Successful Composites Technology Transfer

Applying NASA Innovations to Industry

George N. Bullen

with Foreword by Timothy Shinbara

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This book is dedicated to an incredible group of people at NASA and Northrop Grumman Corporation who took the risks necessary to advance the way we design, develop, make, and assemble space vehicles. It was an honor and once-in-a-lifetime experience to be part of the team.

For MLAS, the risks were compounded by an extremely compressed schedule for a one-off prototype vehicle that had one shot at success when completed. But its successful launch was not the end. The project initiated and invigorated a look at heretofore unthought of manufacturing processes, technologies, and materials for application on space vehicles with extensibility into a wide array of parts and products in other industries.

ABOUT THE AUTHOR

George N. Bullen is an internationally recognized expert and consultant to industry for the manufacture of fixed and rotary wing air vehicles, rockets, missiles, and space vehicles. His expertise includes inhabited and uninhabited aerial vehicles, space vehicle design and manufacture, laser weapon system design and manufacture, and lean processes and applications. He has been awarded 16 U.S. and international patents for technology innovations related to manufacturing, mechanization, robotics, robotics control software, and nuclear testing/quality devices, which are the basis for all current automated systems for the assembly of airframes in the U.S. and Europe.

A Fellow of the Society of Manufacturing Engineers (FSME) and Certified in Production and Inventory Control Management (CPIM), George Bullen has an MBA from Loyola Marymount University and a BSMG degree from Pepperdine University. He maintains membership on the academic boards of major universities and is a member of the steering committees of professional societies. George is founder of the International Aerospace Automation Consortium and co-founder of the international Design, Manufacturing and Economics of Composites Symposium. He is widely published in magazines, conference proceedings, and peer-review journals. In 2014 he received SAE International's Forest McFarland Award, and in 2000 the American Institute of Aeronautics and Astronautics (AIAA) Design Engineering Award for significant advances in aerospace engineering.

PREFACE

This book describes the innovative technologies and processes derived from the highly successful Max Launch Abort System (MLAS) program at NASA. It looks toward the impact that the revolutionary technologies and processes will have on other manufactured products. The MLAS project system's design, manufacturing technologies, and processes are extensible beyond space launch vehicle prototypes, with the capability to enhance other products while minimizing impact to existing systems. In many cases, the extension of the MLAS manufacturing technologies and processes to other products would take minimal effort. Some applications would simply add new functionality or modifications to existing functionality. Several examples of the extensible technology are rapid prototyping; the digital tapestry; forensic engineering analysis; out-of-autoclave cure (OAC); low-cost, vacuum-assisted resin transfer molding (VARTM); and rapid precision assembly (determinant assembly).

Of course, the natural extensibility is to space and aerospace products. But two unrelated aerospace extensions are automobiles and wind turbines. Automobile manufacturers have long seen the advantages of composite materials that add strength and reduce weight. The application of high-strength composites has been restricted to expensive performance automobiles such as Lamborghini due to the high manufacturing cost and slow process times. Wind turbine blades have grown beyond the ability of current fiberglass-over-wood construction to sustain the stresses and environments needed to generate power. The same manufacturing cost and process time inhibitors have prevented wind turbine blade producers from taking advantage of the light weight and high-strength properties of composite materials. The discussions in this book talk about these products and many more—both similar and dissimilar.

The rapid design, development, manufacture, and launch of the MLAS vehicle using geographically diverse "best athletes" combined to produce a complex vehicle in a short time. Documenting these best-in-class processes and technology in *Successful Composites Technology Transfer* will provide a building block for use by other product types across a number of industries.

FOREWORD

A lens by any other name…I first met George “Nick” Bullen at the SME’s Aerospace Automation Consortium event in Dearborn, Michigan. I was a student at Purdue University, only weeks into my graduate studies. Little did I know the impact attending that event and sitting with Nick for dinner at the Henry Ford Museum would have on my professional development, personal growth, and career path as a technologist, engineer, and entrepreneur. It would be a few years later that the Max Launch Abort System (MLAS) would become a blip on my radar, providing another lens by which I view manufacturing technology development.

The MLAS effort incorporated technologies that have a more pervasive impact in other industries than first thought. While the concept of embedding sensors for in-situ data acquisition is not novel, what is described in this book are the advancements of communicating in real-time and acquiring information in support of actionable data-driven autonomy. Such capabilities are the enablers for utilizing the digital thread throughout not only manufacturing and its supply chain, but to analyze the entire product life cycle.

The MLAS experience accelerated developments within manufacturing technologies and processes. For instance, further investigation of part-process monitoring motivated applied research to integrate acquired data back into the manufacturing process in support of in-situ monitoring.

This book is the collection of experiences, both technical and business-related. It is about being adaptive as a strategy, and about rapidly integrating technology development into production as a tactic.

Manufacturing is the discipline that breeds innovation by necessity. President Kennedy shot for the Moon and innovation by-products flourished in the United States. In the same vein, MLAS melded disparate industries' expertise and focused on digital tools, system integration, and affordability to advance extraterrestrial exploration. This book chronicles an embodiment of innovation, which some call *smart manufacturing*, by exploiting digital manufacturing to realize the U.S. return to manned space ventures.

Smart manufacturing and digital manufacturing have been labeled as "the evolving descriptors for business and operational application [of such innovation]" (National Science Foundation [NSF], Smart Manufacturing Leadership Coalition [SMLC] 2014). The President's Council of Advisors on Science and Technology (PCAST) Steering Committee, Advanced Manufacturing Partnership (AMP) 2.0, created the *Accelerating U.S. Advanced Manufacturing* report. It suggests that a key to U.S. manufacturing competitiveness is integrating approaches with digital data. Well before the PCAST ever convened and the AMP 2.0 report was ever published, the MLAS team was well on its way to exercising such guidance as a means by which to achieve a lofty goal; out of necessity, it just made sense to do so.

PCAST contextualizes smart manufacturing as encompassing advanced sensing, control, and platforms for the manufacturing value chain while *digital manufacturing* encompasses data visualization, informatics, and the digital manufacturing technologies themselves. In other words, smart manufacturing includes the things that capture, connect, and manage digital data; digital manufacturing then utilizes those products to analyze, optimize, and act upon the data to make better informed manufacturing decisions. The advancements discussed in this book take these concepts to the next level, explaining how the digital thread extends beyond just a computer-aided design (CAD) model, by employing rapid prototyping-to-production elements and forensic engineering analytics.

MLAS encouraged a multi-faceted approach where each facet provided a perspective not wholly sufficient for the problem, but critically important to the solution. It is through mentorship by Nick Bullen (both professionally and personally) that I employ such a tool set in my own entrepreneurial venture; in the process realizing another extension of the MLAS program achievements. My business endeavors led me into (in certain respects *back into*) the supply chain world.

Supply chain management is well-known as an application landscape for optimization algorithms and methodologies in industries like transportation and energy. Considerations such as route optimization, resource availability, and genealogy are dependent upon information garnered from discrete data. For example, embedding temperature-sensing capabilities at the product/pallet /container level greatly increases supply chain visibility and yields a critical data point for certificates of conformance. As an entrepreneur, I have had the opportunity to develop devices that provide such traceable, recordable, and easily transferrable certificate of conformance information. The very same traceability, genealogy, and data collection requirements were present during the MLAS manufacturing life cycle. In fact, tremendous value was gained by understanding the impact fault tolerance of large composite structures. Information on acoustic and vibration events occurring at the surface was collected to assist in final product integrity assurance.

The justification to motivate increased technology transfer from government-funded evolutions, such as MLAS, to potential commercial, free-marketplace opportunities comes from a personal, albeit trivial, observation. The U.S. Department of Commerce has reported that each $1 invested in manufacturing generates $1.32 for the national economy. A 32% return on investment is compelling enough to further consider ways in which the government may accelerate the technology transfer opportunities of projects like MLAS.

Knowledge gained...now what? It is challenging to transfer knowledge effectively as its packaging and dissemination often have a half-life, an attenuation in quality, if you will. AMT–The Association for Manufacturing Technology clearly understands this as a member-based company serving its members, partners, and other stakeholders. Information can be captured and presented but it rarely retains as high a level of fidelity and relevance as when directly communicated one-on-one. So how do you overcome such a challenge? This book provides such an opportunity. It is a succinct reference with a backstory; it provides context and knowledge so as not to reinvent the wheel or leave the reader thinking he is an island in his development process. I have recognized benefits to such documentation because the data is now more structured and discoverable. If knowledge is chronicled and cataloged, then it is the innovator who finds and uses that knowledge who is critical to society. Albert Einstein said as much when he compared knowledge to imagination: "Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world [stimulating progress, giving birth to evolution]" ("What Life Means to Einstein," *Saturday Evening Post*, October 26, 1929).

As manufacturing technologies, processes, and methodologies evolve over time, it is of considerable value to search out, discover, and digest resources such as this book in an effort to continually improve the lens by which we innovate. It is for this reason that I both appreciate and encourage lifelong mentorship, the capturing and transfer of knowledge, and the Moon shot goals that breed innovation.

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March 8, 2015

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INTRODUCTION

> *"You don't concentrate on risks. You concentrate on results. No risk is too great to prevent the necessary job from getting done."*
>
> —Chuck Yeager

This book is about the Max Launch Abort System (MLAS) manufacturing journey and how it has affected the spread of composites use. It is also about the composites and process technologies' extensibility into other types of applications such as road vehicles, sports equipment, ships, and wind turbine towers and blades.

MLAS PROJECT BACKGROUND

Conducted at the NASA Engineering and Safety Center (NESC), the MLAS project had the goal of demonstrating the feasibility of an alternate launch abort system design as risk mitigation for the crew exploration vehicle (CEV) launch abort system (LAS). The MLAS project concept was to encapsulate the crew module within an aerodynamic fairing, and move the launch abort propulsion system from a tower pulling the crew module, to multiple side-mounted motors pushing the encapsulated service module fairing. A sketch of the concept is shown in Figure 1-1. Consisting of four rocket motors built into the fairing that encloses an Orion module, MLAS is designed to pull the crew away from the main rocket stack during the critical first 2.5 minutes of flight in the event of a catastrophic failure. Invented by Maxime (Max) Faget, the advantage of the MLAS system over the more traditional system is that it reduces the total height of the rocket, lowering its center of gravity, adding stability, and allowing potentially higher fuel load.

The successful launch of MLAS shown in Figure 1-2 was characterized by more than the operation of the vehicle and its systems.

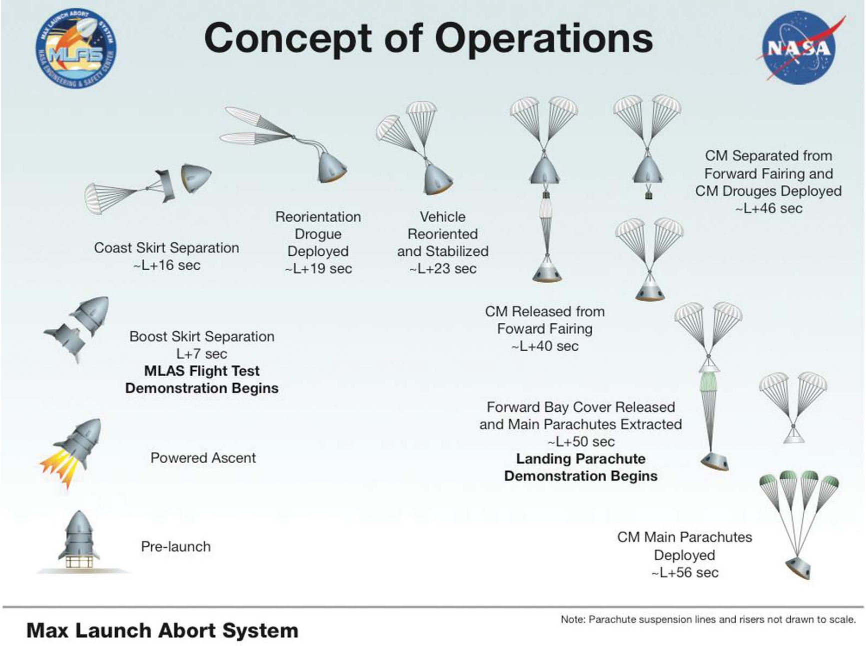

Figure 1-1. MLAS concept. (Courtesy NASA)

A team approach was used to resolve technical problems. Embedded in the system were manufacturing technologies and materials never before used to fabricate a launch vehicle. They included liquid resin infusion using ship construction technology, personnel, and facilities; out-of-autoclave cure of autoclave composite materials in portable facilities; and hand filament winding of composites over paraplast washout mandrels. The use of these innovative manufacturing processes and materials came with risk. But supported by their successful application on MLAS, they are now included as lower-cost options for the fabrication and assembly of space launch vehicles. They meet the precise specifications and strength requirements that these vehicles demand.

CONCEPT DEVELOPMENT

A concept of operations for the MLAS began with pyrotechnic separation of the service module fairing from the ARES I spacecraft

Figure 1-2. Successful launch of MLAS on July 8, 2009. (Courtesy NASA)

adaptor. The primary structure and components of the service module were to remain with the ARES I vehicle. The service module fairing with side-mounted motors was to propel the crew module and associated fairing. The launch abort vehicle would travel on an appropriate down-range trajectory until the crew module and fairing were at sufficient altitude for reorientation. Prior to the reorientation, the service (boost and coast skirts) module fairings would be discarded and the crew module and fairing rotated so that the crew module heat-shield was in the direction of the velocity vector. A drogue or chute then would deploy from the crew module fairing so that the crew module could separate, and the crew module nominal landing systems would be in recovery condition (see Figure 1-1).

The basic emphasis and objective of the MLAS project was to manage the trajectory and the crew module orientation to enable deployment of the crew module landing system. Both active and passive control systems were considered. A passive system was selected. Therefore, the mass properties of the combined components became a critical component for success during the manufacture and assembly of the vehicle.

The MLAS project development and manufacturing approach was organized around technical disciplines that included structures, propulsion, guidance navigation and control, avionics and instrumentation, software, and systems engineering and integration. The project approach was to fast track the design and build effort of the MLAS so that the MLAS test occurred concurrently with the Orion Launch Abort flight testing, scheduled to occur in September 2008. To minimize resource and scheduling conflicts, MLAS used the Wallops Flight Facility for the flight testing, while Orion secured the White Sands Missile Range for testing.

To achieve the aggressive development and manufacturing schedule, MLAS maximized the use of currently available hardware designs and components. Concurrently, NESC had a separate project underway to design and build a composite crew module. Some elements of the composite crew module were incorporated into the MLAS project, in particular, the application of high-strength carbon-fiber composites as an alternative to traditional aluminum.

The development of MLAS required the application of flexible, innovative, and adaptive design, fabrication, and assembly technologies and personnel to accomplish the aggressive schedule and performance criteria. New approaches to existing technology and program management were necessary. The development of MLAS also included the rapid development and use of highly efficient project management tools for design and manufacturing. The rapidly developed, one-off, flight test vehicle required fast and affordable manufacturing processes.

The aggressive schedule and cost constraints for the MLAS program resulted in a unique combination of materials, fabrication, and structural concepts for the MLAS fairing shell. The

18-ft (5.5-m) diameter, 33-ft (10-m) long primary shell structure was composed of large fiberglass sandwich panels cured using the vacuum-assisted resin transfer molding (VARTM) process. Higher-strength, aerospace-grade graphite/epoxy materials were used for stiffness or weight-critical items including external stability fins and motor-cage-strut structures.

Innovation, when coupled with being fast and affordable, entails risk. During development of the MLAS, errors were made. But this also was the genesis for creating the innovative forensic engineering techniques needed to rapidly assess, identify, and determine corrective actions.

LAUNCH TEST

On July 8, 2009, the earth shook as four Thiokol solid rocket motors ignited, propelling a 48,000-lb (≈21,000-kg), bullet-shaped vehicle up and away from its launch pad. Figure 1-3 shows the MLAS test vehicle leaving the launch pad at Wallops Island, Va.

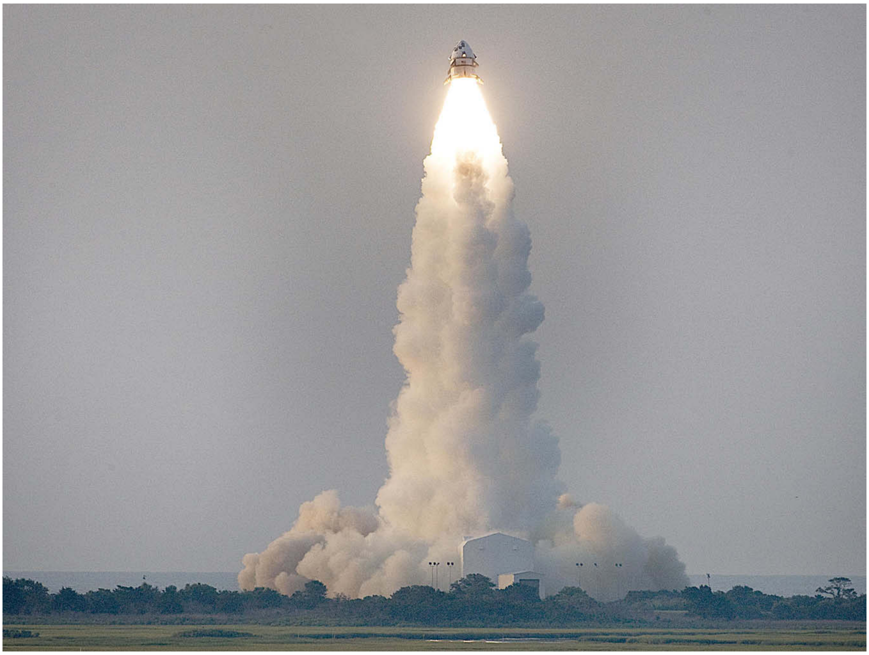

Figure 1-3. MLAS test vehicle launch. (Courtesy NASA)

Approximately seven seconds later, the engines stopped and the vehicle silently coasted upward as the boost skirt drawn by gravity fell away toward Earth ≈7,000 ft (≈2,000 m) below. As the vehicle coasted skyward in a sequence of events separated by seconds, the coast skirt separated and deployed parachutes, the forward fairings fell away, and the crew capsule deployed its parachutes and began its decent toward Earth. The flight test performed at the North American Space Administration's (NASA's) Wallops Island Flight Facility in Virginia was a flawless performance. The MLAS test vehicle components, shown in Figure 1-4, weighed over 45,000 lb (≈20,000 kg) and it was over 33 ft (10 m) tall.

About 3-1/2 months later, if you were to drive 850 miles (1,368 km) down the coast to the Kennedy Space Center in Florida, the ground would shake again. This time, a solid rocket motor of the type formerly used on the space shuttle would ignite, sending an ARES I-X rocket skyward (see Figure 1-5).

