion	
No. Blades	4	Engines	2 x MTE
Diameter, ft	39.4	Rated Power, shp	2 x 5,750
Solidity	0.1095	Drive Rating (hover), shp	9,554
Blade Aspect Ratio	11.6	Fuel Tank Capacity, lb	8,303
Tip Speed (hover/cruise), fps	775/550		
		Aerodynamics	
Wings		Rotor Figure of Merit	0.774
Span, ft	50.23	Download, % GW	5.7
Area, sq ft	450	Aircraft Figure of Merit	0.670
Aspect Ratio	5.6	Drag Area (cruise), sq ft	16.8
Thickness/Chord	23%	Propeller Efficiency	0.826
Flap Chord	30%	Equivalent L/D (260 kt)	6.56
Torque Box Chord	45%		
		Baseline Mission (Land Assault)	
Fuselage		Disc Loading, psf	16.6
Length, ft	48.0	Wing Loading, psf	90
Width, ft	7.67	Empty Weight, lb	26,793
Wetted Area, sq ft	1,140	Mission Fuel, lb	5,255
		Payload (24 troops), lb	5,760
Folded Aircraft		Mission Gross Weight, lb	40,543
Length, ft	51.8	Struc Design GW, lb	43,590
Width, ft	13.5	Max Alternate GW, lb	52,885



JVX System Specification 3-view.

The JVX System Specification tilt rotor was a baseline Marine Mission 8C commonality design with MTE engine, and fallout performance was computed for the remaining missions. The Marines urgently needed to replace their CH-46 helicopters and could not wait for the development and qualification of a new engine such as the MTE. The solution was to design for the MTE, but use an available engine for development and early production until the MTE became available. Fallout performance of a baseline design using the T64-GE-717 rated at maximum power was computed for the Marine missions and the self-deployment ferry mission. Payload vs. range/endurance curves for both engines were presented in Figures 9.2 through 9.11 of reference [22].

For the Army, Navy, and Air Force missions, only the MTE performance was computed, and the wing fuel capacity was increased from the Marine baseline to fill the available wing volume. Any additional mission fuel needed was carried in external tanks, with added weight and drag. For the Navy CSAR mission, radius with design payload was over 60 percent greater than required. For the Army missions, time on station with design payloads was over 15 percent longer than required. For the Air Force CSAR mission, radius with design payload was approximately 20 percent greater than required. The Air Force LR SOF 700-nm-radius requirement was met with a 12-troop payload. For a 24-troop payload, a 450-nm radius was available. The 2,100-nm self-deployment range was exceeded, even with the heavy Army Corps SIGINT equipment.

For the Marine missions, the T64-GE-717 engine achieved or exceeded the payload/range requirements. The MTE engine provided a wide margin in mission radius or payload capability over the required values. Both engines easily achieved the 2,100-nm self-deployment range with the wing extension kit.

JVX Program Briefings

The JVX JTA Flag Officer In-Process Review (IPR) on 3 April 1982 at Ames was the first major external briefing. Vice Admiral Richard Seymour, the Commander of NAVAIR, was the senior officer. Major Robert Magnus was the Marine action officer. Major Magnus was what the Army would call an "Iron Major," since he worked under the Marine 3-star in charge of Aviation. His blunt advocacy of Marine interests to a 3-star Admiral was a sight to behold. The briefing focused on the Draft JSOR requirements and Preliminary Design Analysis (JVX JTA Technical Foundations). We prepared most of Charlie's viewgraphs for the briefing but he organized them. This became interesting when Charlie turned the Preliminary Design Analysis part of the briefing over to me during the presentation without any warning. I was very familiar with the material but had no idea which viewgraph would be next. Charlie was great at reading the audience and reacting in real time during briefings. I learned to review the actual sequence of viewgraphs and to be mentally ready for anything. This sink or swim training proved to be invaluable in the rest of my career.

