ADVANCES IN DESIGN, MANUFACTURING AND TESTING OF THE ALL-DIGITAL V-22

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Abstract

The production V-22 has incorporated the latest technologies and computer-aided techniques and manufacturing processes:

1. CATIA™ (Computer-Aided Three-Dimensional Interface Application) for design. A single authority digital data base that contains all the design information.
2. Digital electronic mockup (EMU) to determine part fit-up and resolve interface problems during the design phase through Digital Pre-Assembly (DPA), instead of creating panic on the assembly line.
3. Concurrent Product Development using over 80 Integrated Product Teams (IPTs) consisting of engineering, tooling, manufacturing, supportability and subcontractor disciplines, working simultaneously on each major part of the aircraft to ensure a "balanced" design. The multiple customers for the V-22 aircraft, USMC, USN, and USAF/SOCOM, are an integral part of the IPTs. An Analysis and Integration (A&I) team ensures consistency across interfaces and an Integrated Test Team (ITT) of contractor and customer pilots perform flight testing.
4. Manufacturing process improvements including the utilization of part features to locate and assemble components; fiber placement of large pieces of composite structure with simple and compound curvature; high speed machining of large monolithic pieces of metallic structure rather than assembling them from pieces; laser optical layout templates driven from the CATIA™ data base to locate composite plies during lay-up; robotic trim and drill cells; automated creation of wiring form boards and numerically controlled, CATIA™ driven, automatic bending of hydraulic tubes.

The results of using these new technologies and processes are compared with 1980's methods.

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Introduction

The V-22 tiltrotor is a unique rotorcraft that can efficiently hover like a conventional helicopter and fly at speeds above 300 knots with the efficiency and comfort of a turboprop airplane. Developed by a team from Bell-Boeing for the U.S. Marines, Special Operations Command (SOCOM), and Navy, six aircraft (tail numbers 1 through 6) designed, built, and tested during the Full Scale Development (FSD) phase, have completed over 1100 hours of flight test. The program is currently in the Engineering and Manufacturing Development (EMD) stage in which four new aircraft (tail numbers 7 through 10) have been built on production tooling. These aircraft are now in flight test at Patuxent River. The plan for the overall development program is presented in Figure 1. Testing will cover all of the structural features of the airframe and the basic USMC avionics and will be completed in 1999. The development and test of the SOF and Navy CSAR configurations which use the same basic airframe but incorporate changes and additions to systems and avionics will continue into the early 2000's.

Although the tiltrotor concept was studied in the 1930's and experimental aircraft were built in the 1950's and 1970's, there were two enabling technologies that matured in the 1980's and allowed a viable production design possible. They were fly-by-wire (FBW) all-digital flight control systems and composites technology for primary structure. The FBW control system allowed an automatically re-configurable control system for all modes of flight and made it easier to design the wing stow system at an acceptable weight. Composites technology provided the choice of materials for optimum design of the structure to meet dynamic characteristics, and strength, cost and weight targets.

Some of the salient design features of the V-22 are shown in Figure 2. The V-22 carries a crew of two to four and has the capability for seating 24 combat troops. Flexibility is added by the ability to carry external cargo up to 15,000 pounds on tandem hooks with individual capacities of 10,000 pounds. An aft ramp allows rapid loading and unloading of internal