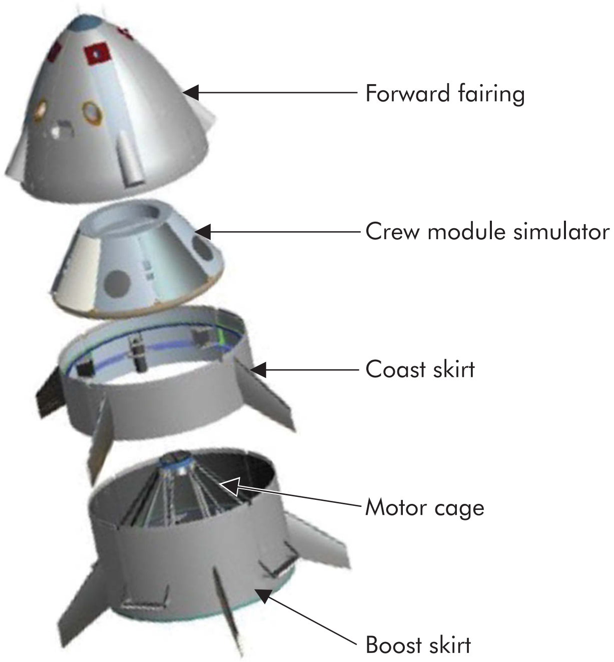

Figure 1-4. MLAS test vehicle components.

Figure 1-5. The ARES I-X lifting off from its pad on October 28, 2009. (Courtesy NASA)

As the rocket lifted and gained speed, the thrust of the motor pushed against the upper section it was carrying, accelerating the vehicle past mach 2. Tremendous load transferred into the frustum and inter-stage connecting the solid rocket motor to the upper section that held the fuel and payload. The successful launch was the first test for the ARES I design that was to become the vehicle to carry a human payload into space as part of the Constellation Program. The human payload would be housed in the Orion spacecraft.

INNOVATIVE APPLICATIONS OF COMPOSITE MATERIALS

Successful launches are not unusual for NASA. What was unusual was the use of composites to replace structural components. The ARES I-X used composites for the critical frustum and inter-stage that connected the solid rocket motor to the upper section of the vehicle.

The MLAS structure was composed of over 90% composites material fabricated using innovative tooling, technologies, and processes produced at geographically diverse locations. All of the pieces and components were shipped to Wallops Island, Va. for assembly.

The application of high-strength composites materials has been resisted by NASA and other space launch and crew vehicle manufacturers for many reasons, one of which is cost. By its nature, the space launch business is composed of high risk, single opportunity, and thus very expensive events. Aluminum has been the material of choice for structure on launch vehicles since Germany's V2 rocket of World War II. Aluminum materials have continuously improved since World War II and the manufacturing methods for large space launch vehicle components have grown with the material improvements. Aluminum is light and inexpensive to buy and use when compared to composites. Aluminum materials' design and strength properties are well understood.

When a space launch vehicle lifts off, years of time and money have been spent to arrive at that precise moment. The world watches as a rare event lifts highly complex and expensive equipment and sometimes humans into space. A failure is at minimum publically embarrassing and expensive. When it lifts human cargo, it also has the potential to be deadly. The risk of highly expensive and publically performed events drives the philosophy of "go with what you know." A dramatic example of material failure was the space shuttle disaster when Challenger broke apart 73 seconds into its flight on January 28, 1986 (see Figure 1-6). The spacecraft disintegrated over the Atlantic Ocean off the coast of central Florida killing all seven crew members (Adams 2011). NASA carried on using aluminum for all of its vehicles as high-strength, carbon-fiber composite materials emerged into use for airplanes, helicopters, and missiles in the 1980s. Composite materials were not ready for use on space vehicles when the space shuttle was being designed and fielded.

When the ARES I-X lifted off from the launch pad 28 years after the first shuttle launch, it incorporated high-strength, carbon-fiber composites in replacement of the aluminum. This material change saved ≈1,400 lb (635 kg), which may not seem like much when compared to the 1.8 million lb (816,480 kg) total weight of the ARES I-X space launch vehicle, but it was. The approximate payload of the ARES I is 55,000 lb (≈25,000 kg) when sending it 217.5 miles (350 km) above the Earth (Brian 2012). Without the weight savings, the aggregate payload lift capacity would be reduced by 1,400 lb (635 kg), which could be used for valuable payload.

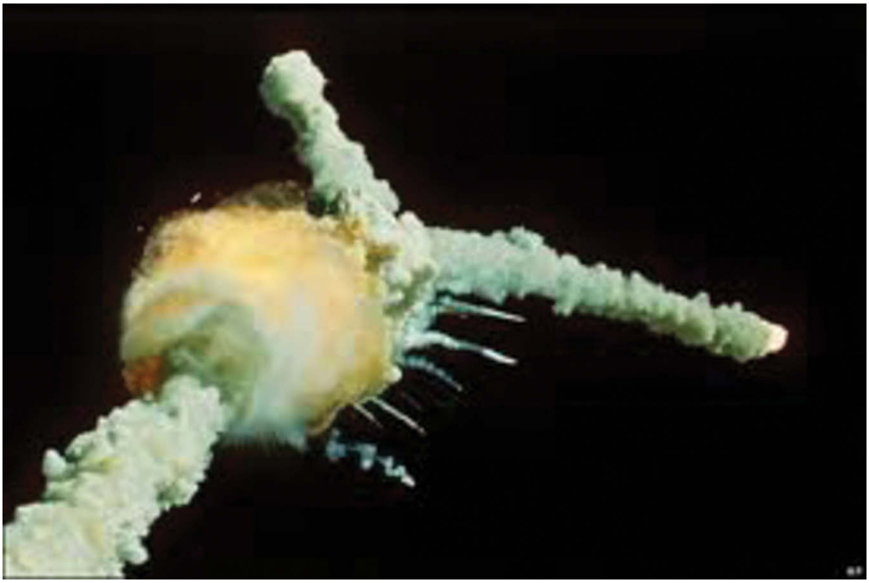

Figure 1-6. The space shuttle Challenger as it disintegrated off the coast of Florida. (Courtesy NASA)

The decision by NASA engineers to incorporate composites into the design of the new launch vehicle was the result of opportunity. The space shuttle had been the heavy lift space launch vehicle for NASA, the United States, and Europe since Columbia was successfully launched on April 12, 1981. President Bush decided to retire the shuttle orbiter fleet by 2010 in favor of the Constellation program that included the ARES I (Allbritton et al. 2013). Thus the opportunity presented itself to NASA to incorporate composite material and leverage the evolution and understanding of the material in the new program. The risk had abated for composite material use for space vehicle structures, but not the cost of manufacturing parts with the material.

Composite Parts Manufacture

The contributors to the cost of manufacturing composite parts are equipment, material, tooling, and processes. The attributes that made composites increasingly attractive for replacing metal parts on air vehicles are also attractive for space vehicles. However, the cost inhibitors for using composite materials are magnified due to the size of space vehicles.

Autoclave Curing

A prime cost consideration for curing aerospace-grade composite materials is the autoclave. Viewed as a necessary but expensive requirement, it is one piece of manufacturing equipment that has complemented the use of composite materials in the composition of modern airframes. As composites have increasingly replaced metal parts, the size and quantity of autoclaves have increased. Today, 20-ft (6.1 m) or even 25-ft (7.6-m) diameter autoclaves, 30–40 ft (9.1–12.2 m) long, dominate the shop floors of factories where composite parts are made for aerospace products. However, because of the size of the parts required for space launch vehicles, new mother-of-all-autoclaves would have to be built, installed, and operated to accommodate their girth.

Besides compaction, consolidation, and cure, autoclaves serve a primary purpose that cannot be provided by other pieces of equipment. They act as large pressure cookers. The autoclave's massive doors are closed and it is pressurized to above the normal boiling point of the water contained in the composite materials but below the resin's cure temperature. If the moisture was not held below boiling during the heat-up process, the part would be ruined.

Out-of-autoclave Cure (OAC)

In recognition of the autoclave's dominance as the prime contributor to the cost and efficient manufacture of composite parts, governments and industry began the drive to find alternatives to autoclave curing of composites. The focus took two approaches for out-of-autoclave cure (OAC) of composites. One approach was OAC of composite materials specifically made to be cured in the autoclave. The other was to advance and mature materials meant to be cured out of the autoclave.

Processes such as vacuum-assisted resin transfer molding (VARTM) have been increasingly used for applications such as ship components and wind turbine blades. However, the VARTM materials and process are not capable of producing parts with the strength and durability properties required for aerospace applications.

Finding an OAC process that yields aerospace-grade composite parts has many benefits besides elimination of the costs associated with buying and operating an autoclave. One advantage is flexibility and facility reconfiguration for production optimization. Autoclaves are fixed-in-place assets once installed and defy attempts to move them or the work they facilitate. Also, without the autoclave, a large barrier to entry for smaller shops would be removed, opening up opportunities for low-cost suppliers who cannot afford them.

In many ways other than size, space vehicle parts are ideal for OAC.

- Space vehicles differ from their airplane, helicopter, and missile counterparts who fly through and maneuver in the atmosphere and perform tasks repeatedly over a long life. An air vehicle's outer surface is tooled smooth to help enable airflow over the surface and minimize drag. Space vehicles race to escape the constraints of the atmosphere and perform very few maneuvers before being discarded as single-use components. This enables the consideration of many OAC composites manufacturing technologies that would not be acceptable for reusable atmospheric-type air vehicles.

- Space vehicle parts make no pretense about finite aerodynamic finish requirements. Therefore, tooling to the inside of the part is possible. Mandrels can be made to the inner mold line (IML) of parts rather than the outer mold line (OML). Encapsulating a part in a mold creates difficulties on a part made for an atmospherically operated vehicle. However, for space vehicles, with the mandrel inside the part, the mandrel is easier to remove and less complex.
- Space vehicle parts are cylindrical. The aerodynamic characteristics of their atmospheric vehicle counterparts are designed for efficient flight through air and have more complex shapes. Complex shapes add difficulty to the manufacturing process.
- Space launch vehicles (for the most part) are single-use items. They are disposable. Airplane and helicopter parts are designed to withstand the rigors of repetitive cycles and a broad range of stresses.

All of these differences contribute to the attractiveness of OAC for space vehicles.

USE OF TECHNOLOGY

The looming challenge to using any type of composites in space vehicles is the size of parts. One option is to break the parts down into manageable sizes. But the problem with segmenting a unified structure is it adds weight due to the hardware necessary to join it together; there is more manufacturing complexity and cost due to the added assembly effort; and assembling parts together that otherwise could be made as a unified structure incurs a strength knockdown penalty. Many of these problems were addressed within the processes and technology used to fabricate and assemble the MLAS vehicle. Many more grew out of MLAS and its lessons learned. The successful application of OAC processes invigorated other activities such as in-situ manufacture of large space structures, unified structures, composite cryo-tanks, and composite crew modules and vehicles.

Many of the technologies described here are not new. What is new is how they are adapted to provide high-quality parts using *unconventional approaches* to manufacturing and assembly. The types of disruptive technology that have emerged as viable for producing aerospace parts are the result of MLAS and the other projects associated with Project Constellation. They have enabled manufacture of the composite cyro-tank, inter-stage, fulcrum, and crew module.

The Digital Thread

The core technology, which allowed the MLAS program to utilize new technologies and parts fabricated and assembled at geographically diverse locations by unconventional tools and methods, was the digital thread. It banded together teams across the country, promoting a new view of interoperability. Common data and standards united design, manufacturing, and final assembly along one common digital thread. The phrase *digital thread* was originally coined as a way to describe using 3D computer-aided design (CAD) data to directly feed computer numerically controlled (CNC) machining of parts, or a composite programming system to create a plan for carbon fiber placement. In both cases, the finished product can be traced back to the original computer model; the unbroken data link is the digital thread.

The digital thread united team members across many technology areas: 3D CAD, product life cycle management (PLM), enterprise resource management (ERP), supply chain management, manufacturing execution systems (MES), and others. A common data exchange format structure was used with common interfaces. Plug-and-play connectivity provided the data producers and data consumers with a link to a common data source at any point in the manufacturing process. The data standard and protocols were established and rooted at the design phase, extended through manufacturing, and continued through to final assembly.

Efficiency was realized by avoiding the redundancy of recreating a centralized data team. Another benefit was minimizing the use of hard tooling, which contributes to cost and schedule inflation. Critical subassemblies and the final assembly came together in exact true positioning at the required tolerances, aligned without gaged assembly tools. The same digital datum was employed within the numerical control system, positioning equipment, and alignment systems.

The digital thread also had an impact on the MLAS supply chain. It sped up the transfer of data—suppliers could pull up the same model out of the commonly shared design database. When changes occurred, information was immediately available in a physics-based exact solid model. Thus suppliers did not have to re-interpret surfaces and data they employed in their manufacturing processes. With the digital thread, design and manufacturing transfer time was greatly improved. The processes of sending out new drawings and having the drawing checkers go through each change were eliminated. Engineering notes digitally identified modifications and unchanged elements of the design or manufacturing plan.

Emerging advances in communication technology were also advantageous in the digital thread, such as interactive design and collaboration, 3D holographic images, smart phone applications for visual work instructions, radio-frequency identification (RFID), and geospatial location for earned value management and progress assessment.

The MLAS program's rapid prototyping approach to a flight vehicle came with risk. The nature of the project required that any defect or failure have its root cause determined quickly. It was important to take immediate corrective action and repair or replace the defective parts, and with minimal or no impact to schedule. One of the unseen benefits of the digital thread was its use for objective analysis of part failure to determine cause and corrective action. (An example of the use of the digital thread to perform forensic engineering on complex parts is provided in Chapter 6.)

Vacuum-assisted Resin Transfer Molding (VARTM)

It is important to note that there were assumptions made by the MLAS team that certain technologies employed in dissimilar industries using the same processes, controls, and methods would result in the same product quality. The MLAS team decided to use the shipbuilding facilities in Gulfport, Miss. to produce the large boost, coast, and forward fairing parts using vacuum-assisted resin transfer molding (VARTM). While there is a common high-level process to produce a part using VARTM, many factors influence an acceptable outcome for specific product types. The culture, environment, controls, methods, tools, oversight, worker skill sets, precision, and quality process can influence the manufacture of a product. What may be deemed as acceptable in one industry may not be so in another.

Using VARTM technology, the shipbuilding manufacturing team in Gulfport, Miss. produces some of the best composite parts for ships in conformance with United States Navy standards. They were chosen for their reputation and cost structure. What was discovered, however, was a divergence from the MLAS requirement to produce parts to aerospace standards in a low-cost environment using low-cost tooling. The shipbuilding processes manufactured to less rigid standards of dimensional and process control. Invariably, VARTM technology can be used to produce identical parts in two separate environments with different outcomes. The digital thread became an important part of the assessment process, uniting divergent cultures in immediate reaction to a part's failure. By using data-driven analysis we were able to successfully identify the issue, revise the schedule, remanufacture the parts, and move on.

MLAS Part Manufacture

All of the parts for MLAS were produced in environments unacceptable to most aerospace original equipment manufacturers (OEMs). Many were produced using little known processes in basic factories that incorporated unique and innovative facility adaptations, with comparatively simple manufacturing equipment or facilities.

The fins for MLAS were produced using out-of-autoclave cure (OAC) of an autoclave material by a rarely used process called de-gassing or in-a-bag cure. The parts were produced at Griffon Aerospace in Madison, Ala. by a combined Northrop Grumman-Griffon team. The Griffon facility has an oven but does not have clean rooms, temperature control, or an autoclave such as one that typically would be seen in a manufacturing facility that produces high-strength, carbon-fiber composite parts. Several adaptive manufacturing technologies developed and tested at the Griffon facility were used on the MLAS. (The in-a-bag cure process and other adaptive technologies are discussed further in Chapter 5.)

One technology that was tested and incorporated in the manufacturing process for MLAS flight-ready fins was Sopers' Engineered Fabric Solutions collapsible clean room and oven. The Sopers' facility in Ontario, Canada provided a collapsible combination oven/environmental clean room that attached to the wall. The system allowed the MLAS team to pull it out when needed and collapse it back against the wall when not use. This made more efficient use of the project's manufacturing floor space.

Another cost-saving, unique manufacturing process was used to produce the graphite/epoxy non-autoclave cured struts, which position and hold the MLAS motor mounts. The motor mounts hold the four Thiokol-Huntsville built, solid-rocket, 95,000 lb (43,091 kg) thrust motors (built in 1988), which are placed at 90° intervals within the bullet-shaped boost protective cover. The struts were roughly 15 ft (4.6 m) long and ≈6 in. (152.4 mm) in diameter at the widest point. A Paraplast® mandrel was poured into a mold and removed to wind high-strength, carbon-fiber material around. The turning mechanism was a wood lathe and the application method was by hand. The process took place in an open shop environment and used in-a-bag cure to compact, consolidate, and cure the part. After cure, the Paraplast was washed away from the interior of the part by steam.

The MLAS team was dedicated to the success of the project but also engaged with other development projects that were going on to maximize their expertise and facilitate efficiency. Another technology that was designed, developed, tested, and validated alongside the MLAS project was the in-situ manufacture of large composite sandwich structures. The in-situ project was activated to test the feasibility of laying down large amounts of prepreg composites on very large structures including skin and core, and then performing all remaining operations to completion in one fixture. The process required hand, mechanized, and automated systems to work simultaneously. The fixture had all the elements necessary to manufacture one 30-ft (9.1-m) diameter piece of unified structure, including the cure-in-place process using a Sopers' pull-out oven and collapsible clean room. The fixture was also tested to incorporate a transport system that removed the need for a crane. From the design, test, and validation phase, a building-block approach was taken to scale up the capability of the in-situ system to handle 50-ft (15.2-m) diameter parts.

TECHNOLOGY EXTENSIBILITY

All of the technologies described in this book have extensibility to other applications in industry. There are many possible considerations for technology transfer based on the success of MLAS and the other projects described. However, rapid prototyping a flyaway vehicle for a one-shot showing is quite different from the production ideal. A controlled and repeatable process performed on a production line where the product has a past, present, and future order quantity is desirable.

The successful adaptation of technologies used for MLAS and other space manufacturing research initiatives demonstrated that the technologies could be used for flight hardware, among other applications. They also could be transferred to other dissimilar markets. The three product groups (among others discussed in this book) where the adapted technologies can be used as competitive discriminators and invigorate existing markets are wind turbines, automobiles and trucks, and commercial airplanes.