Briefings in Washington, D.C. on 19 April included emerging results from the Point Design Analysis and Common Design Options. May was a mixture of giving briefings, refining viewgraphs to include final JVX JTA results, and adjusting our message as we learned. We briefed NASA HQ, AHS, AVRADCOM (Major General Story C. Stevens), NAVAIR, the Pentagon (Army, Navy, Marine, and Air Force 3-stars), and industry (Sikorsky, Bell, and Boeing). The most memorable 3-star was the Deputy Chief of Naval Operations for Air Warfare, Vice Admiral Wesley McDonald. Not only was he very helpful with good questions and advice, he also had a "Golden Arches" flag in his office. During the RFP Task Force we gave a major JVX JTA briefing on 28 June to representatives of 25 U.S. and foreign aerospace companies [100]. Marine Colonel James Creech

(JVX Program Director) and Charlie gave the main briefing while I did the Preliminary Design Analysis portion. Charlie also published an article “JVX, What an Opportunity!” in *Vertiflite* [101].

JVX Request for Proposal (RFP) Task Force

The JVX RFP Task Force worked in the Mart Building in downtown St. Louis. AVRADCOM had moved from the Mart Building to Goodfellow Boulevard on the outskirts of St. Louis, so it was familiar territory. The government draft RFP was mostly developed in June of 1982. During July and August we held industry RFP review meetings. Ken Wernicke was the lead engineer for Bell-Boeing and Gary DeSimmone was the lead engineer for Sikorsky. We eventually received 369 industry comments on the System Specification, Preliminary Design Statements of Work, and Airworthiness Qualification Plan in the Draft RFP; 190 of them were ultimately incorporated.

The government JVX System Specification design showed that there was a feasible design solution for the JVX. The job of industry was to develop better JVX design solutions. It was essential that the System Specification not constrain industry to any specific design. The Joint Services Advanced Vertical Lift Aircraft System Specification made no mention of specific aircraft configurations. It included a dash speed of 275 knots and a 2,100-nm self-deployment mission without refueling with flight time not to exceed 10 hours. The Army Corps SIGINT mission profile included segments at 30,000 feet altitude. These required JVX capabilities were well beyond conventional helicopter technology—hence the name Advanced Vertical Lift Aircraft.

Al Winn (AVRADCOM D&Q) led the JVX RFP Task Force and Marine Lieutenant Colonel Bob Yeend was his Deputy. I worked for Charlie mostly on the System Specification and ADS-10. I reviewed the entire System Specification, and I worked with the engineers to clarify the language, replace required designs with required capabilities, and evaluate the impact on the government design. Jeff Bowles at Ames ran the TR code and worked with the layout team to quantify design impacts. Charlie ruled on significant issues based on evidence we provided. The JTA tilt rotor design evolved to become the JVX System Specification design.

The Air Vehicle Technical Description (ADS-10) had been an important issue since the AAH SSEB. The JVX provided the need and the opportunity to create an ADS-10 that supported state-of-the-art comprehensive analyses and addressed advanced vertical lift aircraft, not just helicopters. A strong team was assembled including Wayne Johnson, Ray Kvaternik, Bill White, and Tex Jones. The ADS-10 they produced was a major improvement. It was complex and included different levels of detail to address different stages of aircraft design development. State-of-the-art comprehensive analyses at the time used modal structural analysis. Since then, the analyses state of the art has evolved to include finite element structural analysis and multibody dynamics, resulting in the need for more detailed data in ADS-10.

JVX acquisition strategy included a competitive 23-month Preliminary Design (PD) Phase with a series of required trade-off analyses by industry. The draft JVX System Specification was to be continuously updated to reflect the requirements definition, trade-off analysis, and other lessons learned. A final System Specification was to be part of the Full-Scale Development (FSD) RFP. Trade studies included Turnover/Deck Spotting, Cabin Width, Drive System Commonality, Multiple Rotor Speeds, Maneuver Load Factor, Armament, Crew Environment, Crashworthiness, Rescue Operations, Radar Cross-Section Reduction, IR Signature Reduction, Vulnerability Reduction, NBC Protection, Lightning/EMI/EMP Protection, Damage Tolerance, and Interim Engine Control. The