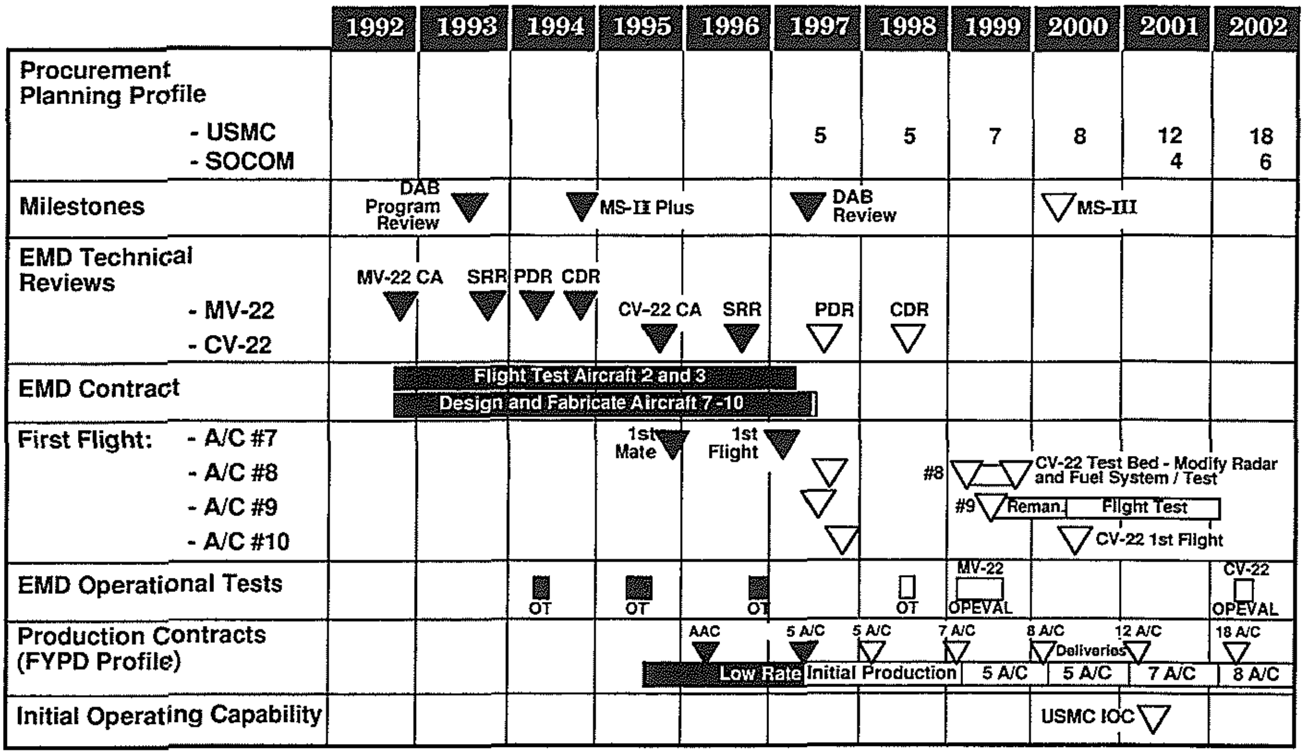

Figure 1. V-22 EMD / LRIP Program Schedule

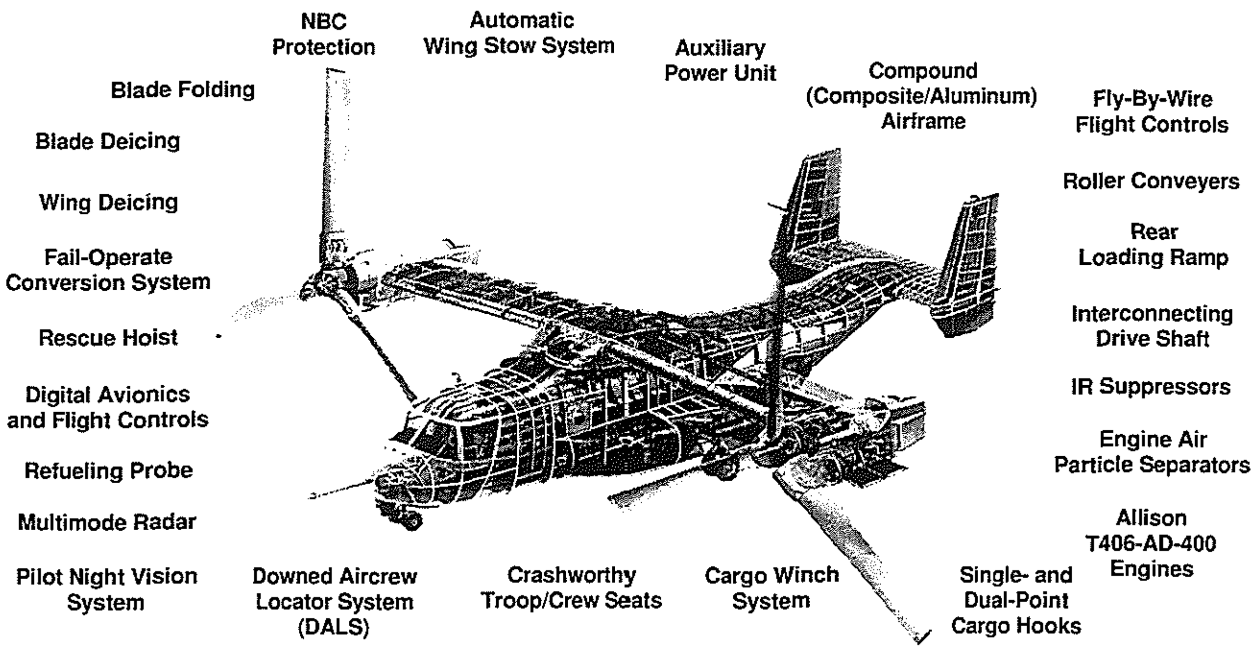

Figure 2. V-22 Multi-Mission Features

cargo. The rotor blades fold and the wing rotates for stowage aboard ship. The V-22 is capable of all-weather instrument flight, day or night, and continuous operation in moderate icing conditions, and at weights up to 60,500 pounds for self deployment. The V-22 structure uses the latest in composite materials and manufacturing processes. A synergistic combination of precision machined aluminum, fiber-placed graphite, and titanium has allowed a significant weight reduction in the EMD V-22. The Night Vision Goggle-compatible cockpit includes conventional controls and digital avionics displayed on four Multi-Function Displays (MFDs) and one Control Display Unit/Engine Indicating and Caution Advisory System (CDU/EICAS).

Mission Performance

The V-22 is a highly flexible, multi-purpose aircraft capable of performing many missions. The V-22 has been the winner in over thirty different mission scenarios identified and evaluated by the US Government, Bell-Boeing, and independent analysis companies.