Wind Energy

The impact of wind energy has been small compared to the vision. As the demand for more output has increased, the response has been to make blades bigger (longer) to turn higher-output generators. At one time, a 131-ft (40-m) blade was considered large. Now 197-ft (60-m), 230-ft (70-m), and 263-ft (80-m) blades are emerging. The push to longer blades has meant that materials, manufacturing processes, and assembly methods previously used are no longer adequate. Wind energy manufacturers are turning to high-strength carbon fiber as the material of choice as blades grow. The size of blades has introduced several challenges to their utilization. Transport, stress on the turbine bearings, gear boxes, and shafts, and manufacturing efficiency have been identified as issues that need to be mitigated to facilitate the larger blades. In-situ manufacturing at the wind farm coupled with segmented molds is an enabler for manufacture of large turbine blades. Made in place, they eliminate transportation costs and pollution (in some cases 164-ft [50-m] blades have exceeded the overland road transport limits). In-situ blade manufacture also reduces the strain on the environment from transport trucks, deforestation to reach the wind farm, and accidents.

The technology developed for MLAS to control its collective mass to assure an accurate launch is a transferable technology to the wind turbine system. Wind turbine blades transfer loads from the blade to the gears, bearings, and internal components of the wind-generating system. As blades grow, the mass imbalance increases the vibration transferred to the gearbox components, shaft, and bearings (Brian 2012). Mass imbalance also creates blade resonance that creates cracks, which eventually degrade or destroy the turbine blades causing catastrophic failure. The mass property control and manufacturing processes developed to balance and align the MLAS vehicle would reduce wind turbine blade vibration and potentially extend the life of wind turbines from 10 to 25 years.

Automobiles and Trucks

The transfer of high-strength, carbon-fiber composites to cars and trucks has been restricted to premium automobiles such as those manufactured by Lamborghini. Manufacturing methods and material costs have prohibited the transfer to cars and trucks even though their advantages to strength, impact, and weight reduction are recognized and desired by car and truck manufacturers. However, low-risk, low-cost filament winding technology using in-a-bag cure (OAC) technology could transfer the benefits of high-strength, carbon-fiber composites to the critical suspension components of cars and trucks. These components could be affordably made and add to the strength and performance of cars and trucks while reducing weight.

Commercial Airplanes

An emerging market for high-strength, carbon-fiber composites is found in the airline industry—commercial airline seats. Until recently, airframes have led the market for the design and use of high-strength composite materials.

The next expansion for use of high-strength composites on airplanes is emerging and will challenge manufacturers to meet demand. Aircraft interiors represent a larger market (by volume) than airframe structures for high-performance composites. Interior components account for as much as 40% of a commercial airliner's empty operating weight. Over the next decade, ≈1,600 new commercial transport aircraft will enter service. Each delivered airplane will require thousands of pounds of composite interior components to increase fuel efficiency and reduce operating costs for the airlines while improving passenger comfort.

The new-build market represents about 6 million lb (2,722 metric tons) of composite components annually for the new aircraft scheduled for delivery between 2013 and 2023. By the time the Airbus A350 and Bombardier C Series enter full-rate production, the OEM market could grow by at least 50% compared to 2012. Prepreg material requirements for commercial aircraft interiors will more than double in the carbon fiber and aramid fiber categories, and the carbon-fiber/glass-fiber (GF) gap will narrow during the forecast period. In addition to new aircraft, the aftermarket interiors segment will make a significant contribution to growth in the use of composites on commercial aircraft during the same forecast period (Composites Forecasts and Consulting 2013).

The airlines' replacement and refurbishment efforts incentivize interior component producers by creating continuous demand for their products during and after the airplanes are delivered. Aftermarket potential is driven by replacement cycles and economic conditions. Generally, passenger seating is replaced every one to two years. Paneling, class dividers, and other major components are turned over every four years. Complete cabin refurbishments take place every six to eight years. Seats represent one of the biggest near-term opportunities. New and replacement seating has the potential to consume 4–5 million lb (1,814–2,268 metric tons) of composites within the next five years.

Switching to composite seats can save from 882–992 lb (400–450 kg) on a single-aisle aircraft. Composite materials also can be used to produce a thinner seat, reducing the thickness by as much as 2 in. (≈51 mm). With the current spacing in the coach cabin, thinner seats mean that on average, a new row can be added every 18 rows without any weight penalty.

The low-cost VARTM technology and in-a-bag cure technologies demonstrated by the MLAS program could enable the ability of composite seat manufacturers to meet the new airplane market for over 10 million composite seats and ≈3.5 million composite galley carts over the next decade.

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2

OVERVIEW OF COMPOSITES IN SPACE LAUNCH VEHICLES

> *"The vehicle explodes, literally explodes, off the pad. The simulator shakes you a little bit, but the actual liftoff shakes your entire body and soul."*
>
> —Mike McCulley, astronaut

INTRODUCTION

Cancellation of the United States manned space program directive Project Constellation and redirection to commercialization of human space flight has driven the need to leverage composites for construction of space launch/lift vehicles, particularly in the Max Launch Abort Systems (MLAS), composite crew modules (CCM), and ablative thermal protection systems (TPS). Use of composites for such wide-ranging products demonstrated the viability and benefits of unique use of manufacturing methods for construction of these critical components.

To enhance the commercial viability of the transfer of launch and space capsules from the government domain to the commercial market, there is the need to combine the benefits of composites for space flight. For successful technology transfer, the benefits of significant weight reduction, unified structures that reduce cost, manufacturing complexity, and lead time, and greater structural design limits are necessary.

Out-of-autoclave (OAC) materials and autoclave materials cured using OAC methods will expand the entrants into the launch and human flight market niches. As the traditional method for cure of composites, the autoclave is an expensive piece of equipment (U.S. $25–50 million). For an autoclave to be large enough to accommodate a large space launch vehicle, 49 ft (≈15 m) diameter, a long lead time is needed for its construction. Thus the cost and lead time of traditional curing methods will limit the entrants to the space vehicle market, therefore prohibiting what might be innovative and dynamic solutions to the inclusion of composites into the designs of these vehicles.

Advances can be realized by leveraging the advances made in composite design and manufacturing on the ARES I inter-stage, composite crew module, Max Launch Abort System, and the ablative thermal protection systems to expand their testing beyond the demonstration stage. To commercialize their use by other industries outside the domain of large corporations dedicated to the development of launch vehicles, the low overhead and innovative manufacturing approaches for space structures would significantly enhance the approach to manufacture of expensive expendable and reusable space vehicles. This would result in cost reduction, increase composite material utilization, and minimize time to market for these nationally critical vehicles.

Launch vehicle components, as shown in Figure 2-1, are huge in comparison to any aircraft produced today. Although the quantities produced are fewer than for the largely composite 787 and the Airbus A380, launch vehicles contain more composites by magnitude than both vehicles combined. Therefore, the annual use of composite materials for aerospace is estimated to double by inclusion of composite components on launch vehicles and their inhabited and uninhabited crew modules.

Technology innovation used on the inter-stage of the launched ARES I demonstrated the transfer of loads to the skin. Use of composite materials resulted in a 1,400 lb (635 kg) weight reduction over its aluminum counterpart with increases in all aspects of strength while reducing manufacturing complexity.

Out-of-autoclave cure and production of unified structures are two emerging and promising technologies that have demonstrated cost savings on other vehicles. However, the drawbacks to the large integrated structure are:

- Large tools are change-sensitive; smaller tools are easier to remove and change, and are capable of producing additional units in parallel to recover schedule.
- Field maintenance of damage repair might require changing out a large part of the vehicle as opposed to a smaller piece.

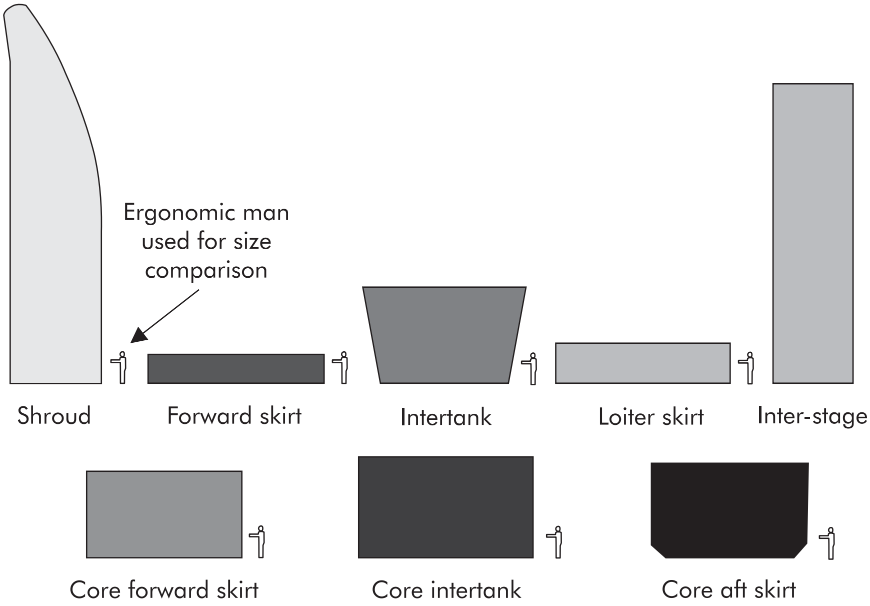


Figure 2-1. Example of launch vehicle part size.

Change will also come about from the uses of composite materials and their applications beyond “black metal,” as well as other advancements such as embedded sensors for health monitoring systems, nano-coatings to increase efficiency and reduce drag, and increased material strength without the use of autoclaves. This is a significant shift from the 90-year tradition of box-frame interior construction of aerospace structures.

Research shows that composites demonstrate a greater resistance than steel or aluminum to the salt elements. However, recent research has shown that continued exposure to moisture can cause the composite materials used for aircraft structures to absorb moisture. This adds hidden weight and facilitates mold growth at the micro level, thereby reducing aerodynamic efficiency. Nano-particle research has resulted in several coatings that show promise to mitigate this issue.

There is one important difference between a composite component for a space launch vehicle and one for an airplane. Most (if not all) exterior skin parts for an airplane have their outer mold lines (OMLs) tooled so they are smooth, enhancing airflow across their surfaces, thereby reducing drag. A mold for a space launch vehicle can be tooled to its inside or outside surface. The rough OML presents little drag penalty as the rocket motors push the space vehicle's payload up through and out of the Earth's atmosphere quickly, mitigating concern or consideration for disruptive airflow. Therefore, the most expedient and cost-effective tooling option (OML or inner mold line [IML]) can be chosen. As part of the Boeing-Northrop Grumman ARES I proposal team, the Huntsville group had to consider OML/IML control and many other differences between airplane and space launch vehicle manufacture when considering composites for space parts.

THE AUTOCLAVE

The cost and complexity of the autoclave system, which is currently the process of choice for curing high-performance aerospace parts, warrants the evaluation of alternative methods that may result in lower cost while providing the same level of quality and functionality. *Cost* is defined as all operations associated with the acquisition, operation, and maintenance of the autoclave technology.

During fabrication, compaction and temperature cure of composite parts are done in the autoclave. This process is time consuming, labor intensive, and requires expensive and dedicated capital expenditures. Overall, the majority of the cost associated with composite assemblies is tied up to the fabrication or manufacturing cost.

In simple terms, an *autoclave* is a union of a high-pressure vessel and an oven; it can deliver both high temperature and high pressure, usually in an inert environment, such as nitrogen gas. The main capital cost driver is the pressure part, which dictates the autoclave shape and wall thickness. An autoclave is programmable, allowing the operator to define the thermal and pressure cycles as required by process specifications. The temperature triggers resin flow and promotes cross-linking, which results in gelation and then solidification of the resin. As the part is usually made up of many plies of material (20+ for some), pressure is used to eliminate voids and assure good lamination. Bad lamination and void presence can compromise the material's characteristics, causing expensive scrap or even failure if the defect is not caught during inspection.

Autoclave Process and Curing Alternatives

This section will analyze the current process and its potential alternatives, which could replace the autoclave as the sole medium of cure. A simplified version of the current composites manufacturing process is shown in Figure 2-2.

The process starts with raw material (prepreg, most commonly carbon fibers in an epoxy matrix) procurement and quality inspection. To increase the shelf life, the prepreg is stored in a freezer until it is needed in production. After pulling from the freezer, the material is cut into plies of the appropriate shape and size as specified by the design, and combined into kits.

The next phase differs based on the cure method used. For autoclave curing, the plies are laid up on a part-specific tool, in a certain stacking sequence, position, and orientation. If required, titanium or other material can be inserted between the layers, and stiffeners added through z-pinning, bonding, or fastening. The part is then vacuum bagged and sealed so air bubbles and voids are squeezed out, and to minimize resin leakage during cure. The parts, together with the tools they are laid up on, are taken to the staging area, stacked onto racks, and placed into the autoclave.

After the cure cycle is complete, the racks are taken out, and the tools are transported to the breakout area. There the bagging is removed and parts are separated from the tools. The tools are cleaned and taken back to the layup area for reuse. The parts are inspected for thickness and any visible surface defects, and then sent on to trimming and drilling.

Once parts are trimmed to their final shape and size, they go to the nondestructive inspection (NDI) area, where ultrasound and/or x-rays are used to find any significant voids, delaminations, or other defects. Destructive testing also can be used, and it is performed on test panels (coupons), which are inserted into every cure load. If there was a problem during the cure cycle, the test panels are tested for cure level by thermo-mechanical

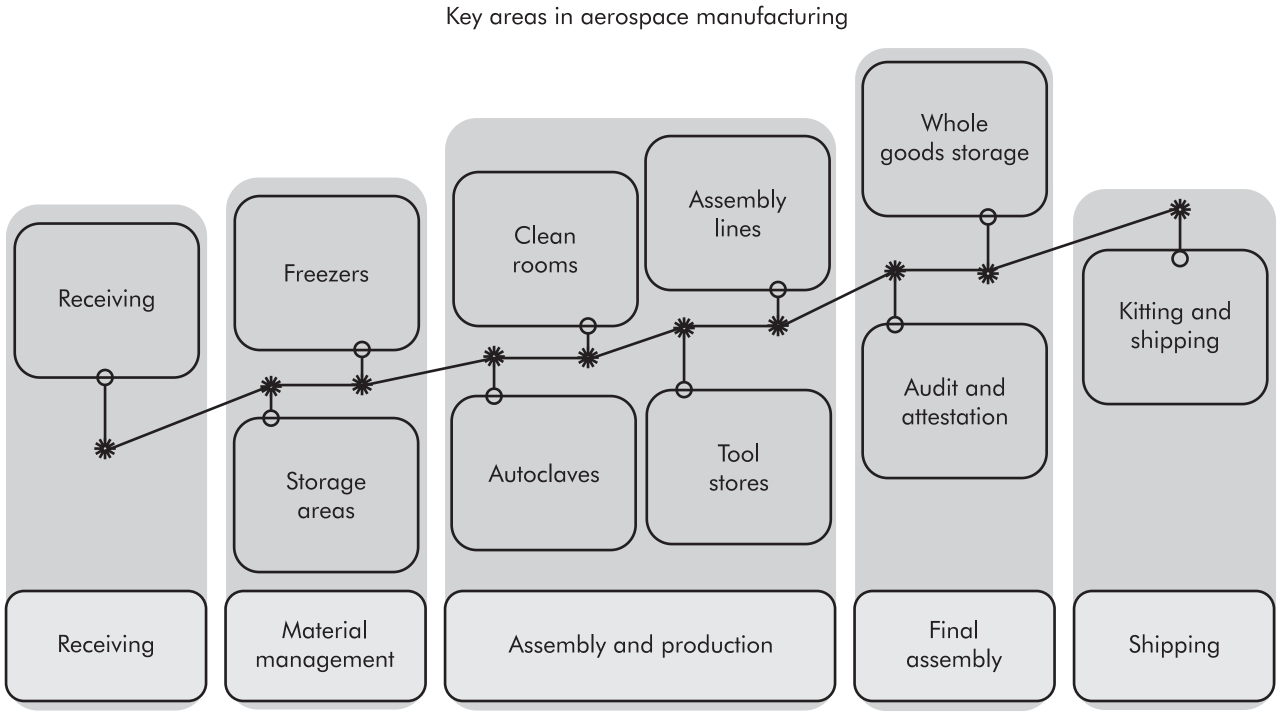


Figure 2-2. Composites manufacturing process.

analysis of the glass transition (T_g) point (ASTM E 1545-00). The focus of the testing methods may vary based on the cure process used. For example, parts produced with resin transfer molding (RTM) are checked for fiber alignment as fibers may move during resin injection (Jones 1999).

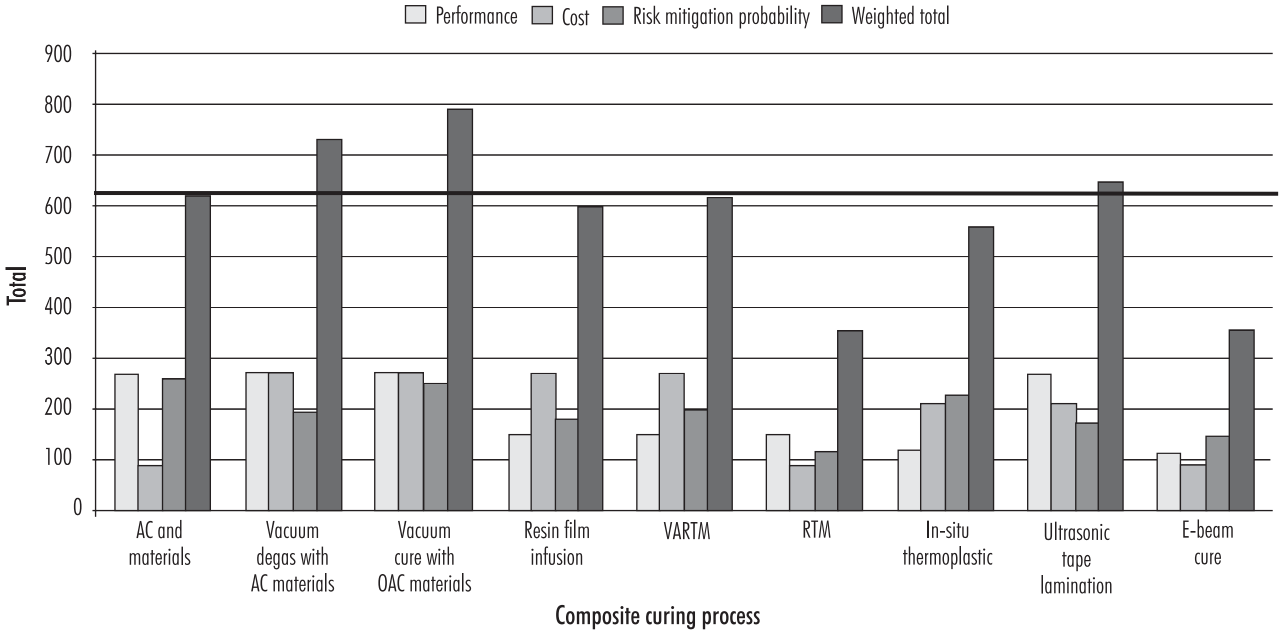
The first step in the study of out-of-autoclave methods is to define the attributes of the autoclave that contribute to the satisfactory requirements for cure. The attributes include:

- Provides uniform compaction—compaction is often inadequate by manual lamination methods;
- Reduces the number of intermediate debulk operations required;
- Provides reasonably consistent high fiber to resin volume ratios (e.g., ≈60% fiber);
- Pressure provides the mechanism to minimize voids and porosity;
- Keeps absorbed moisture in solution;
- Minimizes the extent of porosity from moisture or volatiles proportional to applied pressure; and
- Compatibility with numerous material systems.