Turnover/Deck Spotting study considered options to improve deck spotting on LHA from required to desired (46 to 55 aircraft) and to increase rotor diameter. Design options included quad landing gear and tail folding. Cabin Width and Drive System Commonality studies considered a land-based variant with cabin width increased from 72 to 90 inches and rotor diameter increased from 38 to 43 feet. The Multiple Rotor Speeds trade study considered multiple cruise-mode rotor speeds including an option to use hover rotor speed in cruise to raise drive system limited power for better dash speed and maneuver capability.

The JVX RFP developed under Army leadership was eventually cleared to be released by the Army in December 1982 after the Office of the Secretary of Defense (Dr. Richard DeLauer, Undersecretary of Defense for Research and Engineering) approved the acquisition strategy [102]. This included approval to go directly from the PD Phase to FSD without a Full-Scale Prototype. The PD Phase included an extensive program of wind tunnel testing and simulation to support scaling up from the XV-15 concept demonstrator (25-foot rotors) to a full-scale System Specification JVX design (39.4-foot rotors).

JVX Acquisition Strategy and Competition

The Pentagon acquisition strategy for JVX envisioned a teaming arrangement for a single development program followed by splitting of the team for production competition. To reduce risk and increase competition, the acquisition strategy was adjusted to include a competitive 23-month PD Phase followed by a single FSD contract. Bell Helicopter Textron and Boeing Vertol announced a JVX teaming agreement on 7 June 1982. Teaming of the two prime contractors with the strongest technical background in tilt rotor technology made ensuring viable competition for the JVX development program much more challenging. Bitter experience had taught us that competition is necessary to ensure the very best efforts from industry. We therefore expanded our efforts to encourage industry interest in JVX by undertaking a specific effort to urge Sikorsky to compete for JVX by teaming with another prime contractor. Charlie led this effort and I joined him to provide technical support for two key briefings. In October 1982 we briefed Buzz Hello, Vice President of Rockwell's Aircraft Division (formerly North American Aviation) to encourage a partnership on JVX.

On 23 November 1982 we briefed Sikorsky leadership including Bob Daniell (CEO), Bill Paul (Executive VP), and Bob Zincone (VP Research and Engineering). Our case for JVX was that 1) Rockwell was willing to partner on JVX, 2) the PD Phase would give a Sikorsky/Rockwell team 23 months and about $50 million to develop a competitive JVX design, and 3) Sikorsky should not underestimate the ability of the competition to make serious mistakes.

We reminded Sikorsky that they thought Bell had UTTAS locked-up because of their Huey experience and almost decided not to submit a proposal. Instead Bell lost the Phase I UTTAS competition and the UH-60 Blackhawk was in production at Sikorsky. It was a strong case, but in the end Sikorsky declined to bid on JVX and signed up to demonstrate X-Wing on the S-72 Rotor Systems Research Aircraft (RSRA).

JVX Program Funding and Executive Service

During the JVX JTA, the Pentagon was busy negotiating both funding and executive service for JVX. Emerging information revealed that the Navy was insisting that the Army (as executive service) had to put up more funding than the Navy. The JVX Memorandum of Understanding (MOU) [103] signed by the three service secretaries on 4 June included service funding shares of 46 percent Army, 42 percent Navy, and 12 percent Air Force. We had naively thought that the service with the strongest technical background in tilt rotor technology would be executive service. We were wrong. The Army JVX missions were for SEMA. Traditionally the Army's SEMA mission needs had been met with modified off-the-shelf fixed-wing aircraft. Ultimately the Army was not willing to fund a new advanced VTOL for SEMA. In January 1983 *Aviation Week* [104] reported that the DoD had restructured JVX with the Navy taking over as the executive service and the lead for the airframe development while the Army would be the lead for the MTE engine development. Airframe funding would be 50 percent Navy, 34 percent Army, and 16 percent Air Force. MTE funding would be split equally between the services. Two weeks later the Navy released a JVX RFP to industry [105]. It was basically the JVX RFP developed under Army leadership because the Marines were not willing to delay the program. The RFP included a Draft System Specification [106] that, as far as I can tell, was unchanged from the version developed under Army leadership.