The multiple design mission key performance parameters (KPP) and aircraft capabilities are presented in Figure 3. The V-22 meets or exceeds all mission requirements. In addition, the independent variables used in the compliance calculation all have built-in buffers to ensure that the required KPP's are met at the end of EMD in 1999.

	Key Performance Parameter	MV-22 Projection	CV-22 Projection
Pre-Assault / Raid (18 Troops)	200 NM	214 NM	-
Land Assault (24 Troops)	200 NM	275 NM	-
Land Assault (10,000 Lb Load)	50 NM	50 NM	-
Amphibious Assault (24 Troops)	2 x 50 NM	2 x 71 NM	-
Amphibious Assault (10,000 Lb Load)	50 NM	111 NM	-
Self-Deploy (With Refueling)	2100 NM	2565 NM	2627 NM
Long Range SOF Missions	500 NM	-	503 NM
MV-22 Cruise Speed (V_{MCP} at 3000 Ft / 91.5°F)	240 Knots	275 Knots	-
CV-22 Cruise Speed	230 Knots	-	261 Knots
Survivability	12.7 mm	12.7 mm	12.7 mm
V/STOL / Shipboard Compatible	Yes	Yes	Yes
Aerial Refueling	Yes	Yes	Yes

Figure 3. V-22 Projected Capabilities for Prime Missions

For the Marine Corps, the Osprey's speed and range provide an expanded battle-space that complicates the enemy's ability to defend their territory. Figure 4 shows the increased combat reach the Marines will have while making an amphibious assault, relative to the capability of the present Marine assault medium lift aircraft, the CH-46. The range capability of the Osprey permits the amphibious fleet to use the sea as operational maneuver space. This increased capability allows greater standoff distance for the amphibious fleet, thus avoiding coastal minefields and missile defenses. It also enhances the element of surprise by providing a capability for feint and deception.

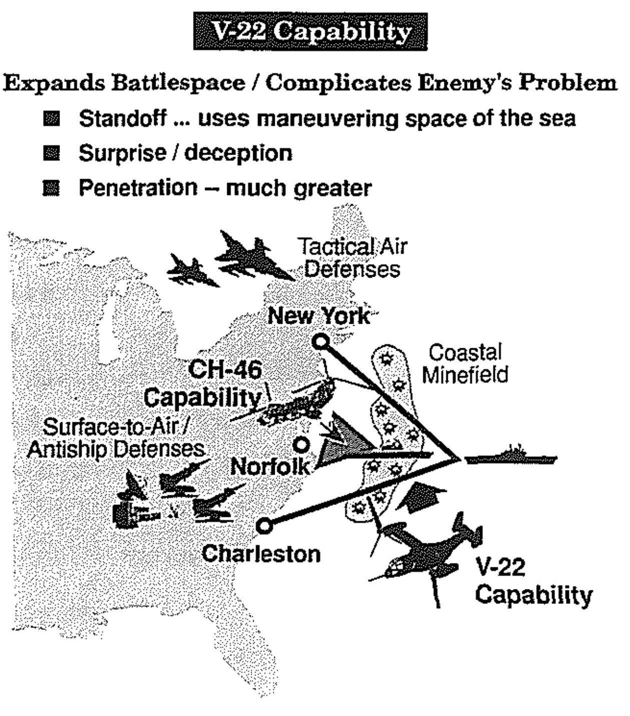

Figure 4. Enhanced Reach in War

Special Operations Forces (SOF) require high-speed, long-range V/STOL aircraft capable of penetrating hostile areas. The SOF variant of the V-22 will meet this requirement. The SOF V-22 is capable of covert penetration of medium to high threat environments in low visibility, while employing self-defensive avionics and secure, anti-jam, redundant communications. The SOF V-22s inherent long-range and self deployment ability maximizes mission security and minimizes logistics cost. It has an unrefueled combat range sufficient to satisfy current and emergent military needs and carries a built-in refueling boom for range extension. The SOF V-22 has the necessary speed to complete most operations within one period of darkness and can operate from air capable ships without reconfiguration or modification.

Figure 5 portrays the potential advantages of using the V-22 in the initial stage of "Operation Eastern Exit", the evacuation of 61 Americans and several foreign Ambassadors from the US Embassy in Mogadishu, Somalia. The actual evacuation by CH-53Es, carried to waters off Somalia by the USS Trenton (LPD-14) from its anchorage off Oman, took 87 hours and included three aerial refuelings per helicopter. With the V-22, the same mission could have been flown directly from Oman using two aerial refuelings with a total mission time of less than seven hours.