This is then considered as a baseline for trade studies. Relevant out-of-autoclave processes are evaluated in Figure 2-3.

The composite part is laid up on the mold tool and placed in the vessel. Initially, a vacuum is applied within the bag; it is held until the pressure inside the autoclave is high enough to take over and the vacuum is then released. Thermocouples and pressure gages are used to monitor various aspects of the cure, such as whether a bag is holding vacuum, the control temperature, and pressure. The control temperature can be measured either on the autoclave surface (free air cure), or on a test panel or even individual parts, depending on the process specifications.

The main controllable parameters for autoclave composite cure are pressure and heat (energy). If the same materials were used, regardless of being cured in the autoclave or out of the autoclave, they would likely need the same level of heat and pressure applied during the cure cycle to achieve the same quality. The energy can be delivered to the material in many ways, non-exclusive to the autoclave, such as a regular oven (not a pressure vessel, it operates at atmospheric pressure and is significantly cheaper to build



AC = Autoclave cure, OAC = Out-of-autoclave, VARTM = vacuum-assisted resin transfer molding, RTM = resin transfer molding

Figure 2-3. Out-of-autoclave process evaluation matrix for Constellation structures.

and simpler to operate), heated blanket, e-beam, UV radiation, etc. A comparable level of pressure to eliminate voids can be delivered via presses (resin transfer molding [RTM], compression molding), expansion tool molding, or possibly even ultrasonic de-bulking. Another avenue is to tweak the materials to reduce the void content to desired levels with only vacuum bagging.

In conclusion, there are no unique attributes that can only be delivered by the autoclave. The question at hand is whether another process, or a combination of processes, can deliver the attributes simultaneously in a more efficient and inexpensive manner, while producing the same quality part. It is also possible that the materials used can be modified to achieve the same properties with different cure parameters.

OUT-OF-AUTOCLAVE CURING PROCESSES

There are two approaches for out-of-autoclave curing. One is to modify only the process, keeping the materials unchanged; the second is to modify the materials so that high pressure is not required. The advantage of the first approach, if achievable, is that ideally there would be no need to requalify the materials, which is a costly and lengthy process in the space and aerospace industries. The advantage of the second approach is that it opens up a wider array of possible processes. The best solution for out-of-autoclave curing may be a combination of both material and process innovations.

Out-of-autoclave curing is a characteristic of each of the following composites manufacturing processes.

- *Resin transfer molding* (RTM): This is a promising process already in use with many parts. The concept consists of laying up the fiber inside the mold and then injecting the resin while pressure is applied via a press. RTM requires lower-viscosity resin, which may alter the desired material characteristics. Also, the fibers can be misaligned during the resin injection process, or there could be areas (voids) where the resin does not reach—both resulting in lower-performance parts.
- *Vacuum-assisted resin transfer molding* (VARTM): This is a variant of RTM processing, where vacuum is used as the other half of the molding tool. Fibrous preforms are placed in a mold

and then saturated with liquid resin. The resulting layup is then bagged for vacuum curing. Both RTM and VARTM processes can be supplemented with oven post-cure.

- *Vacuum bag cure*: In this process, the prepreg is cured in an oven, while only the vacuum, without pressure, is applied. This method requires modified resin systems to achieve low void content.
- *Compression molding*: In this process, either prepreg or wet layup is placed in a female mold. A matching die male mold is then fitted and the part is subjected to high compression loads via a large tonnage press. Heat may be applied through embedded heating elements in the mold.
- *Expansion tool molding*: The laminate is molded in a female tool with a relatively low coefficient of thermal expansion. A matching male mold with a higher thermal expansion coefficient is placed on the part, and the assembly is then heated. The difference in expansion coefficients results in pressure being applied to the part while it is thermally cured.
- *Filament winding*: Dry (prepreg) or wet fibers are wound on a mandrel, which may be structural or removable (non-structural). The mandrel typically expands during oven curing, resulting in pressure being applied on the laminate. Note that filament-wound parts also can be cured in the autoclave.
- *Pultrusion*: A constant cross-section preform is pulled through a resin batch and heated die. A variation of this process, called *pulforming*, involves pulling prepregs about a curved die.
- *E-beam curing*: Electron beam is applied to the wet layup as it is applied to the tool (also can be used with prepreg). The process uses e-beam-curable resins, which usually contain cationic initiators that are sensitive to e-beams.
- *UV curing*: This is similar in concept to e-beam curing, except that ultraviolet light is used to impart energy to the resin. Care must be exerted so as not to damage the resin and fibers.
- *Ultrasonic tape lamination* (UTL): Robotic equipment uses ultrasound for debulking and ply consolidation.

In addition, special consideration should be given to manufacturing processes used for honeycomb structures. Material properties for honeycombs are low when not bonded, and special handling and processing is required. Another option is to co-cure or bond the honeycomb structures after laminate cure.

Out-of-autoclave Materials

Following is a list of preferred resins. The first three are currently cured in autoclaves. They have a wide array of properties and historical performance data available; therefore, their continued application is highly desirable. The resins are listed both as a baseline for material consideration and as potential candidates for out-of-autoclave curing if their cure properties or process can be adjusted. The last three resins can be cured at or close to room temperature, with lower pressure, and could, therefore, avoid the necessity for an autoclave.

1. Cycom 977-2 modified epoxy prepreg offers controlled flow, high toughness, and is aerospace and space approved (Cytec 2005).
2. Cycom 977-3 modified epoxy prepreg has a higher service temperature than 977-2 with excellent hot/wet properties, and is aerospace and space approved (Cytec 2005).
3. Cycom 754 modified epoxy resin is designed for vacuum bag curing at low temperature. It can be cured under pressure if required and is used in marine systems (Cytec 2005).
4. HexPly 8552 is a high-performance, tough epoxy matrix for use in primary aerospace structures. It has good impact resistance and damage tolerance, and offers controlled flow (Hexcel 2005).
5. Vinyl ester is commonly used with VARTM processes. It cures at room temperature, but has poor bonding to fibers relative to high-temperature resins (Epoxy Systems, Inc. 2013; Alfred 2004).
6. The 404 isophthalic resin belongs to a family of room-temperature-curing resins called isophthalic polyesters (Ramkumar et al. 1986).

MANUFACTURING PROCESS EVALUATION

The following criteria impact the choice of process for a particular part.

1. Part count: Some methods are cost effective only if a large part count is produced (the part cycle or rate of manufacture must be high).
2. Tool and equipment cost: A market survey of the process cost for each method should be performed. Evaluation should be based on the normalized cost of each method.
3. Part configuration limitations: The versatility of the products produced by each method must be measured. Some processes cannot be used to generate complex parts.
4. Labor/manpower: The number of hours required to support each process must be evaluated.
5. Material selection: Some processes are limited to a certain set of materials, which limits their versatility for part manufacture.
6. Skill level: Different processes require different levels of skill to operate and maintain the tools and materials.

Material evaluation criteria include:

1. Curing temperature: Lowering the temperature at which a resin cures can lead to cost advantages during the processing phase. However, care needs to be taken in considering the resulting material properties as lower cure temperature generally correlates to lower performance temperature.
2. Strength: Alternative resins for out-of-autoclave processing must match or exceed the relative high strength of typical autoclave resins.
3. Cost: The price of out-of-autoclave resins and their processing must be competitive with current autoclave resin systems.
4. Weight: Since aerospace composite applications are weight critical, density of the resin is important to compare.
5. Curing time: Long curing rates will result in longer cycle times and more expensive processing.
6. Adhesion: The resin must adhere well to the fibers to maintain adequate part properties.

The pressure necessary to reduce voids, or a viable alternative to it, is considered inherent in the process and material selection considerations.

Filament winding and pultrusion methods rely on applied tension during processing, so they are limited to fiber-reinforced material only. Whiskers or particulate reinforcements cannot be used for these processes. E-beam and UV curing processes require resins that are sensitive to electrons or UV light.

Cycle Time

Although autoclave processing is time consuming, with full cure cycle times usually in the 10–12-hours range, large autoclaves can cure many parts at a time. The fastest cycle time is with the pultrusion method, which continuously processes parts at a rapid pace. Compression and expansion tool molding tend to have rather slow cycle times as the molds can generally hold only one part. For simple and/or smaller parts, molds can be designed to produce multiple parts, which is often done with RTM, but still not as many as in the autoclave. Similarly, filament winding processes can only have one mandrel in the winding jig at a time. VARTM is somewhat different, as molds tend to be cheaper, half the mold being a vacuum bag.

Equipment and Tooling

When composite manufacturing methods are compared based on combined equipment and tooling cost, the autoclaves are generally the most expensive. High-pressure vessels are generally heavy and expensive. E-beam and UV methods are a relatively new technology, lacking maturity in tooling and equipment design, so the costs are high for now. Pultrusion and filament winding require a special tool to lay up the composites, adding to their cost, but overall they are cheaper than the autoclave. Expansion tool molding equipment requires precisely matched molds and mold materials with specific thermal expansion properties. On an individual part, mass-production-scale basis they are still cheaper than the autoclave; however, producing different parts quickly increases the associated cost. RTM has moderate costs related to tooling (molds), resin infusion equipment, and presses. However, it is known to create maintenance issues, at least with current technology. VARTM is considered cheaper than the RTM process, and can use regular tooling and a heated oven. It has lower operational costs due to the elimination of presses. These processes are compared in Figure 2-3.

Maintenance to keep the equipment working is an operational cost that must be considered. Autoclaves require many hours of regular maintenance by highly experienced staff. However, according to a preliminary analysis, these costs appear to be less than 5% of the total operational cost. Methods involving resin infusion can cause some headaches, both with the presses and the resin infusion systems, which are prone to clogging.

Part Design

When designing composite structures, it is desirable to have a manufacturing process that allows as much versatility as possible, allowing for a variety of part shapes, sizes, geometries, and materials to be chosen. A single process that is able to produce the full product line would be ideal. The autoclave is pretty close to this goal, having size as its only (but important) limitation. But increasing autoclave size quickly increases capital costs.

VARTM is good in that size is much less of a limitation, while it handles most of the part complexities and ranges handled by the autoclave. Compression and expansion tool molding, as well as RTM are not necessarily limited by size, but they can generally handle only simpler geometries if good compression and resin penetration is to be assured. The main limitation for filament winding is dependent on a part's geometry, as convex shapes are virtually impossible to handle. Also, filaments wound in non-geodesic paths have a tendency to move due to the applied tension. Pultrusion is limited to parts of continuous cross-section; therefore it has limited applications in aerospace. E-beam and UV curing methods could potentially cure a wide array of parts; however, these methods are still being developed (Hasegawa 2004).

Process Parameters

The autoclave allows for various temperature and pressure cycles to be set, therefore allowing various materials to be cured. Similarly, RTM, VARTM, and compression and expansion molding processes can allow for different pressures (except VARTM, which is limited by vacuum/atmospheric pressure) and various temperature cycles. However, they require lower-viscosity resins that can be infused into the molds. Also, fibers may move during mold compression and special tracer fibers need to be inserted to allow fiber direction monitoring.

SURVEY OF PROMISING OUT-OF-AUTOCLAVE PROCESSES

The following processes seem to show the most promise for the industry segment analyzed. Note that e-beam and UV curing can be combined with RTM/VARTM and UTL methods to provide a potentially faster process.

- Vacuum bag cure: The process itself is relatively simple; however, improvements need to be made to further reduce void content. It promises significantly lower capital cost, requiring only a vacuum source and an oven. The ability to achieve full vacuum is critical, and some modification in the prepreg material may be necessary.
- VARTM: This process promises a significant savings in tooling. However, it needs further tuning to achieve the best fiber volume and overall material properties. VARTM is particularly attractive as it allows for large structures to be built. It also can be combined with e-beam or UV curing for faster curing times.
- Ultrasonic tape lamination: Debulking is achieved with an ultrasonic horn while e-beam or another energy source is used to achieve in-situ curing. This process may require significant capital investment, but it could lead to high production rates and decreased operational (labor) costs.

These are reasonable options for the manufacture of large structures. Within the industry, the vacuum-bag and VARTM/RTM type of methods seem to be the most prominent.

Innovative Curing Technologies

More innovative approaches, while bearing more uncertainties, could lead to significant benefits over the common composites manufacturing processes and autoclave curing.

One of these approaches is electrical curing, where an electrical field (voltage and current) is applied to a composite material in such a way as to induce cure. This method has already been in development in the area of nano-imprinting (Crivello and Mowers 1998; Crivello

2002) where electrical current is applied to cure thin resin films. The development objective is to extend this method to full composite parts and evaluate its feasibility for industrial applications.

The advantage of the electrical curing method, if successfully developed, is the fact that electricity is readily available in industrial environments, and is relatively easy to apply. For comparison, e-beam curing requires an e-beam source, potentially expensive robotic equipment for moving this source around the composite part, and a clear path between the e-beam source and the part being cured. As a result, it is a challenge for such a method to simultaneously apply pressure (vacuum) and energy (e-beam) to the part being cured. Electricity can be easily applied inside a vacuum bag to a part with complex geometries. A conducting foil is simply attached to the part, which acts as an electrode.

Another promising method, which can be used alone or in combination with another method, is the frontal or “chain” curing method where a localized reaction is initiated and then self-propagated throughout the material (Chechilo et al. 1972). In frontal polymerization, curing takes place by initiating a localized cross-linking reaction, which then propagates throughout the epoxy resin (Chekanov et al. 1997). In another variation, a UV-curable resin is used in a combined UV-RTM process. The cross-linking reaction is initiated at one end of the mold and it is self-propagated by the heat produced from the initial cationic photopolymerization reaction (Ilyashinko et al. 1997; Hasegawa et al. 2004). The heat from the initial reaction area causes a thermal cationic reaction in surrounding areas not reached by the UV light, effectively creating a chain cross-linking reaction. The advantage of these methods is that they expand the applicability of current methods, such as UV curing. Chain curing reaches areas otherwise not reachable by UV light, either due to a part’s shape, mold design, or use of materials not transparent to UV rays (such as carbon).

There are a variety of technologies already in the market or under development in academic and commercial institutions. So there are likely alternatives ready for deployment on the manufacturing floor that could fully replace the autoclave. And there are a variety of promising processes that are worth further research and development.

IMPACT DAMAGE DETECTION

Many factors influence the design criteria for composite parts manufactured for air and space vehicles. One factor is impact damage that can occur during manufacture, transport, storage, and vehicle operation, the result of which is difficult to detect.

The current method to investigate impact damage of composite parts is visual and based on observation of an indentation. It is often subjective and uses a “walk around” approach that relies on the visual acuity of the observer for impact indent discovery. The definition for an actionable indent is also subjective, relying on the observer’s assessment of depth and size from a given distance. Based on a visual assessment, the observer decides if further evaluation and repair are needed. The observation method is even more difficult when aircraft decks pitch in bad weather or stressful conditions reduce visibility (Bullen and Shinbara 2008).

Larger structures, such as space launch or transport vehicles, compound the observation method due to their size and access difficulty. The inspection of large structures is complex, time consuming, and costly. The inspections must be done, however, because if an impact indentation is large enough and goes unobserved, the result can be catastrophic failure. Further, if the part is in a flight-critical area, the result can be a lost vehicle or worse. Therefore, probabilistic methods are used in calculating the design factors for safety. They are intended to conservatively compensate for worst-case impact to composite parts used on space and aerospace vehicles. The parts are designed to withstand a robust impact to compensate for unobserved/undetected impact(s), thus protecting the integrity of the flight structure. Designing parts for impact probability improves the chances that the vehicle will operate successfully if the impact indent goes unrepaired. However, this design approach adds weight to the vehicle. It also adds cost and complexity to the manufacture and operation of air and space vehicles that use composite parts in their fabrication.

Embedded Sensors

It is important to note that some of the technologies described in the following paragraphs have been evaluated in the past. The value of automatic impact detection, assessment, location determination, and notification for composite parts has been recognized for decades as a means of reducing manufacturing cost and airframe weight. However, the evolution of computer technology and its associative software, as well as the advancements of the sensing technologies, have reinvigorated interest in evaluating automatic impact detection. Therefore, the technologies described are hybrid combinations of older technologies (albeit improved) integrated with new technologies, such as radio frequency transmission and identification, and software and computing capability.

The described technologies, test results, and their potential do not address in-flight health monitoring that would occur with embedded sensors for events such as ballistic impact. The sensors described are meant to be attached or embedded at the beginning of the manufacturing, transportation, and storage process and would be removed before flight and replaced on landing. Although seemingly the same, they are not. However, they may eventually coalesce into a single airframe health evaluation system. The remove and replace technology for composite part impact detection is mature and would add value to the design, manufacture, transport, and storage of aircraft structures.

Embedded sensors provide a reliable and accurate determinant of impact damage. They are able to measure the impact energy and use it to determine if the impact is outside the allowable threshold. The measurement also can be used to accurately and quickly locate the damage for further assessment and repair. By using sensing technology affixed or embedded into the part, it becomes possible to monitor the part's impact health throughout its life cycle. Successful impact health monitoring will lower manufacturing costs, reduce weight, and lower operational complexity. Parts can be designed for flight without the inclusion of materials specifically added to mitigate worst-case events that rely on subjective observation methods. In addition, flight operations can reduce the cycle time between missions by eliminating one of the tasks required before launch or takeoff.

One technical solution for large structures is comprised of systems that provide reliable health monitoring to enable condition-based maintenance. The application of these systems results in reduced manufacturing and life cycle costs. The reduced costs are derived from eliminating unnecessary inspections, minimizing inspection time and effort, and extending the useful life of new and aging space and aerospace structural components and parts. In-situ measurement of the structure's vibration signature can provide first-level, qualitative damage detection, localization, and assessment capability, which can signal the presence of structural damage and localize the area where more precise, quantitative nondestructive evaluation is needed.