JVX Source Selection and Development Risk

When JVX became a Navy program the Army technical community was expected to drop JVX and focus on LHX. We did not want to abandon JVX until it was safely under contract. Charlie was able to negotiate with Dick Lewis to allow three engineers (Charlie, Bill White, and myself) to participate in the JVX Source Selection. The Source Selection started in early February and continued to mid-April 1983. Our NAVAIR friends were gracious hosts and made room for us in their Crystal City, Virginia, offices. I was seated next to Steve Zalesch in the Evaluation Division. Dudley Cate from the HELCOM study was Chief of Weights for the Evaluation Division. He arranged second-shift copy machine access and allowed me to copy Navy weight statements.

NAVAIR had a DEC VAX-11/780 (32-bit super mini-computer). It ran one shift a day and was so overloaded that interactive response was excruciatingly slow. Fortunately Andy Kerr knew the NAVAIR computer czar through 2GCHAS work and arranged an introduction. To my surprise the VAX was left on and turned over to me as the only user on second shift. It was wonderful. I worked two shifts—with people on the first shift and with the VAX on second shift. My VAX work was mostly developing hands-on familiarity with the TR code, modifying it to address Source Selection technical issues, and modeling the proposed industry JVX design.

We were very disappointed when there was only one JVX proposal from industry. Bell-Boeing proposed the Model 901 tilt rotor, which eventually was developed into the V-22 Osprey. The job for the Source Selection was now to determine if the proposal was technically acceptable and to negotiate a PD Phase SOW appropriate for funding originally intended to support two contractors. Bill White worked with Charlie and Bonnie Jones, the wonderful NAVAIR KO, to invest the extra funding in risk reduction (e.g., structural testing, wind tunnel testing, and simulation). I worked with Charlie on the technical issues.

The fundamental question was the risk of scaling up from the XV-15 concept demonstrator (25-foot rotors) to a full-scale Bell-Boeing Model 901 (38-foot rotors) without a full-scale prototype. This concern existed both in the Source Selection and in Congress. Navy Captain Jim Magee, Office of the Chief of Naval Operations (OPNAV), asked NASA (John Magee, no relation) for help with Congress. John Magee produced a NASA White Paper on JVX Program Risk [107] in March to support OPNAV in their work with Congressional Staff. The Source Selection debate included risk reduction during the PD Phase (mostly Charlie and Bill White) and modeling the proposed Bell-Boeing Model 901 in the TR code. Technology inputs to the TR code that were needed to match the Model 901 design were compared with the government technology inputs developed and documented during the JVX JTA. Specific technical issues included increased contingency weight (eventually implemented by NAVAIR) and modeling of 3D effects on wing drag because of lift (implemented in TR code based on XV-15 data from John Magee). The Model 901 fuselage design used honeycomb core sandwich construction based on the Boeing Model 360 tandem helicopter demonstrator. This eventually became a major issue for NAVAIR and resulted in a last-minute change to a "Black Aluminum" fuselage when there was no time to develop a new state-of-the-art composite detail design. I do not recall if honeycomb core was an issue during the Source Selection.

The final Source Selection meeting with the NAVAIR 2-star Admirals included briefings by both NAVAIR and Charlie. Charlie's much greater experience in briefing flag officers was apparent. The 2-stars also knew that Secretary of the Navy John Lehman wanted JVX to succeed. The end result was the award of a JVX PD Phase contract to Bell-Boeing and the beginning of what became V-22 development.