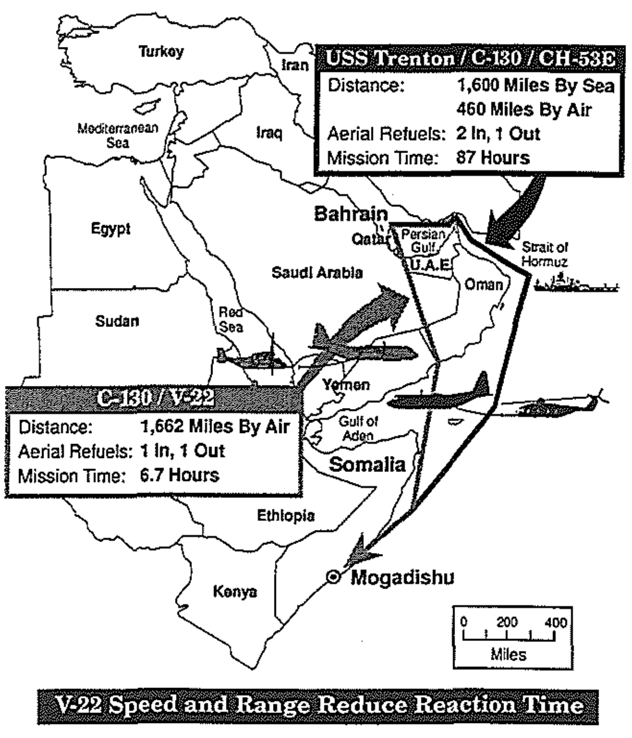

Figure 5. Operation Eastern Exit - Comparing Helicopter and V-22

Similarly, in an April 1980 attempt to rescue US embassy personnel in Iran, an 87 hour mission could have been performed by the V-22 in less than 7 hours without the attendant problems of refueling at Desert One.

Search and Rescue variants of the V-22 have been studied for the US Navy Combat Search and Rescue (CSAR) mission and for civilian SAR applications. Typical SAR missions often require extended range and speed combined with extended time-on-station to perform the necessary search. The ability to combine speed, range, and time-on-station with the ability to hover and recover victims, means the SAR V-22 can provide a great improvement over the current necessity for combining fixed-wing aircraft for search and land or ship-based helicopters for pickup.

An illustration of the SAR capability of the V-22 is shown in Figure 6. Flying from North Germany, the V-22 could perform SAR missions covering all of Germany and the surrounding seas.

SL/ISA; 1 Hour Loiter; 4 Rescuees;
7,825 Liters Fuel; Includes 1,210 Kg Fixed Useful Load

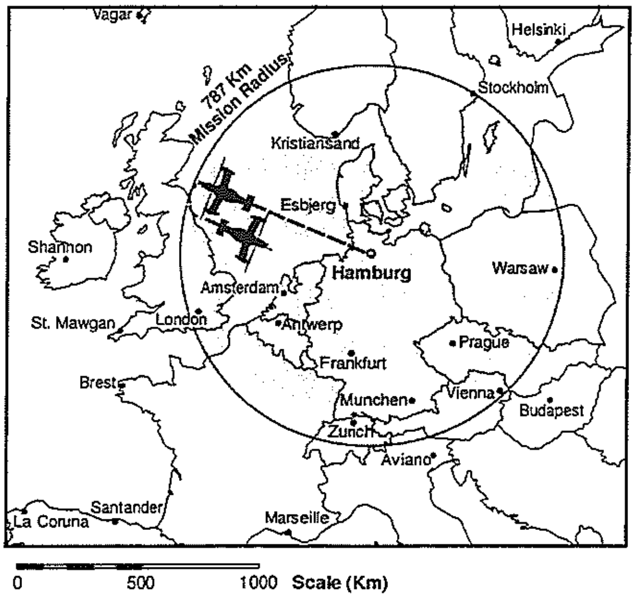

Figure 6. V-22 Osprey Search and Rescue

Design and Manufacturing Processes

Past experience indicates 80% of a product's life-cycle cost is determined by decisions made during the first 20% of the product design cycle, a fact which encouraged Bell-Boeing to adopt a new approach to designing the production V-22 which would ensure that robust decisions were made during the crucial early stages of design.

Concurrent Product Definition (CPD) includes near-simultaneous design, analysis, and planning by engineering, manufacturing, logistics support disciplines, and active participation by the customer. This leads to reduced flow times, lower procurement and operating costs, and higher quality products. The traditional, functional product development flow had organizational barriers between critical areas like engineering, planning, tool fabrication, and manufacturing. These barriers inhibited good communication during the critical engineering, manufacturing, and product support phases.

The CPD approach integrates all disciplines from the beginning of the product development process using Integrated Product Teams (IPTs), a functionally transparent management approach and a single digital data base for all product information.

Over 80 IPTs consisting of engineering, tooling, manufacturing, customer, supportability and subcontract disciplines, worked simultaneously on each part of the aircraft to ensure a balanced design. They had the authority and responsibility (including budget) for their portion of the product. At the major system level, Analysis and Integration teams (Segment A&Is) ensured consistent application of requirements by the teams with allocation and mediation of requirements across interfaces. Typical parameters that were allocated to the IPT's were weight, drag, reliability, maintainability, design-to-cost, life-cycle cost, subsystem cost, etc. Above the Segment A&Is, the Air Vehicle A&I ensured overall consistency and adjudicated conflicts. The multiple customers for the V-22 aircraft are an integral part of the A&Is and IPTs.

The tool that facilitates all IPT activities is the graphics-based CATIA™ software. It provides a single-source, computer-generated, three-dimensional definition of the total product and its individual parts. As illustrated in Figure 7, CATIA™ facilitates the cross-talk among all functional disciplines from preliminary design to product support.