Three primary technologies have been identified as feasible to sense, locate, and alert personnel to instances of impact energy upon composite materials. Those technologies are:

1. Acoustic-ultrasonic (AU) sensors, which use sonic signatures;
2. Accelerometers, which detect material movement; and
3. Radio frequency (RF) sensors, which detect vibration phase shifts.

Acoustic-ultrasonic Sensors

AU is an active non-destructive sensing method, which consists of monitoring acoustic signals propagating in a structure as a result of an induced pulse or impact. When acoustic energy caused by an impact is passed through a composite material, the sound waves are detected by a monitoring sensor.

The AU method is the combination of the acoustic emission (AE) method and the ultrasonic method of sensing an induced pulse or impact. The AU system consists of a set of pulser and receiver sensors and data acquisition hardware and software. Pulsers excite the structure. Receivers record the propagating pulse signal in the path of the pulser-receiver. The acquired waveforms are processed to estimate the signal properties such as arrival time, amplitude, and shift in the dominant frequency. Any change in signal properties indicates the variation of the pulser-receiver path as compared to the baseline.

One major drawback to the use of acoustic-ultrasonic sensors is that it requires the ability to mitigate or filter ambient noise found in manufacturing/assembly environments. The most effective deployment of acoustical emission technology requires the sensor head to directly interface with the composite skin via a "couplant" layer to maximize the sensor's sensitivity to the composite skin relative to the ambient noise. The couplant is the interface between the device and the part skin. Some common layers include: vacuum greases, water-soluble glycols, and solvent-soluble resins.

Accelerometers

Accelerometers are instruments or devices for measuring acceleration wherein a sensor(s) converts an electrical signal into a measurement to determine the amount of mass displacement or movement. Considered one of the simplest applications of microelectromechanical systems (MEMS), such MEMS-based accelerometers rely on contacting the surface (test mass) with microscopic spring systems to gage the rates of changes in motion or detect points of impact. Piezoelectric material is commonly utilized to translate stress caused by motion into electrical charges for data capture. Sensitivity requirements drive the size and shape of the accelerometer's surface area.

One inhibitor to the use of an accelerometer is that it may involve a large footprint per sensor as well as contact to the surface of the material to be monitored. Further, the technology is applied to parts that require transportation and movement. Environmental conditions degrade the ability of the sensors because some accelerometers require a stable environment and stable condition to operate properly.

Radio Frequency Sensors

Microwave proximity RF sensors measure the amplitude of the vibration of materials to which they are affixed. The RF sensor's output shows significantly different amplitudes depending on the level of impact energy and the distance of the impact from the sensor. RF sensors offer a non-contact approach to detecting submicron phase shifts from the resonance signal initially created by the sensor. As a part would move due to vibration caused by impact, the sensor's nominal phase would shift. Onboard sensor electronics then correlate the shift to determine the vibration frequency.

A drawback to the use of an RF microwave proximity sensor is that it hovers about .2 in. (5 mm) above the surface to be monitored. It needs to be supported by an independent stand or fixture that is not connected to the impact material to stabilize the sensor. A relatively long stand-off distance needs to be used to protect the sensor against mechanical impact from vibration. The complexity of the fixturing and application and sensitivity of the system to contact would introduce process difficulties if used in industry.

NANO-COATINGS

The "skin" of spacecraft and aircraft is an interface between the internal and the hostile external environment experienced by the vehicle. It encounters stressors such as water-based electrolytic agents that can cause gradual corrosion; surface scratches caused by handling and maintenance in depots as well as during take-off and landing under sandy conditions; and fatigue stresses associated with vibration and thermal shocks that are routine aspects of their service conditions. The combination of aggressive environments and stresses leads to numerous field maintenance problems with the potential of being catastrophic. Maintenance programs are designed to mitigate such failures, but these measures add considerably to the operating cost of the fleet.

Smart, multi-functional, corrosion-resistant coatings with embedded sensors capable of providing on-line condition assessment of damage due to fatigue are needed. Developments in nano- and micro-technologies offer effective materials and device solutions that will allow for the development and application of such multifunctional coatings. Integration technologies are emerging, enabling the use of multifunctional coatings to mitigate the environment's effects on composite parts.

Advanced coatings integrate three key technologies:

1. Bio-inspired "lotus leaf" micro-texturing with super-hydrophobicity (see Figure 2-4);
2. Embedded anti-corrosion nano-particles, which can bleed into fresh metal that is exposed due to scratches; and
3. Structural health monitoring sensor arrays using integrated micro-technologies.

Numbers 1 and 2 will protect materials from corrosion.

At the University of Arkansas, Fayetteville, a group directed by Professor Ajay Malshe, Ph.D. is developing unique nano-material chemistries and manufacturing processes to deposit nano-structures in the form of "micro-textured" coating,

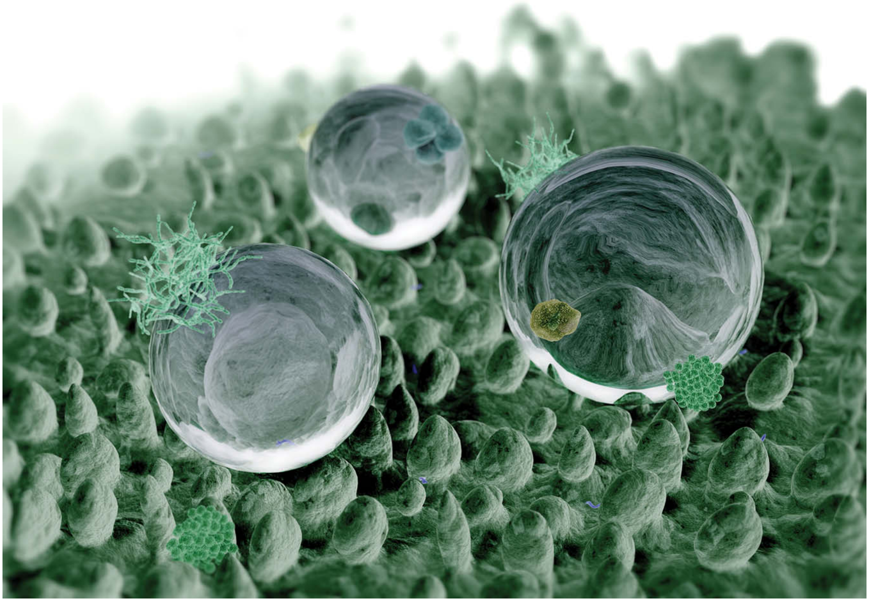


Figure 2-4. ESC-deposited, lotus-inspired superhydrophobic coating. (Courtesy William Thielicke)

mimicking bio-inspired lotus leaf surface morphology, to achieve super-hydrophobicity.

Dr. Malshe and his research team have also integrated and interconnected microelectromechanical (MEMS) pressure sensors on flexible polymer substrates (see Figure 2-5), which could be used on the wings of aircrafts to provide useful condition assessment data. The sensors can be integrated on the same substrate with control application-specific, integrated-circuit (ASIC) electronics as well as with wireless platforms.

TECHNOLOGY TRANSFER

Wind Energy

Due to the high cost and falling supply of oil, the world energy crisis is forcing engineers and scientists to focus their efforts

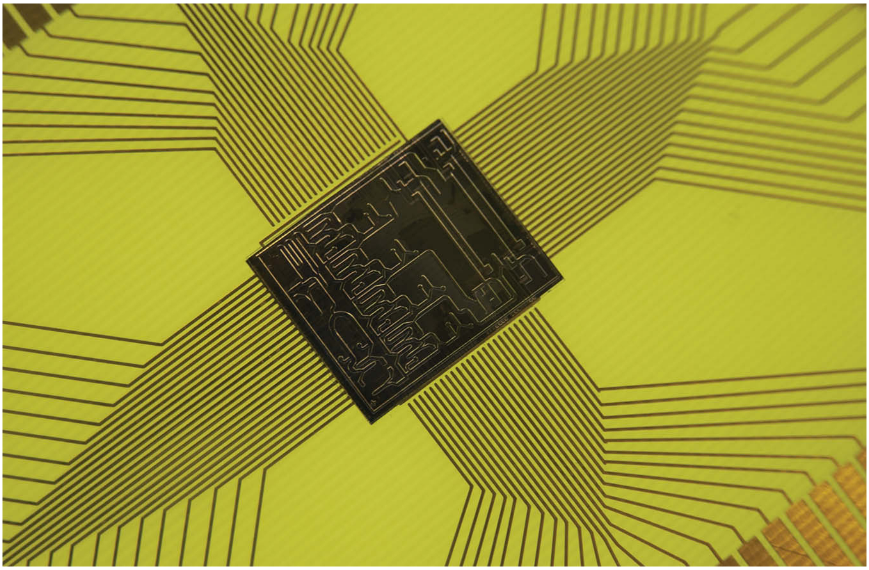


Figure 2-5. MEMS sensor and ASIC flexible package platform.

on fully optimizing and harnessing renewable energy sources, including wind and solar energy.

In the case of wind energy, the rotor blades are now designed to last more than 30 years. With the new turbine architecture using modern variable pitch and variable speed, it is envisioned that a power output of 2+ MW is possible. However, as new technologies are deployed, new reliability issues must be addressed and resolved.

The design of wind turbine blades combines complex shapes to improve aerodynamic efficiency using different materials such as fiberglass-graphite composite and balsa wood. Failure of one rotor blade on the turbine results in catastrophic damage of the entire power supply system. To address failure issues, what is needed are “smart” rotor blades with embedded, wireless, lightweight sensors. This would provide continuous monitoring over the life of the blade, detecting fatigue damage, crack initiation, moisture absorption, wind gusts, and lightning strikes. In addition, these sensors would be capable of addressing issues such as “blade-vortex” interaction.

An embedded sensor array capable of monitoring strain, fatigue, crack initiation, acceleration (including pitch, gyro, and rotor position), temperature, moisture, lightning, and wind pressure is a key element in developing a structural health monitoring system (SHMS) for wind turbine blades. Such an SHMS should continuously monitor the onset and progress of structural damage, enabling users to make rapid and accurate diagnosis of significant structural events. This technology would reduce inspection and maintenance costs. Now there are SHMSs that comprise a network of devices, such as integrated organic thin-film sensors, control modules, and RFID circuitry for wireless communications, which can be attached to a turbine blade.

Sensor Technology

Inorganic semiconductors using amorphous and microcrystalline silicon have recently been envisioned as the sensing elements to overcome the limitations of conventional sensors. However, the high Young's modulus (29,008 ksi [≈200 GPa]) of inorganic materials limits the use for applications with flexible polymeric substrates. This is due to the large stiffness mismatch generated in the interface of the inorganic semiconductor elements and the flexible films, which may lead to irreversible plastic substrate deformations, degrading the sensor performance in terms of reliability and repeatability.

Conversely, the use of semiconductors with low Young's modulus (725 ksi [5 GPa]) organic material as the sensing element is expected to minimize the induced stress concentration in recently demonstrated strain sensors (pentacene). Improved overall performance in terms of sensitivity has been achieved by adopting pentacene-carbon nanotube (CNT) composite material. It is therefore easy to envision a set of flexible sensors to meet the stated requirements of SHMS for wind turbine blades.

The sensor arrays are based on an active matrix configuration in which each sensor can be addressed by thin-film transistor (TFT) sensors, as shown in Figure 2-6. A row of pixels is selected by first applying appropriate voltages to the TFT gates connected to the row. Desired voltages are then applied to each pixel through the data lines to read the data from each sensor cell. Non-selected pixels are completely isolated from the voltage operation of the selected pixels.

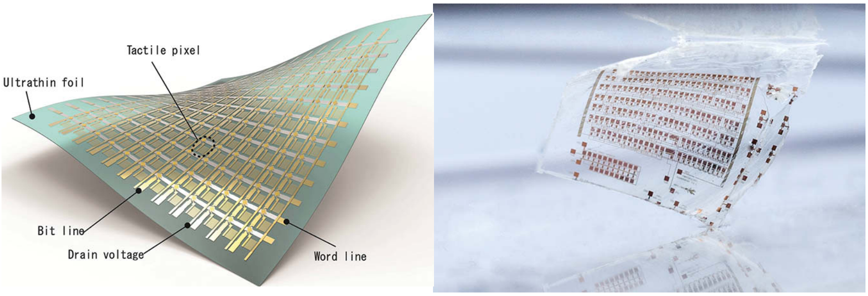


Figure 2-6. Thin-film transistor sensors.

Therefore, the TFT active matrix can be considered as a switch for selecting and isolating the pixels (sensors). It is proposed to employ these flexible polymer-based health monitoring sensors so that a significant reduction in blade maintenance, downtime, and cost can be achieved. These lightweight, wireless, and cost-effective polymer-based sensors can be embedded in the composite structure or surface-mounted onto the blades with protective polymer coating.

Aerospace

Under the auspices of the Department of Defense's Multidisciplinary University Research Initiative (MURI) program, an investigation was made of the conditions for monitoring aircraft and helicopter blades using an array of surface-mounted embedded sensors in .0039 in. (100 micron) coating on the top of the blades (Varadan and Saxena 2009). With wind tunnel testing, it was proven that the coating does not affect the aerodynamic conditions. Figure 2-7 shows a helicopter with blades containing coatings and piezoelectric materials that flex when subjected to electrical fields, not unlike the way human muscles work when stimulated by a current of electricity sent from the brain. NASA, the Defense Advanced Research Projects Agency (DARPA), the U.S. Army, and The Boeing Company have spent the past decade experimenting with smart material, actuated rotor technology, which includes the piezoelectric materials. Tests in a NASA wind tunnel of this smart rotor hub confirm the ability of advanced helicopter-blade active control strategies to reduce vibrations and noise.

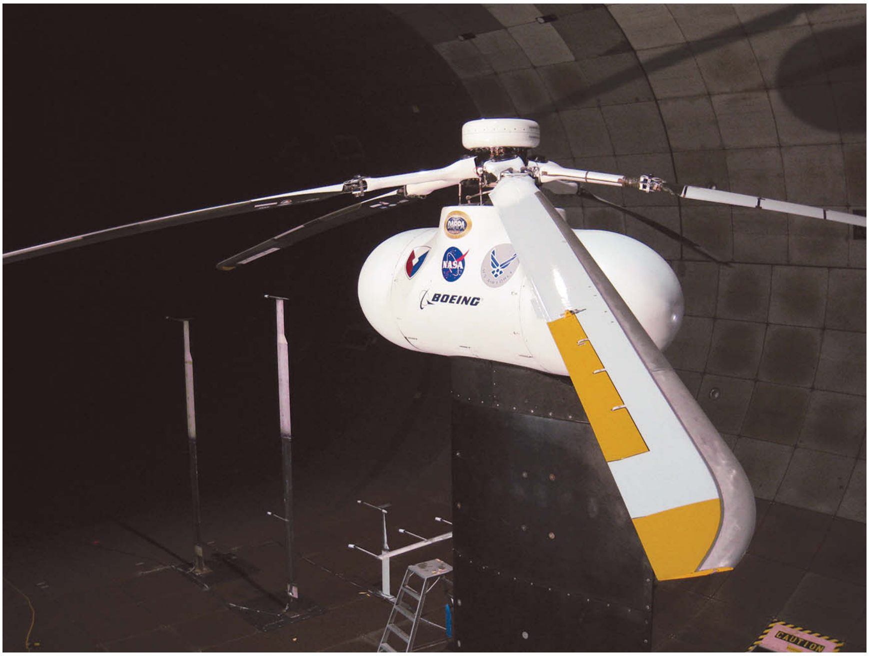


Figure 2-7. Helicopter with blades containing coatings and piezoelectric materials.

Researchers with Sandia National Laboratories and Purdue University are using sensors and computational software to help design a better wind turbine (see Figure 2-8). The achievements of this project include:

1. In-flight health monitoring and damage assessment of critical aircraft blades in real time;
2. Development of a "smart skin" coating for helicopter blades to reduce transonic flows on the advancing blade, reducing vibration levels, power divergence, and noise; and
3. Successful testing of the coating for rain, sand, and particle erosion.

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Figure 2-8. Jon White, a Ph.D. candidate at Purdue University, conducts a field test on one of the Sandia experimental wind turbines in Bushland, Texas.

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3

COMPOSITES IN INHABITED SPACE VEHICLES

"One doesn't discover new lands without consenting
to lose sight of the shore for a very long time."

—Andre Gide

INTRODUCTION

Thursday, January 15, 2004, posting: 4:31 p.m. EST (2131 GMT) Washington (CNN)—Saying, "The desire to explore and understand is part of our character." President Bush Wednesday unveiled an ambitious plan to return Americans to the Moon by 2020 and use the mission as a stepping stone for future manned trips to Mars and beyond (O'Brien and King 2004).

A year earlier at the Jet Propulsion Labs (JPL) in Pasadena, I joined a combined industry and NASA team to develop a strategy to decide how we might get people to Mars. We had three primary options on the table to discuss:

1. Leave for Mars from the Earth.
2. Build a ship in low Earth orbit, fuel it, populate it, and leave for Mars.
3. Build an assembly base on the Moon and use the available water to manufacture fuel and support the resident technicians and scientists to build a ship, fuel it, and launch for Mars.

After interviewing astronauts and scientists about the difficulties of working in space without the benefit of gravity, and considering the number of trips to orbiting fuel depots to fill their tanks for a trip to Mars, it was decided that the Moon with its water and gravity was the best option.

The shuttle was designed to operate at altitudes between 115 miles (185 km) and 596.5 miles (960 km). The actual altitude it flies for any given mission depends on its target. For example the International Space Station is 180–190 miles (290–306 km) up, while the Hubble Space Telescope is 360–370 miles (579–595 km) up.

The space shuttle is limited in altitude because it cannot carry infinite fuel. Even if the orbiter is lightened and the cargo bay is used for fuel, it is not going to go higher than 600 miles (966 km). By design, the space shuttle was never meant to go any higher than altitudes within low Earth orbit (LEO). Large amounts of acceleration and fuel would be needed to achieve escape velocity from Earth's gravity.

Just how high can you get for $200,000? If you pony up the money to the good folks at Virgin Galactic, you will reach an altitude of approximately 68 miles (109 km) above the surface of the Earth. That's 6.2 miles (10 km) above a boundary known as the Kármán line, where by most definitions, the atmosphere ends and outer space begins.

There is a great amount of difference, complexity, and degree of difficulty between flying with humans up into an area where space begins and quickly returning, and going where the Space Shuttle went and sustaining operations while working and conducting experiments. Life support, fuel, thermal protection for returning, and many other considerations must be incorporated into an inhabited space vehicle.