The V-22 Osprey has gone on to achieve great success with the Marines (MV-22) and the Air Force (CV-22). It is planned to be used for the Navy shipboard re-supply mission (CMV-22) and is also planned for use by several foreign governments. Although the Army never acquired the V-22 for its own use, the tilt rotor concept is being vigorously pursued by the Army as part of the Joint Multi-Role Technology Demonstrator program, and the Bell V-280 Valor is currently undergoing flight testing for potential future Army missions.

Observations

My engineering adventures were wide ranging and extended far beyond Ames, but they were always based on a solid foundation of hands-on government technical capability. The Army-NASA partnership in rotorcraft aeromechanics, structures, and propulsion at Ames, Langley, and Lewis was based on world-class facilities and researchers. The origin and focal point was the Army-NASA collaboration at Ames, AMRDL HQ, and in subsequent years, AFDD. These technical resources, and the hands-on experience of our team, enabled us to support major rotorcraft acquisition programs with quick turnaround testing and analysis, and realistically evaluate industry testing and analysis. Government research was augmented with contract research performed by industry and academia. Contract research ranged from small theoretical efforts, through hardware development and test, to VTOL concept demonstrator aircraft (e.g., the XV-15 and XH-59). The Eustis Directorate (in subsequent years, ATL, and then AATD) supported a large contract research program with in-house testing and analysis while the Army-NASA partnership emphasized in-house work.

Army Aviation had a substantial D&Q technical community. This included technical ground and flight testing to produce engineering-quality data and engineering qualification to ensure that Army aircraft were both safe and effective (full System Specification capabilities). The development of qualification criteria and plans plus the engineering analysis and evaluation of contractor qualification data required substantial in-house technical capability. This grounding in the engineering realities of rotorcraft development and modification provided an important balance to the not yet proven technical possibilities emerging from research.

Major technical challenges such as development of new or substantially modified aviation systems, unexpected development problems, or technical problems with the fielded fleet got an all-hands on-deck response. A government (Army, NASA, and Joint Service) technical team was assembled with access to industry and academia as needed. The depth and breadth of the government rotorcraft technical community and the technical leadership to identify, assemble, and lead the A-team were essential to success.

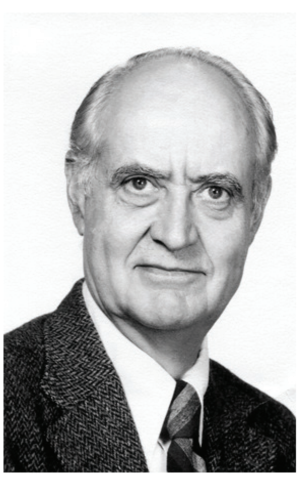
Computer capability was rapidly improving and Army-NASA development of design and analysis codes gave us world-class tools designed to fit our needs. The government technical community must be able to work with many different VTOL concepts on a fair basis and not be limited by the "tribal knowledge" of individual contractors. This need resulted in the in-house development of flexible tools based on fundamentals, and formed by exposure to a wide variety of ideas and approaches from government, industry, and academia.

Friends, Colleagues, and Mentors

Aircraft designers have substantial freedom to develop creative solutions within the space bounded by available technology and affordability ("laws of physics" and "laws of economics"). The goal of design is to maximize operational effectiveness. Operational effectiveness comes from many things including doctrine, organization, training, material, and leadership. Thus, the technical R&D that enables better aircraft (Materiel) must be supported by military art R&D to understand how to best use new technical possibilities. A team that enables new aircraft development must include both technical people (government and industry) and operational people (soldiers, sailors, marines, and airmen). I have been blessed to work with many dedicated, mission-oriented professionals, both technical and operational.

This memoir of the first 8 years of my career in the Army-NASA partnership is dedicated to the friends, colleagues, and mentors who made it all possible. Many are mentioned in this account, but I am sure some have been overlooked. I have learned from you and grown in many ways during our work together. Our work has supported development of aircraft that fly around the world in the service of our nation and has significantly advanced rotorcraft technology. Thank you.

Three great leaders and mentors stand out from the rest. They taught me much about life, leadership, and engineering. I am truly blessed to have worked with and for them.



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Index