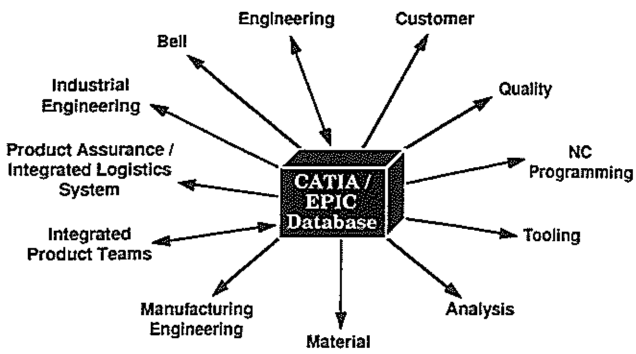

Figure 7. CATIA / IPT Processes

CATIA™ allows the creation of three-dimensional models such as the landing gear bay shown in Figure 8 (very similar to virtual reality) that permit engineers to assess designs early and eliminate the building of expensive hardware mockups. The elimination of hardware mockups (difficult to maintain in the latest configuration) saved 150,000 man-hours on the V-22 EMD program. Parts are then digitally pre-assembled to catch design errors early, when changes are least expensive, prior to fabrication.

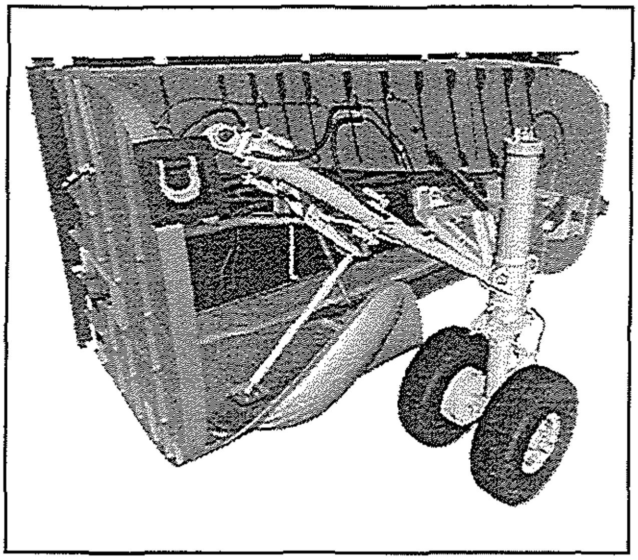

Figure 8. Landing Gear Solid Model

VERICUT, a tool for providing Numerical Control programming concurrent with product design, uses the same CATIA™ data base. The NC programmers "fabricate" their part electronically (using VERICUT) to determine cutter feeds and speeds. Once the part has been "electronically fabricated" the original design model is over-laid on the fabricated part and any areas of divergence are immediately apparent to the NC programmer who can then take appropriate corrective action.

VALISYS™, a valuable quality control software tool also tightly integrated with the CATIA™ system, provides a necessary link between engineering and manufacturing. It provides the capability to check the engineering design to verify and ensure that the geometric dimensioning and tolerances are correct to the standard, and it allows part tolerances to be represented in the three-dimensional models. Where these tolerances are critical for the assembly of detailed parts, they are labeled as key characteristics.

Since variations can occur during manufacturing, VALISYS™ performs quality checks to ensure that part integrity is maintained throughout the fabrication process. VALISYS helps design quality into not only the product, but also the manufacturing process.

Using CPD, IPTs, DPA, VERICUT, and VALISYS lowers cost and increases product quality. These benefits were validated early in the product development process and disseminated to the IPTs if corrective action was required. The result has been increased quality because individual parts are designed with producibility and ease of assembly considered from the beginning; this, in turn, permits proper manufacturing tolerances and decreased variation so parts fit correctly the first and every time. As an example, the three sections that comprise the V-22 airframe were successfully mated in one-half hour (excluding fastening). In FSD this process took several days.

Manufacturing Technologies and Systems

To develop the V-22, Bell-Boeing is incorporating some of the most technically advanced manufacturing systems available today. These systems are integral parts of the CPD process, and Bell-Boeing is investing in them to take full advantage of the cost and economic benefits they generate for military and commercial applications.

When comparing the traditional manufacturing technologies employed on the FSD V-22, to the advanced systems being used to manufacture the EMD configuration, the evolution is profound. Now, advanced machines, utilizing the CATIA database, robotically manufacture large, one-piece composite sections and high-speed-machine single-piece aluminum frames from billets for the V-22. These systems allow engineers to eliminate hundreds of parts and dedicated tooling. Four important systems being used are optical lay-up template, trim and drill cell, advanced technology assembly, and fiber placement.