Going to the Moon, landing, staying awhile, lifting off, and returning to Earth increases the complexity level of space travel by magnitudes. Going to Mars and returning increases the complexity almost beyond comprehension. When three-time Astronaut Carl Meade was asked why the proposed design of the new ALTAIR Lunar Lander was so robust compared to the Apollo Lunar Lander, he responded that Apollo spent only a few hours on the Moon, ALTAIR would spend days and weeks. He also mentioned that we were extremely lucky. If one Apollo mission had dwelled but a few hours longer, the entire crew would have been fried alive by a solar flare. This time we needed to rely on technology, planning, forethought, previous experience, and luck; and not just technology and luck alone. Listening to him speak about the critical nature of a space vehicle sustaining life so far from home heightened my already intense feeling of responsibility.

In 1978, I was part of a team in Iran that acquired passes to get up close to a display of Soviet space hardware at an international industrial display for Shah Reza Pahlavi. As we examined the inhabited Soviet space vehicle on display, we were reminded of the common phrase of the time, "The Soviets believe if you have enough thrust, you can get anything into space." The vehicle we examined was all steel and could have served as a diving bell. The arc-welded butted seams still had the marks from a hard wheel disk grinder used to grind down the welds so they were flush with the surface of the vehicle. Did it work to get people into space and back? Yes it did. And the construction enabled the interior to be more spacious as the steel provided the needed strength without sophisticated construction to reduce weight.

The Soviets eventually realized as NASA had from the beginning that for every pound or even ounce of weight saved in the vehicle body, more fuel or payload could be carried per launch. Composite materials used for inhabited space vehicles offer the advantages of a robust vehicle, and the strength and stiffness to open up the interior for better comfort and utility without the weight penalty for strong materials such as steel. That is why NASA continues a vigorous program to develop composite materials for inclusion in space vehicles.

THE COMPOSITES USE MANDATE

Internationally, industry is using composites in Earth-bound and space transportation vehicle construction. NASA is leveraging the existing composites knowledge base, including expertise and technologies that exist within industry. This is being accomplished with rapidly expanding flexible assembly systems and "game theory" simulation to maximize manufacturing and assembly, and flexibility and efficiency.

The NASA Authorization Act of 2005 authorized, "The [NASA] Administrator [to] establish a program [(Constellation Program)] to develop a sustained human presence on the Moon, including a robust precursor program to promote exploration, science, commerce, and U.S. preeminence in space, and as a stepping stone to future exploration of Mars and other destinations." Innovative and developmental technologies are required to realize this vision for space exploration (VSE).

Central to the VSE is the development of new crew and cargo transportation vehicles for missions beyond low Earth orbit. These mass-critical vehicles were developed under NASA's Constellation Program, which included the ARES I Crew Launch Vehicle, the ARES V Heavy Lift Cargo Launch Vehicle, the Orion Crew Exploration Vehicle, and the ALTAIR Lunar Lander. Novel and lightweight structural concepts for these vehicle systems involved the judicious use of composite materials, with their high strength-to-weight and stiffness-to-weight ratios.

COMPOSITE CREW MODULE

The NASA Engineering and Safety Center (NESC) Composite Crew Module (CCM) team was chartered to develop a crew module design tailored for use with composites. Led by NESC, the project team was a partnership between NASA and the companies that provided the design, manufacturing, and tooling expertise. Partners included nine NASA Centers; the Air Force Research Laboratories; and contractors from Alcore, ATK, Bally Ribbon Mills, Collier Research Corporation (HyperSizer), Genesis Engineering, Janicki Industries, Lockheed Martin, and Northrop Grumman Corporation (NGC). The CCM team operated in a virtual environment, electronically connecting participants across the country.

The crew module design was to characterize design drivers such as geometry, mass, manufacturability, inspectability, repairability, damage tolerance, crashworthiness, micro-meteoroid and orbital debris tolerance, and radiation shielding. The CCM team's constraints were to retain the reference design's outer mold line, maintain the inner mold line to within 1.5 in. (38.10 mm), and maintain the interface points at the launch abort system and the service module. This was a parallel effort to the NASA and Lockheed Martin metallic crew module referred to as Orion (launched and interfaced with other hardware modules). The CCM was designed to the same loading environment as the metallic crew module. A primary intent by NASA was to gain experience designing, analyzing, and testing flight weight composite structures for potential future space missions.

The CCM was constructed of honeycomb sandwich panels and solid laminates. It was weight optimized to over 50 loading scenarios. Three of the loadings were selected for test validation: internal pressurization, parachute pull, and abort launch system thrust force.

The "as manufactured," full-scale CCM primary structure with fiber optic and traditional strain gages attached is pictured in Figure 3-1. Additional test data instrumentation included optical and acoustic gages and sensors.

The CCM project made use of the composite materials' strength, weight efficiency, and flexibility of fabrication. To gain the most benefit from the composites, engineers performed trade studies to explore the design space and find an optimum set of panel concepts, dimensions, and layup stacking arrangements. The analysis tools rapidly evaluated design alternatives and with enough fidelity to discern performance differences in competing vehicle configurations and design features.

Figure 3-1. Full-scale CCM primary structure with fiber optic and traditional strain gages attached. (Courtesy NASA)

To complete the project, NASA continued with the CCM structural design and included fabrication and tooling expertise on its team in a collaborative environment (see Figure 3-2 and Figure 3-3 that depict parts of the final products).

ALTAIR LUNAR LANDER

On December 16, 2008, NASA released a draft request for proposal to seek industry support for the design of its ALTAIR lunar lander vehicle, part of NASA's Constellation Program. ALTAIR would be designed to deliver four astronauts to the Moon's surface late in the next decade.

Shortly after the NASA request, I was assigned as manufacturing team lead on the ALTAIR proposal team at Northrop Grumman Corporation. It became a point of pride for NGC to win the ALTAIR contract because Grumman Corporation had built

Figure 3-2. Installed parachute fitting. (Courtesy NASA)

Figure 3-3. Lower shell/backbone pi bond. (Courtesy NASA)

the Apollo lunar landers and the legacy of that program was still deeply embedded in its reputation and tradition.

Historical Design Review

One of the manufacturing team's first activities was to acquire the original Apollo lunar lander designs, bills of material, work instructions, build books, logs, notes, and other available information about the original lander, the only vehicle to transport humans to the Moon and back safely. We found a wealth of information located in archives and the company library consisting of original documents and drawings.

Another task was to locate the people who worked on the original Apollo lunar lander. We searched for names on retrieved documents, located individuals from the Grumman personnel archived records, and then sought out the identified people for interview. To our surprise, we located many former Grumman employees who worked on the Apollo lunar lander; some still worked for Northrop Grumman Corporation. They had stayed on after Northrop acquired Grumman. Some were located in El Segundo near where our proposal team was assembled.

Reviewing the Apollo manufacturing and test documents coupled with the interviews of former Apollo engineers, technicians, and managers provided us with an expert knowledge base. It gave us a better understanding of the challenges, lessons, and solutions that were transferable to ALTAIR. Some of the technology and processes that were puzzling to our team became clear as we began to better understand the challenges the first team had faced when they were designing, testing, and manufacturing the Apollo lunar lander. We had been building and testing various components as part of our anticipation for release of the proposal from NASA based on assumptions that were modified and, in some cases, thrown-out as the result of this new information. Many times in interviews when a former Apollo engineer or technician would hear what we were doing or going to do he would say, “Nope. Won’t work.” He would then explain the reason for building the original part and how it was changed as the result of feedback after the first flight to the Moon. The documents and interviews enlightened our team with a wealth of information that changed some of our part materials, designs, and manufacturing processes based on the input. The time invested at the front end would pay off if we were awarded the project and then began to design and build test parts.

There were differences between the Apollo project and the ALTAIR project. But the plan was to leverage the past performance and knowledge base by integrating it with current expertise and advanced materials and manufacturing processes.

NGC was the only company to have designed and manufactured 13 human-rated lunar modules. Six landed with humans on the surface of the Moon and safely returned. Of the remaining seven, one carried humans into Earth orbit and two carried humans into Moon orbit and returned. The other lunar modules were used for test and development. The NGC legacy of space exploration also included the manufacture of current space products such as Space Ship 1 & 2, White Knight 1 & 2, the Space Shuttle wing, and the Chandra X-ray telescope. Figure 3-4 shows the Apollo lunar module subassembly, the Chandra X-ray telescope being lowered into a thermal vacuum chamber, and a B-2 being sprayed with coatings using robotics technology.

New Design's Use of Composite Materials

From the start, it was integral to the NGC ALTAIR proposal to build the ALTAIR lunar lander using mostly composites and advanced manufacturing processes. The ALTAIR design leveraged the use of composite materials to facilitate weight savings and an open interior architecture. The new design is represented in Figure 3-5. The two-stage ALTAIR configuration is composed of the ascent module (pressurized/crewed), lunar ascent, rendezvous and docking, and crew return to Orion vehicle. The docked ALTAIR and Orion inhabited space vehicle concept is shown in Figure 3-6.

Central to the success of landing on the Moon was a design that enabled the vehicle's mass center of gravity to be aligned around the engine. The composite design incorporated a descent

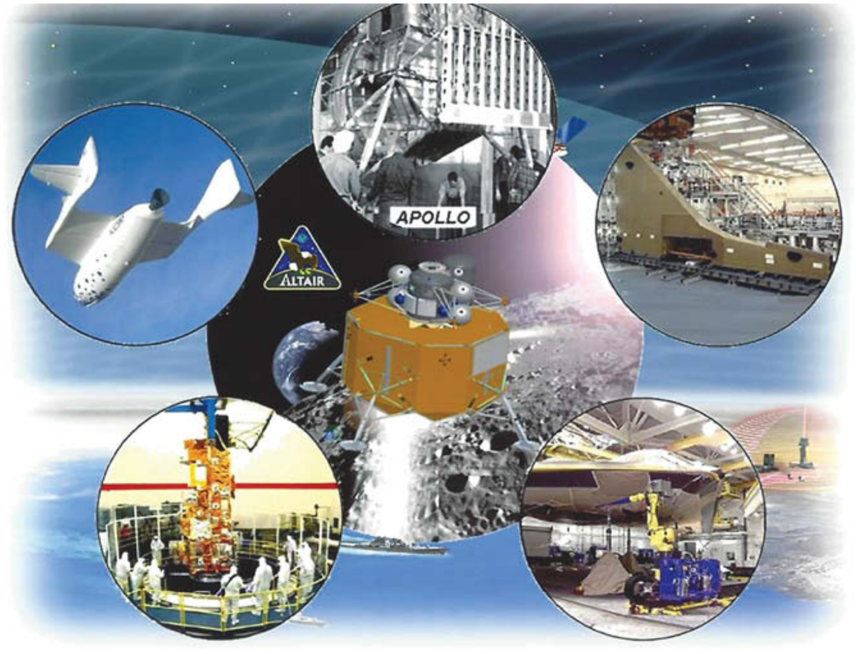

Figure 3-4. Representative NGC manufactured products, past and present, which would contribute to ALTAIR. (Courtesy Northrop Grumman Corporation)

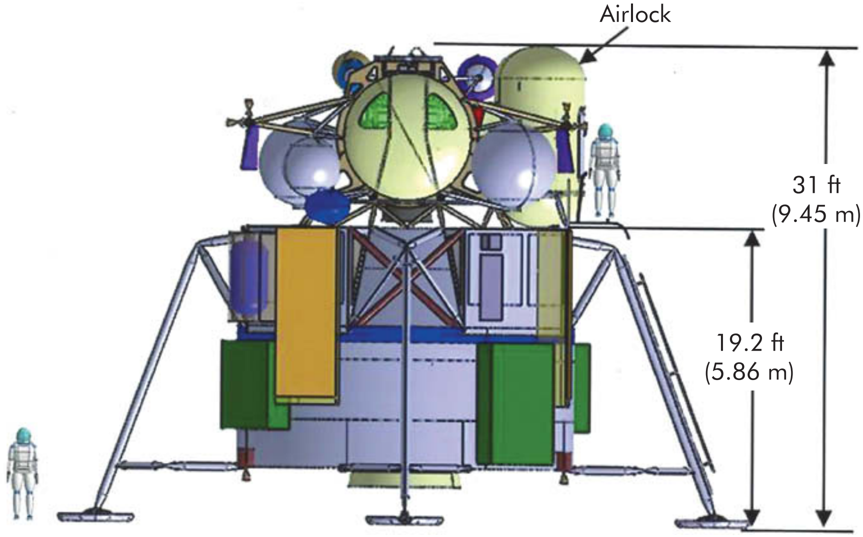

Figure 3-5. Composite material ALTAIR concept design composed of the descent module stage, ascent module stage, and the airlock to be left on the Moon's surface. (Courtesy NASA)

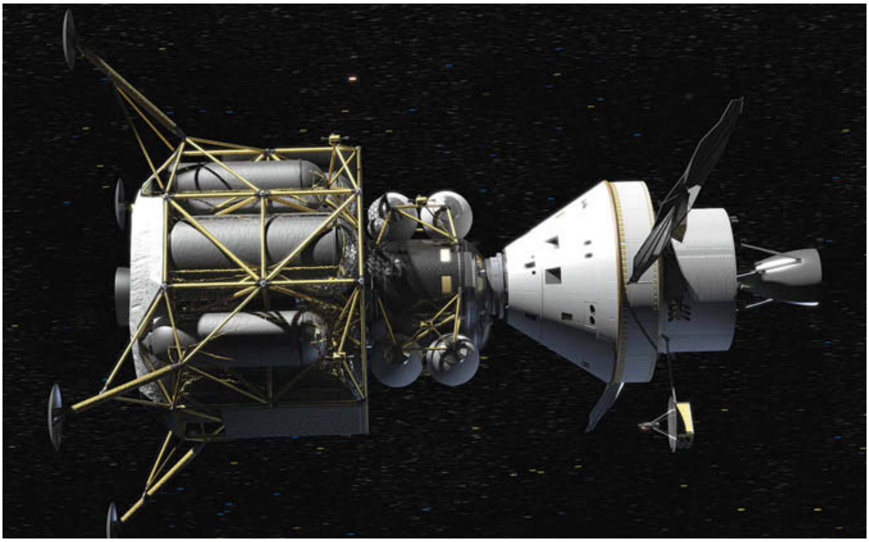

Figure 3-6. The docked ALTAIR and Orion inhabited space vehicle concept. The total stack mass is 143,407 lb (65,185 kg). (Courtesy NASA)

module configured around a composite cryogenic LOX/LH2 toroidal tank arrangement. The load-bearing LOX and LH2 tanks were contained within composite inner and outer skirts. The inner skirt had provision for descent engine and support structure installation. The composite outer tank skirt had structural provisions for landing gear, composite RCS struts, and subsystem installations. The toroidal tank notional layout is shown in Figure 3-7.

The mostly composite landing gear is cantilevered off the side of the descent module within a truss assembly. The assembly is composed of the primary strut; two secondary struts; landing shock-absorbing attenuators; one up-lock mechanism; strap-severed, two electrically detonatable cartridges (the second cartridge adds redundancy); two down-lock mechanisms; spring-loaded deployment latch mechanism; and foot pad.

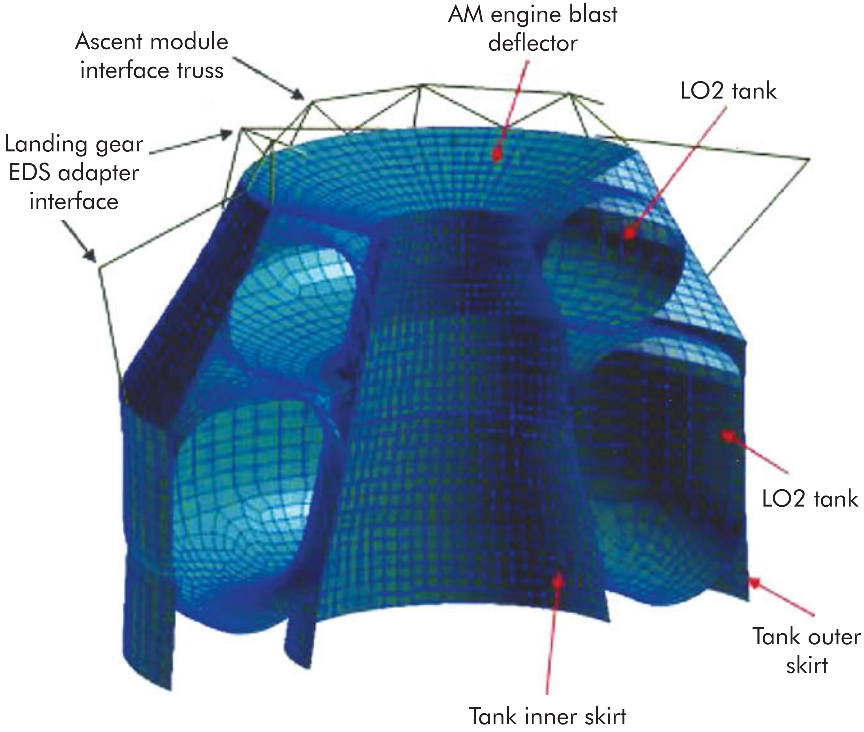

Figure 3-7. Toroidal tank notational layout. (Courtesy NASA)

Of particular concern was the manufacturing method and technology to produce the composite cryogenic LOX/LH2 toroidal tank. To meet this challenge, a uniquely designed and configured fiber-placement machine was designed to build the toroidal tanks. Figure 3-8 and Figure 3-9 show the machine's concept and configuration, respectively.

Advanced Tooling for Composites

Fabrication of the tooling for ALTAIR was based on automated systems that leveraged the use of digital design linked to manufacturing methods. Woven into the methods was a common "3D digital thread" that extended from design, through production, and across the supply chain. The capability included automatic synchronization of configurations, digital high-fidelity simulations, graphic planning, and digital manufacturing processes that reduced tooling, tolerance accumulation, and product variability. The approach optimized the manufacture and production of the ALTAIR lunar lander. It identified manufacturing requirements and recommended design enhancements for manufacturability.