Optical Lay-up Template

For flat or simple contour parts, hand lay-up using composite broad-goods is often the manufacturing process of choice. To improve the efficiency of hand lay-up, new technologies and manufacturing concepts are being used to build the V-22. Bell-Boeing has implemented a new, laser-based ply locating system called Optical Layup Template (OLT) in the composite manufacturing facility. The system combines laser technology and various optical components with data supplied by CATIA™ to project a three-dimensional image of a detail onto a contoured lay-up tool, Figure 9. This three-dimensional capability means the laser line will conform to ply lay-up surfaces, thus eliminating the need for labor-intensive locating templates previously needed to fabricate composite parts. Coupling OLT with CATIA™ allows changes to engineering designs to be made instantaneously with no need to fabricate new templates. Reduced template fabrication results in major savings in the cost of producing storing and maintaining expensive templates.

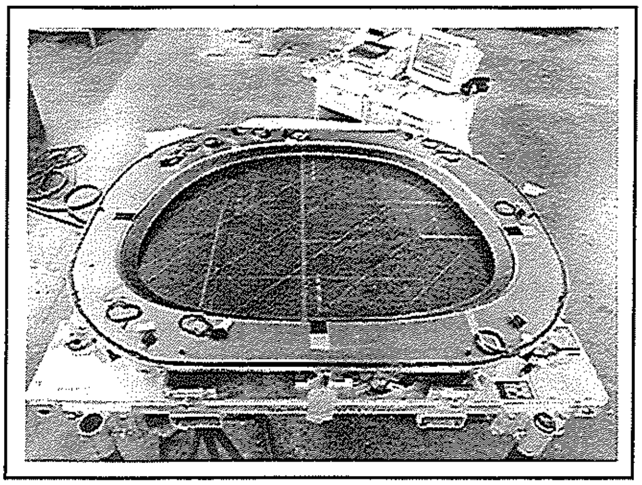

Figure 9. Optical Layup Tool

Trim and Drill Cell

The Trim and Drill Cell combines the latest technologies in locating, fixturing, trimming and inspecting composite parts. Parts are located in the cell utilizing a universal holding fixture that is programmed from data downloaded from CATIA™ to match the part contour. This process has eliminated the need for individual trim templates for every part, reducing non-recurring tooling costs and recurring tool maintenance costs. The parts are trimmed utilizing an abrasive water jet system, a very high velocity water stream with abrasive particles. The cell then installs locating and tooling holes utilizing a precision drilling head and inspects the parts before it is removed. By combining the direct use of the single source digital data and the repeatability of an automated machine tool, recurring costs are reduced and product quality is significantly improved while reducing variability.

Advanced Technology Assembly

Advanced Technology Assembly (ATA) is another process being used in manufacturing to support the CPD process. ATA is used to precisely locate machine drilled holes in aircraft parts that are subsequently used to assemble the detail parts. The application of this process is made possible through the use of the single source 3D CATIA™ data base. Early in the design process the manufacturing engineers and tool designers determine the location of these coordination holes. These holes are then firmly fixed in the engineering 3D dataset to ensure coordination throughout the design and fabrication process. The application of this technology significantly reduces the non-recurring tooling required for assembly tooling as the part is its own tool. This again eliminates the recurring cost to maintain and modify these tools downstream.

Fiber Tow Placement

Fiber tow placement technology is an important part of the effort to reduce V-22 cost and cycle time while improving quality. Fiber tow placement provides the means to automate the lay-up of composite materials in complex convex and concave surfaces while maintaining precise quality standards. Fiber tow placement eliminates the need to create sheets of composite material, cutting them to size, and laying them up on a tool by hand. A fiber tow placement machine in Figure 10 creates a ply from strands of one-eighth inch-wide fiber tape, or tows, as the tape is laid up on the tool.

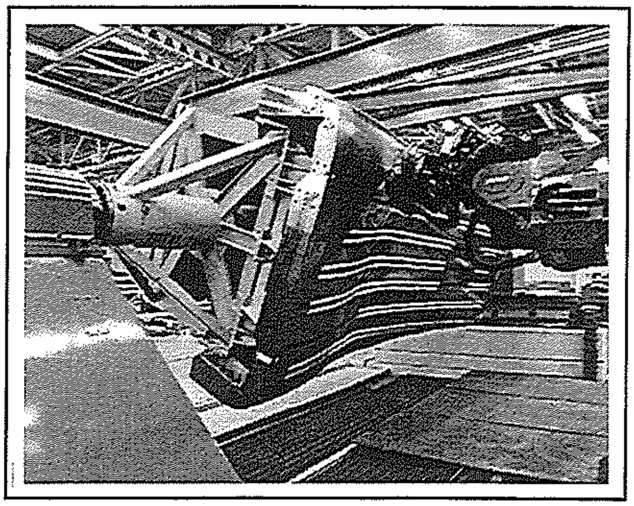

Figure 10. Fiber Placement of Aft Fuselage

This system is an important part of the CPD process using 3D digital data to perform its assigned tasks. The fiber placement system, coupled with CATIA™ capabilities, has changed the way V-22 composite parts are built. These types of capabilities equate to significant savings in labor. For example, 70% reductions in trim and assembly labor and 50% in composite manufacturing labor have been achieved.

Significant Improvements From FSD To EMD

There are many success stories in all facets of the EMD design and manufacturing. We will describe a few in this section and show some appropriate improvement metrics.

- Weight reduction
- Design to cost (DTC) reduction
- Wing stow system redesign
- Aft fuselage section redesign
- Aircraft fuselage redesign
- Aluminum frame high speed machining
- Rejection reports
- Integrated testing

Weight Reduction

At the end of the FSD program, the weight empty of the V-22 aircraft had grown to almost 35,000 pounds. At the beginning of the EMD design phase the data bank of weight reduction ideas left over from the FSD phase was distributed to the IPTs and used in the design effort to drive the weight down by 2828 pounds. This resulted in a weight empty of 32,105 pounds in January 1993 (Figure 11), just after EMD contract award. As of May 1997 , over four years later, the status weight is 32,102 pounds. The weight empty is expected to be under the specification weight empty of 33,140 pounds at the end of OPEVAL. All performance predictions and guarantees have been made at the higher weight for conservatism.

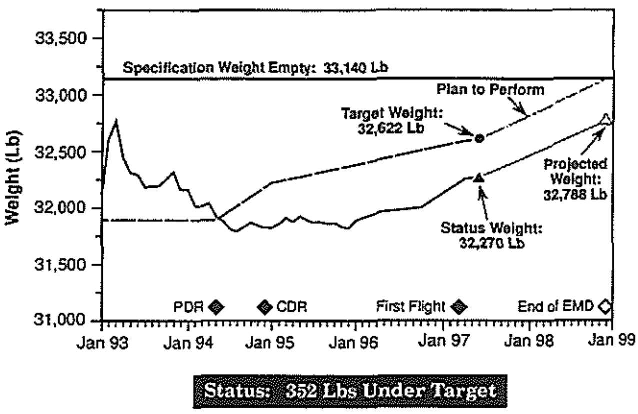

Figure 11. Weight Empty History

Design-to-Cost Reduction

The changes that were made to the FSD design and manufacturing processes were also instrumental in reducing the unit cost. Figure 12 shows a steady decrease from $41M in January 1993 to the present $32.2M, a decrease of 23%. The $32.2M cost can be reduced further by up to $4.1M per unit by including currently identified Cost Reduction Initiatives (CRIs) and Producibility Improvement Plans (PIPs), and programmatic initiatives such as multi-year procurement. If the total package of identified initiatives is implemented the total unit cost reduction from FSD can be as high as 33%.

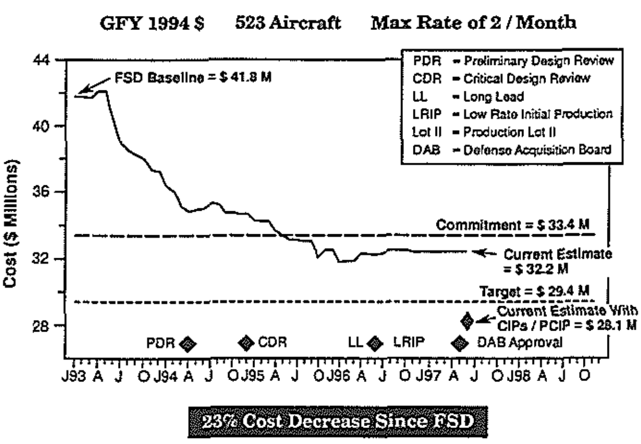

Figure 12. Recurring Flyaway Cost Estimate

Wing Stow System

To minimize aircraft spotting factor and minimize readiness time (when aircraft are brought to the flight deck from hangar deck storage) the V-22 was required to automatically fold into a compact size in 90 seconds. The folded aircraft is shown on the side elevator of an LHD in Figure 13.

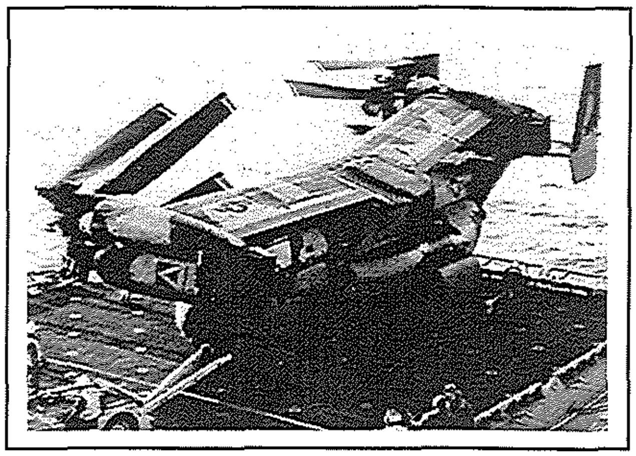

Figure 13. Folded Aircraft

By redesigning the FSD wing folding system the weight was reduced by 300 pounds and the cost by $200,000 per aircraft. Also the system is now easier to install and access to components under the wing is greatly enhanced.

Aft Fuselage Section

The FSD aft fuselage, from the rear ramp hinge to the attachment of the empennage, was designed to combine 9 hand lay-up skin panels and 157 stiffeners.

During the EMD redesign for producibility the skin thickness and stringer/frame placement was thoroughly examined to optimize the use of the fiber placement equipment. The result is a one piece fiber placed skin with 17 cocured continuous stringers and a total cost reduction of 53%.