The advanced tooling for manufacturing of composite structure (ATMCS) system targeted for ALTAIR automated the tool design process and optimized the tool build types. Traditionally, most

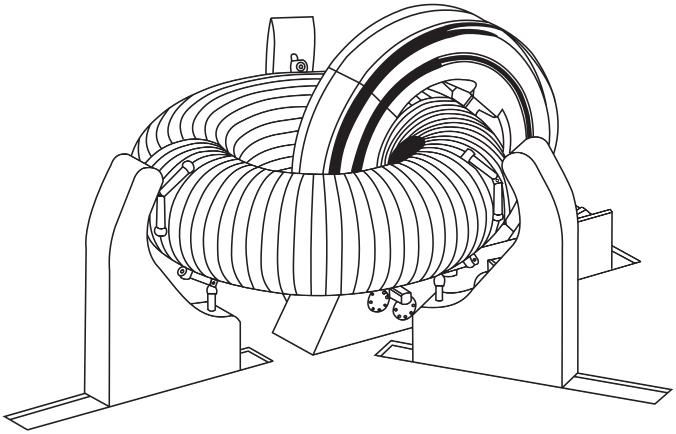

Figure 3-8. Concept drawing for the fiber-placement machine's main axis. (Courtesy M. Torres)

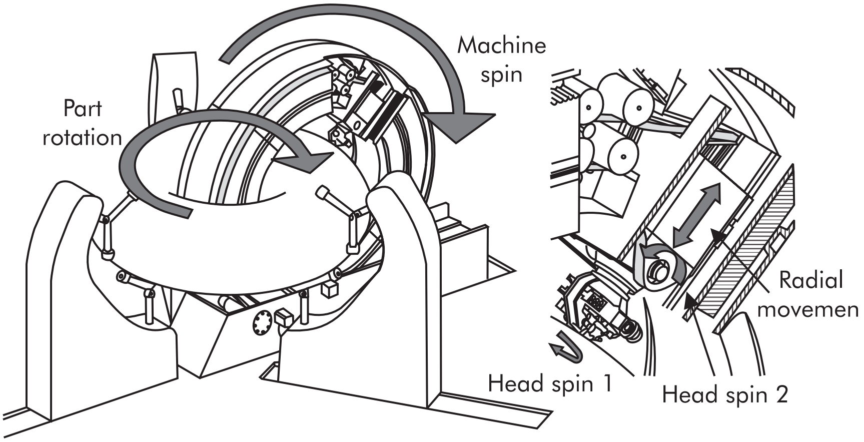

Figure 3-9. Fiber-placement machine configuration. (Courtesy M. Torres)

tools are designed by conventional, manual methods that use 3D computer-aided design (CAD) systems. These methods usually require the designer to spend substantial time in defining a tool's surface and attributes.

The U.S. Air Force Directorate ATMCS program was developed by Northrop Grumman as an expert system to automate tool design, NC programming, and virtual work instructions. NGC began using ATMCS on its aerospace programs and saw significant improvements to operations. The system is currently licensed for commercial use.

ATMCS is an automated CAD tool. It uses CAD drawings of parts, created in CATIA® or Pro/E®, as a basis for generating tool designs, NC programs, and virtual work instructions. The designer chooses the type of tooling being built (e.g., resin transfer molding, master model, ply locator template, trim and drill, integral stiffened, billet, and egg crate) and the tool material (e.g., steel, carbon, or composite) from a prioritized "best-choice" decision box. The tool designs are dependent on the ATMCS expert system's object-oriented, structured knowledge base for application of design rules. The actual part drawing is then specified and can be viewed. The designer defines the characteristics (e.g., part surfaces and boundaries) and can edit the default tolerances provided by the system. ATMCS uses all of this data as well as program-specific, knowledge-based design rules to generate tool drawings.

The completed CAD drawing can be output to CATIA or other formats. Additional features not included in the default process (e.g., material thermal expansion, springback calculations, and analysis) can be run manually within ATMCS by the designer. The digital tool design drawing, generated by ATMCS, can be used by other CAD/CAM systems to do a variety of tasks (e.g., numerical control cutting, composite ply location and nesting, material requesting, and cost estimating). As a result, overall cost estimates are improved because the system provides precise material specifications, nesting programs to cut raw materials for kitting, and estimates process build times.

ATMCS's rapid design generation allows for easier updates with changing part configurations and enhances the Integrated Product Team's communication and process. Northrop Grumman's main subcontractors also use this automated CAD tool. The system saves considerable time and money in tool design, as well as high savings in tool fabrication, actual part fabrication, and assembly. Quantification of ATMCS's benefits is readily available, based on the comparison of the original F/A-18 C/D airplane program to the new E/F airplane program. Northrop Grumman achieved a 97% documented time savings in tool design/tool manufacture by using ATMCS to generate tool structure designs for E/F versus the conventional CAD method. Composite tools are also preferred for composite materials to minimize thermal mismatch. Time savings of 60% were realized by using ATMCS to generate steel billet tool designs over the conventional CAD method. This savings also yielded a positive cost variance of 60% of the funds allocated for this effort, which were returned to the U.S. Navy.

Extensive savings have been documented in the rest of the fabrication process. Tool fabrication time decreased substantially using ATMCS. A typical composite header board tool, originally taking one week to fabricate, now requires only six hours, an 85% time savings. The improved tooling accuracy has led to easier part fabrication and assembly processes. The ATMCS expert system was targeted for application on the ALTAIR lunar lander and was applied on the Max Launch Abort System (MLAS) vehicle.

THERMAL PROTECTION SYSTEM

Ablative materials are required to protect a space vehicle from the extreme temperatures encountered during the most demanding (hyperbolic) atmospheric entry velocities, either for probes launched toward other celestial bodies, or coming back to Earth from deep space missions. To that effect, the resin-impregnated carbon ablator (RICA) is a high-temperature, carbon/phenolic thermal protection system (TPS) material designed to use modern and commercially viable components in its manufacture. Heritage carbon/phenolic ablators intended for this use rely on materials that are no longer in production (i.e., those used for Galileo, Pioneer Venus); hence the development of alternatives, such as RICA, is necessary for future NASA planetary entry and Earth re-entry missions.

RICA's capabilities were initially measured in air for Earth re-entry applications, where it was exposed to a heat flux of .009 MW/in.^{2} (14 MW/m^2) for 22 seconds. Methane tests were also carried out for potential application on entry of Saturn's Moon Titan, with a nominal heat flux of .0009 MW/in.^{2} (1.4 MW/m^2) for up to 478 seconds. Three slightly different material formulations were manufactured and subsequently tested in the plasma wind tunnel at the University of Stuttgart in Germany (PWK1) in the summer and fall of 2010. The integrity of the TPS was well preserved in most cases, and results show great promise (Esper and Lengowski 2012).

There are several major elements involved in the creation of a successful ablative TPS material. The choice of fabric and resin formulation is only the beginning. The manufacturing process relies on careful choices of temperature, pressure, and time. It must result in a material that survives heat loads with no delamination or spallation. Several techniques have been developed to achieve this robustness. Variants of the RICA material showed no delamination or spallation at intended heat flux levels and their potential thermal protection capability was demonstrated. Three resin formulations were tested in two separate samples each manufactured under slightly different conditions. A total of six samples were eventually chosen for test at the PWK1. In the most extreme case, the temperature dropped from 5,432 to 122° F

(≈3,000 to 50° C) across .7 in. (1.8 cm), which demonstrated the material's effectiveness in protecting a spacecraft's structure from the searing heat of entry. With a manufacturing process that can be easily recreated due to a robust manufacturing readiness level, RICA has proven to be a viable choice for high-speed hyperbolic entry trajectories, both in methane (Titan) as well as in air (Earth) atmospheres (Esper and Lengowski 2012).

TECHNOLOGY TRANSFER

Firefighting and Protection

Fire-safe rooms and forest fire trucks are just two areas where NASA's thermal protection system (TPS) could be used to save lives. Each year, more than 2,500 people die and 12,600 are injured in home fires in the United States, with direct property loss estimated at $7.3 billion annually. Fire spreads quickly; there is no time to gather valuables or make a phone call. In just two minutes, a fire can become life-threatening. In five minutes, a residence can be engulfed in flames (FEMA 2014).

Heat is more threatening than flames. A fire's heat alone can kill. Room temperatures in a fire can be 100° F (≈38 °C) at floor level and rise to 600° F (≈316 °C) at eye level. Inhaling this super-hot air will scorch your lungs. The heat can melt clothes to your skin. In five minutes, a room can get so hot that everything in it ignites at once. This is called flashover (FEMA 2014).

The incorporation of a closet lined with a thermal protection system as part of a lifesaving fire-safe room could provide a person or persons a place to go when a fire breaks out. Since most fires occur at night when people are asleep, the rapid spread of fire impedes exit from the house. A closet lined with a TPS and venting could provide a place to go rapidly to avoid flames and survive.

Worldwide, many firefighter fatalities in the last 10 years have resulted from being trapped while trying to escape a fire. While firefighters are supposed to have their own individual fire shelters with them, this is not always the case, especially with reinforcement firefighters coming from other locations. Also fires shift quickly, and have trapped even the most astute firefighters when winds shift.

Firefighters normally remain close to the engine or the water line. This is a major fire rule. Airborne commandos transported via helicopter use soft tanks and small relay water pumps. They protect themselves with a long-distance water line, equipped with emergency taps every 300 ft (≈91 m) and supplied by a flat tank fed by the helicopter in a glade. Firefighters who set up long-distance water lines are protected by suitable T connectors. Nevertheless, accidents have occurred, especially in situations where there are sudden ignitions, engine and/or pump breakdowns, or even unexpected lack of water.

In regions where remote firefighting takes place, a thermal protection “tent” constructed using RICA could be deployed for rapid shelter. The TPS-RICA shelter would provide a lightweight structure to shelter forest firefighters from heat, flame, and embers.

Submersibles

It seems logical that the materials and processes used to manufacture inhabited space vehicles, which must withstand the outer-space environment, would be extensible to a vehicle used for inhabited undersea exploration.

Inhabited and remotely piloted underwater vehicles can leverage the use of inhabited space vehicle manufacturing technology and composite materials. The same design and material attributes that have driven both NASA and commercial space vehicle designers and developers to begin aggressively looking at and incorporating composite materials have invigorated the designers and builders of inhabited underwater vehicles to do the same. Significant effort since 1995 has resulted in materials and processes that have been successfully applied to underwater vehicles (Graham 1995; Mahalingappa 1995).

Under a contract issued to Boeing Research & Technology (BR&T), OceanGate, the Applied Physics Laboratory at the University of Washington (APLUW), and Boeing have validated the basic hull design for a submersible vehicle able to reach depths of 9,800 ft (≈3,000 m). With its large 180° borosilicate glass dome, the new vehicle offers clients a chance to examine the environment, collect samples, and deploy technology in subsea settings in person and in real time. When commercially available in 2016, Cyclops reportedly will be the only privately owned, deep-water (greater than 6,600 ft [≈2,000 m]) manned submersible available for contracts (see Figure 3-10). A follow-on 19,685 ft (6,000 m) version is slated for completion in fourth quarter 2016 (Composites World 2013).

The Cyclops submersible features a 7-in. (≈178-mm) thick, carbon-fiber hull that uses proprietary Boeing manufacturing technology based on automated fiber placement. OceanGate says the ability to accurately place thousands of individual strips of pre-impregnated fiber using the proprietary technology overcomes many of the hard-to-control variables surrounding

Figure 3-10. OceanGate's Cyclops submersible. (Courtesy OceanGate, Inc.)

traditional filament winding processes. The hull is designed to withstand the high compressive load of 300 bar or 4,300 psi (≈3,000 m of head).

The use of carbon fiber makes Cyclops significantly lighter than other subsea manned submersibles, so deployment operations will be faster, easier, and cost efficient. While in the water, Cyclops' five crew members can comfortably observe the ocean depths through a massive glass dome, which offers unobstructed views for at-depth inspections, environmental assessments, discussion, decision making, and observation.

Operating at depths beyond 3,281 ft (1,000 m) with remotely operated vehicles (ROV) is extremely difficult as they require large, heavy tethers and specialized support vessels. Cyclops does not require tethering and allows its five crew members to observe underwater environments for up to eight continuous hours. Using a patent-pending submerging launch, retrieval, and transport (LRT) platform, OceanGate can operate a manned vehicle at much lower costs than most other manned vehicles and, in many cases, even less expensively than ROVs (Thompson 2011).

Oil Platforms

As concerns over oil resources grow, many countries and companies are searching for petroleum deposits on the depths of the ocean floor. Large offshore oil rigs are being constructed to search for oil. Many oil companies are beginning to use composite solutions for the pipes and tubes that rigs rely on to expel and produce petroleum.

Composites are fast taking over as superior alternatives to other traditional materials, even in high-pressure and aggressive environmental situations. Applications of composites are increasing tremendously along with the concurrent need for knowledge generation in the area. With technology innovations and developments in processes and products, composites have become attractive candidates for applications in oil, gas, piping system, topside applications, down-hole tubing in subsea, and other areas (Babu et al. 2009).

Oil companies normally use carbon-fiber composites because of their high strength and modulus compared to their density. However, fiberglass is used occasionally, for example, when corrosion protection is needed between metal pieces, or if it is a requirement that the material not conduct electricity.

Efficient and economical adaptation of composite materials to offshore applications is becoming an attractive research area. Important issues such as the aging effects in a marine environment and the load transfer between different fibers have to be dealt with in designing and fabricating composite products for offshore applications. The amount of energy required for fabricating FRP composite materials for structural applications, with respect to conventional materials such as steel and aluminum, is lower, and this works to an economic advantage.

Applications

Until recently, the use of high-performance GRE piping was limited in use for onshore fluid transport (i.e., oil, fresh water, injection water, seawater, and other fluids). Efforts in the composites industry are being directed to extend the usability of GRE piping to other types of aqueous fluids (fire water, waste, ballast water, seawater cooling, etc.) in transport to offshore platforms.

A glass-reinforced epoxy (GRE) piping system offers one solution for use in the offshore environment against highly corrosive fluids at various pressures, temperatures, and adverse soil and weather conditions (especially in oil exploration, desalination, chemical plants, fire mains, dredging, potable water, etc.).

Composite coil tubing is replacing the existing steel coil tubing for high-pressure, down-hole applications in offshore platforms. The tube can be coiled or uncoiled on a drum and is easily transported to the location of the wells. The tube is comprised of a thermoplastic liner at the inner surface, over-wound with a structural thermosetting laminate. Unlike steel coil tubes, composite tubes are effective for insertion into horizontal wells.

A pressure riser is the pipeline that connects the rig on the water's surface to the well bore at the seabed. It must separate the oil, gas, and drilling fluids from seawater. The weight of the riser is drastically reduced with the use of composite material as an alternative to heavy metallic risers. Composite risers can be designed to withstand highly corrosive chemicals, salts, and fluids under different environmental conditions, thus improving the durability and life cycle costs for offshore platforms.

High-pressure accumulator bottles are used to accommodate the relative motions between the platform and the riser. In the case of tension leg platforms, a telescopic joint is used at the upper extremity of each riser. These joints require a tensioning system capable of storing and releasing large amounts of energy as movement takes place. Tension is applied through gas-pressurized tensioners with accumulator bottles. In older designs, steel accumulator bottles were used, but recently considerable success has been achieved with composite bottles, which offer significant weight and cost savings. They are less than one-third of the weight of equivalent steel bottles and can withstand very high internal pressures.

Caissons are attractive applications for composites as an offshoot of GRE piping technology. In general, caissons are used to allow the service fluids to enter or leave the sea. They are located at splash zones in the sea water. Caissons are designed to withstand flexural fatigue loads created by waving loads and corrosion from aqueous fluids in the sea.

The weight of the topside rig assembly could be substantially reduced by using composite products such as pultruded glass/phenolic gratings for floors, walkways, and handrails, along with enclosures and heat protection walls, etc. Composites have been successfully demonstrated for applications such as accumulator bottles for riser tensioning systems, blast relief systems, fire walls, enclosures, modular housing panels, etc. (Babu et al. 2009).

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4

COMPOSITES IN UNINHABITED SPACE VEHICLES

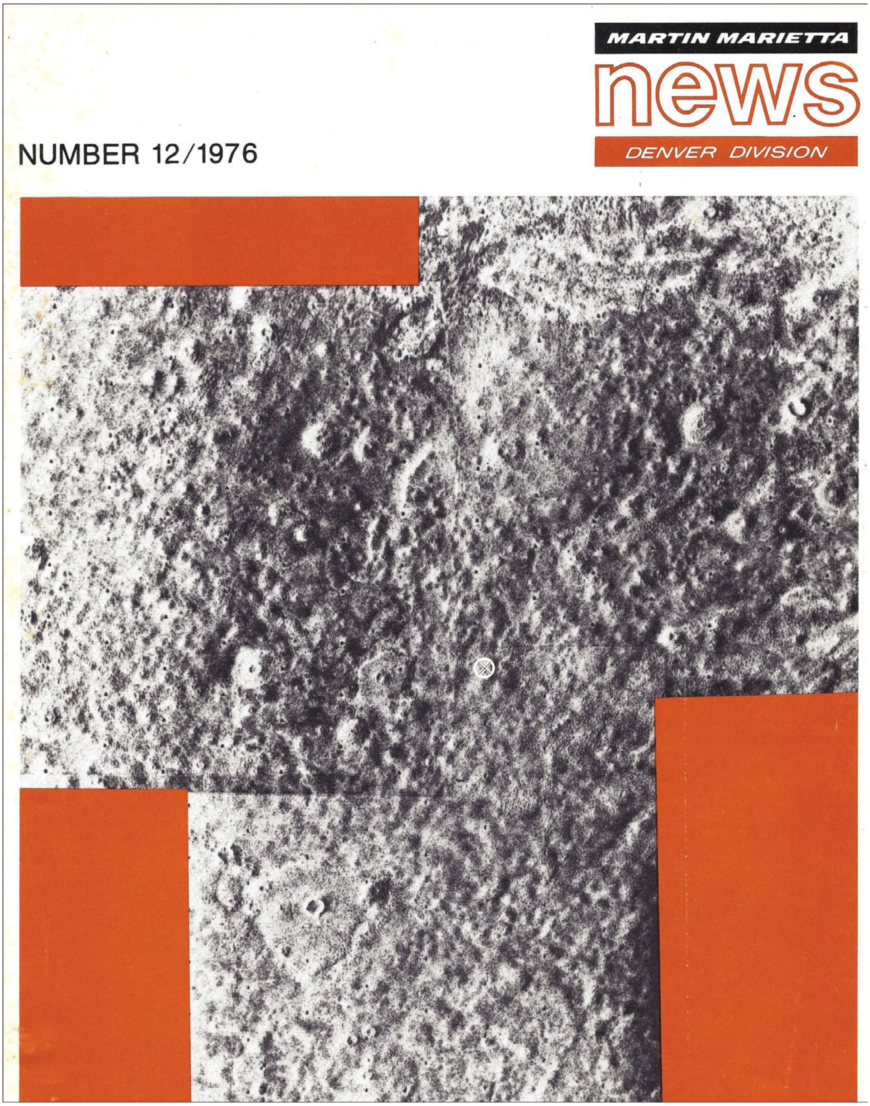
"The desire to reach for the sky runs deep in our human psyche."