Aircraft Fuselage Redesign

A summary of the significant cost drivers, parts count and fastener count, for the forward, center, and aft fuselage sections are shown in Figure 14. In both cases

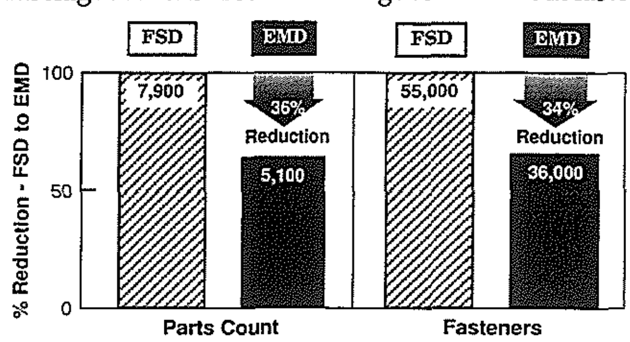

Figure 14. Fuselage Modules - Parts Count and Fastener Reductions

the reduction from the FSD design to EMD is about one-third. For fasteners this reduction has a profound effect on cost because each fastener needs to be procured, the hole must be located, drilled and inspected, and the assembly inspected again after fastener insertion and tightening.

Aluminum Frame High Speed Machining

One of the most significant early design decisions in EMD was the granting of authority to the IPTs to optimize materials use. During FSD the whole primary structure was designed in graphite composites. In EMD most of the complex frames were produced by high-speed machining of aluminum. The results were extremely favorable, as shown on Figure 15. Not only were part count (39 to 1), fastener count (258 to 0) and tool count (46 to 2) reduced with an attendant reduction in cost of 37.5%, surprisingly, the weight of the part was also reduced from the all-composite unit by 18%. This indicates that a very careful choice of materials and design must be made to achieve the optimum solution.

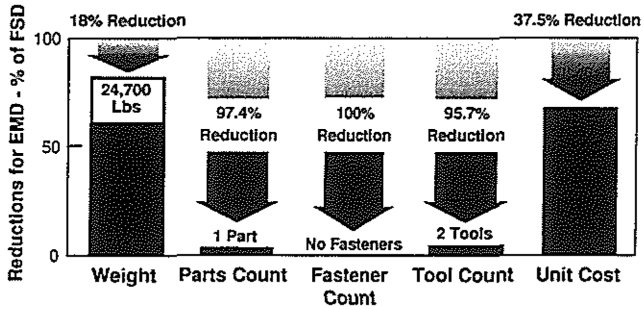

Figure 15. Aluminum Frame High-Speed Machining

Rejection Reports

As a visual summary of the concepts discussed earlier, Figure 16 shows that Rejection Reports, a metric of the problems encountered in the manufacture and assembly phases, have been reduced by 60% from FSD to EMD.

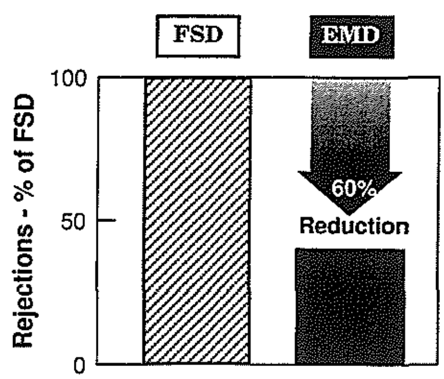

Figure 16. V-22 Rejection Reports - FSD to EMD

This means less scrap, less rework, less handling of parts, less shortages, less out of sequence installs, and translates directly into less unit cost in production.

Integrated Testing

In February of 1993, the US Navy's V-22 Osprey Program Management Team established a new way of managing its flight test program based on the Air force Combined Test Force concept.

The ITT is an IPT within a much larger IPT organization that includes design and manufacturing as well as flight test. From the beginning, government and contractor managers agreed that the best way to make the ITT concept work was to truly integrate all personnel by physically locating them side-by-side. No one was excepted. Pilots, engineers, managers, and maintainers were all co-located to maximize interaction, communication and awareness of potential changes.

The Flight Test Review Board (FTRB) is a major success for the ITT. The premise behind the FTRB was to reduce, or eliminate the need for deficiency reports because they are written too late in the acquisition process. At the Board all "squawks" are reviewed and defended by the author to ensure adequate justification existed for generating the "squawk", if so, the "squawks" are handed to Bell-Boeing representatives for correction and/or disposition.

During EMD an integrated customer Development Test/Operational Test (DT/OT) effort is planned. This means that the OT personnel will form a detachment to work closely with the DT personnel. Even with the operational testers participating in DT they will still conduct an independent OT and operational evaluation (OPEVAL). It is expected that the familiarity they gained during DT participation will reduce the need for proficiency flying prior to their dedicated operational test periods.

Concluding Remarks

The V-22 is an extremely capable and uniquely versatile vehicle that has developed and incorporated many new and exciting technologies. These include design and manufacturing processes, as well as innovative new analysis and test methods. The V-22 team is looking forward to the MV, CV and other exciting derivatives reaching their operational units. We expect that the aircraft will be equally useful to US friends and allies.