—Cesar Pelli

INTRODUCTION

If you look closely, you will see a small X in the center of Figure 4-1 marking the anticipated landing site of the Viking 2 Mars lander (Staff 1976). The composite photo was taken by the Viking 2 Orbiter on August 16, 1976 on the surface of Mars from a distance of about 2,100 miles (3,360 km). It is located in the eastern end of Utopia Planitia on Mars: 48° North and 226° West. The lander actually set down at 47.97° North and 225.67° West at 4:38 p.m. (MDT) on Friday, September 3, 1976. The accuracy was not bad for 35+ year old technology. I was watching the big screen at the Denver Division of Martin Marietta with my colleagues from the Engineering, Manufacturing, Production, and Development Lab (EMPDL) as little pixels slowly formed discernible images. My responsibility had been to help develop and test various materials to minimize weight while meeting the power and duration requirements for the batteries that powered the Viking 2 lander. This small contribution to the Martin-Marietta-built Viking 2 Mars lander (see Figure 4-2) made us proudly anticipate each pixel as it formed the first images sent back to Earth on our big screen.

Voyager 2 launched on August 20, 1977, from Cape Canaveral, Fla. aboard a Titan-Centaur rocket. On September 5, Voyager 1 launched, also from Cape Canaveral aboard a Titan-Centaur rocket. The mission objective of the Voyager Interstellar Mission (VIM)



MARTIN MARIETTA

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Figure 4-1. Viking 2 Mars Lander targeted landing site. (Courtesy Lockheed Martin)

was to extend NASA's exploration of the solar system beyond the neighborhood of the outer planets to the outer limits of the Sun's sphere of influence, and possibly beyond. This extended mission is continuing to characterize the outer solar system environment

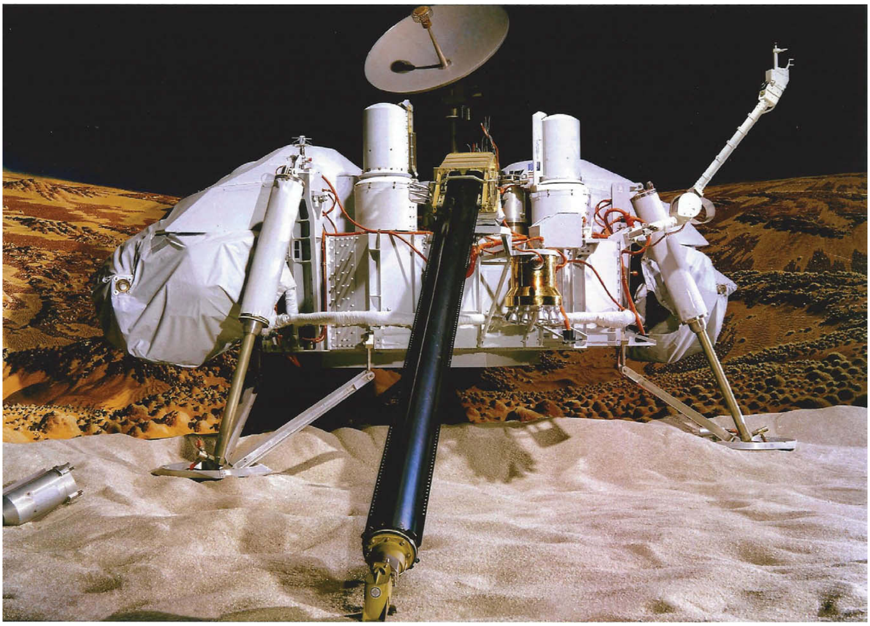

Figure 4-2. Viking 2 Mars Lander. (Courtesy NASA)

and search for the heliopause boundary, the outer limits of the Sun's magnetic field and outward flow of the solar wind.

As of September 2013, Voyager 1 was at a distance of 18.7 billion km (125.3 astronomical units [AU]) from the Sun and Voyager 2 at a distance of 15.3 billion km (102.6 AU). Voyager 1 is escaping the solar system at a speed of about 538.5 million km (3.6 AU) per year, 35° out of the ecliptic plane to the North, in the general direction of the solar apex (the direction of the Sun's motion relative to nearby stars). Voyager 2 is also escaping the solar system at a speed of about 493.7 million km (3.3 AU) per year, 48° out of the ecliptic plane to the South.

A total of 11,000 work-years were devoted to the Voyager project through the Neptune encounter. This is equivalent to one-third the amount of effort estimated to complete the great pyramid at Giza for King Cheops.

The heliopause has never been reached by any spacecraft; the Voyagers may be the first to pass through this region, which is thought to exist somewhere from 8–14 billion miles (12.9–22.5 billion km) from the Sun (see Figure 4-3). This is where the 1-million-mile-per-hour (1.6-million-km-per-hour) solar wind slows to about 250,000 miles per hour (402,336 km per hour)—the first indication that the wind is nearing the heliopause. The Voyagers should cross the heliopause 10–20 years after reaching the termination shock. They have enough electrical power and thruster fuel to operate at least until 2020. By that time, Voyager 1 will be 12.4 billion miles (19.9 billion km) from the Sun and Voyager 2 will be 10.5 billion miles (16.9 billion km) away (see Figure 4-4).

Boeing unveiled its hydrogen-powered Phantom Eye unmanned airborne system during a ceremony in St. Louis on July 12. The demonstrator, which will stay aloft at 65,000 ft (19.812 km) for up to four days, is powered by two .5-gal (2-L), four-cylinder engines that provide 150 hp (111 kW) each. It has a 150-ft (45.7 m) wingspan, will cruise at approximately 150 knots (173 mph or 278 kph) and can carry up to a 450-lb (204-kg) payload (Jackson and Haddox 2010).

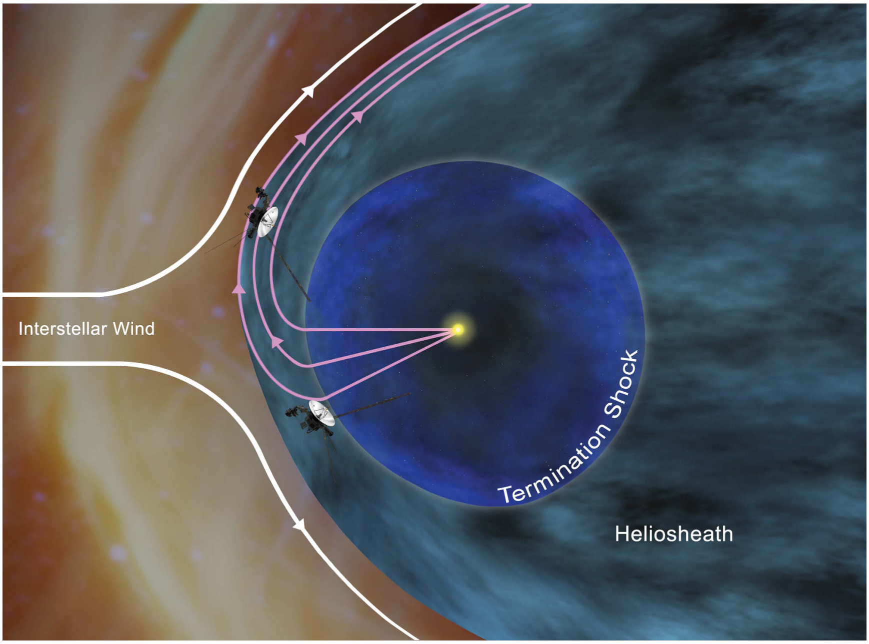

Figure 4-3. The solar system showing the heliopause. (Courtesy NASA)

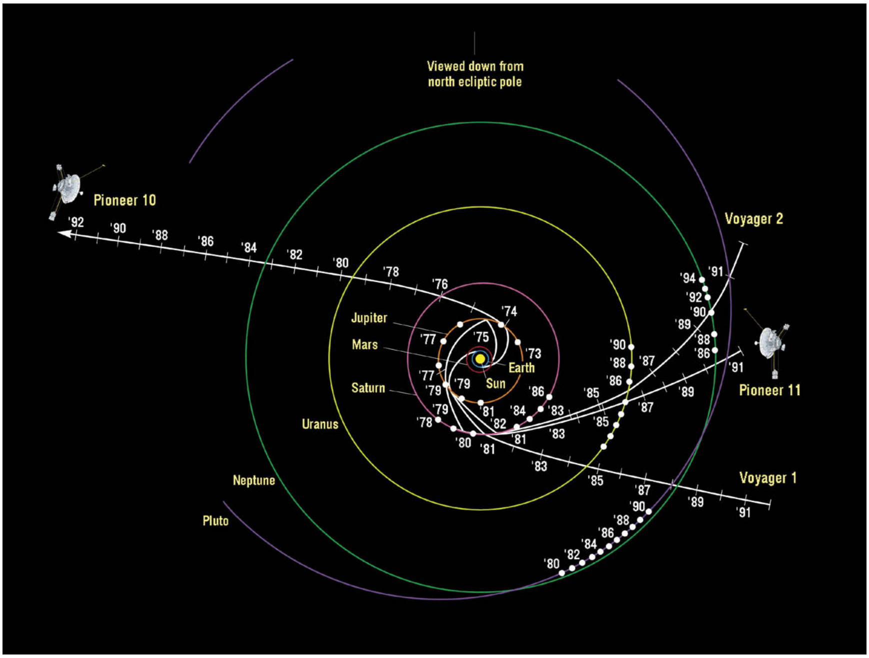

Figure 4-4. Voyager 1 and Voyager 2 positions in 2020. (Courtesy NASA)

Uninhabited space vehicle missions and their scopes range from just at the boundary of space, in low Earth orbit, to beyond our solar system. They are sent into space to land on the Moon or Mars, orbit Earth or Mars, pass by other planets and moons, and even purposely crash into other moons or planets to understand their surface compositions.

NASA successfully bulldozed two spacecraft into the Moon's South Pole in a search for hidden ice. First, a 2.2-ton (2-metric ton) empty rocket hull smacked the Moon's South Pole. Four minutes later, the camera-and-instrument laden space probe made its death plunge. The intentional crashes kicked up miles of lunar dust. The Lunar Crater Observation and Sensing Satellite was a robotic spacecraft operated by NASA. The mission was conceived as a low-cost means of determining the nature of hydrogen detected at the polar regions of the moon. The satellite guided an empty upper stage on a collision course with a permanently shaded crater that kicked up evidence of water at the Moon's poles.

DESIGN REQUIREMENTS

The missions assigned to uninhabited space vehicles (USV), such as satellites, landers, and voyagers, have common requirements that can be enhanced by the application of new manufacturing processes and materials. Considerations for the USV design include aerodynamics, configuration, propulsion, trajectory, mass properties, cost, operations, reliability, and safety.

The USV's three primary missions of exploration, observation, and communication are complicated by their packaging and launch requirements. Every USV must be packaged to fit within the protective covering at the top of the launch vehicle. Included in the packaging requirements is the additional integration hardware necessary to coordinate the separation of the USV from its protective covering and the launch body. Space is at a premium within the protective covering. The creative placement of USV components, parts, structure, and hardware to satisfy the mission requirements and objectives is critical to success. The compact USV that resides within the protective covering at the top of the launch vehicle on Earth is transformed when separated and sent on its solitary journey into space. Arms, antennae, solar arrays, and scientific hardware unfold to reveal an object that is reminiscent of a butterfly emerging from its cocoon. The success of a single-purpose-built, very expensive, highly complex piece of scientific hardware is complicated and depends on the completion of its metamorphosis.

Further complicating the design specifications for a USV is the need to withstand the vibration and stress of the Earth departure stage, to the main engine cutoff, and then the separation portions of its journey into space.

To date, the only way to achieve the propulsive energy to successfully launch a spacecraft from Earth has been by combustion of chemical propellants. There are two groups of rocket propellants, liquids and solids. Many spacecraft launches involve the use of both types of rockets, for example, solid rocket boosters attached to liquid-propelled rockets. Hybrid rockets, which use a combination of solid and liquid, are also being developed. Solid rockets are generally simpler than liquid, but they cannot be shut down once ignited. Liquid and hybrid engines may be shut down after ignition and conceivably could be re-ignited.

Expendable launch vehicles are used once. The U.S. Space Transportation System (STS) or Shuttle is a reusable system. Before its retirement, most of its components were refurbished and reused multiple times.

For low-Earth-orbit vehicles, the launch vehicle must provide a much larger part, or even all, of the energy for the spacecraft's orbital speed, depending on the inclination. For interplanetary launches, the vehicle has to take advantage of Earth's orbital motion as well to accommodate the limited energy available. The launch vehicle accelerates in the general direction of the Earth's orbital motion (in addition to using Earth's rotational speed), which has an average velocity of approximately 62,137 mph (100,000 kph) along its orbital path. In the case of a spacecraft embarking on a Hohmann interplanetary transfer orbit, the Earth's orbital speed represents the speed at aphelion or perihelion of the transfer orbit, and the spacecraft's velocity merely needs to be increased or decreased in the tangential direction to achieve the desired transfer orbit (Hohmann 1960). The trajectories have to be considered in the structural design, stress analysis, fabrication, and assembly of the payload and its protective nose cone.

Launches from the East coast of the United States (the Kennedy Space Center at Cape Canaveral, Fla.) are suitable only for low-inclination orbits because major population centers underlie the trajectory required for high-inclination launches. High-inclination launches are accomplished from Vandenberg Air Force Base on the West coast, in California, where the trajectory for high-inclination orbits avoids population centers. An equatorial site is not preferred for high-inclination orbital launches. They can depart from any latitude.

To lift itself off the ground, the launch vehicle must exceed 1 g of thrust (by definition, 1 g is the rate of acceleration caused by the gravitational field at the surface of the Earth). However, lifting off at 1.1 g would be a very slow, unstable, fuel-consuming ascent. So instead, launch commands go for as much thrust as they determine the vehicle and payload can handle. This ends up being about 5–7 g of thrust, though it is throttled back during the phase when the vehicle passes through its maximum aerodynamic pressure. Some launches have exceeded 13 g of thrust, placing heavy loads and stress on the payload.

Besides the forces that affect the vehicle payload during launch, rocket-induced vibration and ignition overpressure response environments need to be predicted. This is necessary to evaluate their impacts on critical components and mechanisms (Caimi et al. 2001). The vibration produced by the burning of the solid rocket propellant in the first-stage booster is called *thrust oscillation*. The vibrations (oscillations) come in the form of waves, which travel up and down the length of the rocket like a musical note through an organ pipe. One of the biggest challenges in rocket design is developing avionics (aviation electronics) that can function in this vibrating environment.

Vibration is not just a rocket issue, thus all electronic hardware is tested for its ability to handle shock and vibration. While it may seem like a simple concept, vibrations or shaking can have a powerful effect on a rocket's avionics, hardware, and any payload, including humans, onboard. Shock and vibrations come from sources including the thrust of the solid rocket motors or boosters at lift off and during flight, the burning of rocket propellant, and the speed a rocket travels, which can exceed four times the speed of sound (Sauser 2009).

DESIGN, MANUFACTURING, AND ASSEMBLY CONSIDERATIONS

Several different disciplines contribute to analysis of the conceptual design, manufacture, and assembly methodology used for uninhabited and inhabited space vehicles. A different tool is used by each discipline and, in some cases, iteration between two or more analysis tools is required. This coupling can be visualized as a design structure matrix (DSM) or "N-squared" diagram. Each box along the diagonal represents a contributing discipline's analysis, and the lines represent the flow of information. Information fed forward through the design process is represented by lines on the upper right of diagonal, while the lines in the lower left are feedback (Young et al. 2009). A notional DSM representative of the one used for the Max Launch Abort System (MLAS) is shown in Figure 4-5. Feedback between the disciplines performing the trajectory analysis, weights and sizing analysis, and manufacturing variability analysis closes the performance and configuration of the launch vehicle. The feedback between those disciplines responsible for evaluation of operations, reliability, and cost closes the economics of the vehicle (Young et al. 2009).

While the digital thread and DSM design interaction streamline many aspects of USV design, manufacture, and integration, the primary challenge to design and manufacturing remains the one-off nature of the USV product. Compounding the design challenges is the unique nature of the requirements for each mission.

Each USV is custom designed and assembled to meet its mission requirement, resulting in a collection of components aggregated into a final shape. The final shape is either compacted to fit within the space limitations of the launch vehicle or designed with a customized structure to facilitate its attachment to the interior of the protective nose cone. While the attach structure may seem a minor consideration of the design, it is complicated by the transference of launch forces, vibration, and oscillations expected on its journey. The assembly also must have the mass properties necessary to facilitate alignment of the center of gravity to the center line of the launch vehicle. Compounding these issues, companies and universities manufacture USVs using varying design approaches for attachment, integration, and deployment. The variability drives design and manufacturing complexity and cost.

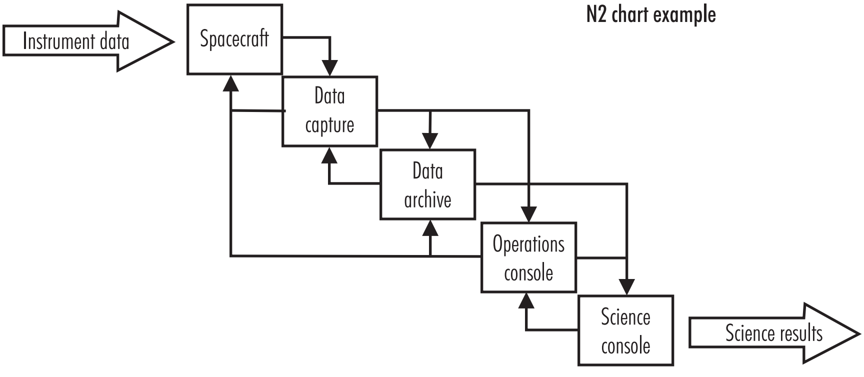

Figure 4-5. Design structure matrix or or "N-squared" diagram.

EXTENSIBILITY OF TECHNOLOGY

Biomechanical Applications

MLAS and its associated research projects focused on stretching the use of composite materials and new manufacturing processes to enhance inhabited space vehicle, uninhabited space vehicle, and launch vehicle structures. Along the path to the selected MLAS manufacturing processes and materials were trade studies. The studies were used to determine the process and material technology readiness levels, manufacturing readiness levels, and risk for transition to production on space vehicles. Promising new processes for future space vehicles with potential for extensibility to other products included biomechanical applications for composites manufacturing and shaped memory composites.

One of the major breakthroughs of the Wright brothers was the ability to control and maneuver their aircraft. Roll control was provided by a unique idea called wing warping. The central cells of the wing are held in place by wire rigging so that the vertical struts cannot move relative to the wings. But the outer cell of each wing is wired differently. There are no cross wires on the outer struts except at the front. The leading edge of each wing is kept straight by the rigging wires, but the rear portion of each wing can move relative to the rest of the wing. There are additional control wires at the rear of the wing that connect the wing tips to a pedal at the foot of the pilot. As the pilot pushes the pedal, the wire pulls on the wing tip and the shape of the outer panel changes. Because of unequal forces on the wings of the aircraft, the aircraft will roll or bank in the direction of the smaller force. (The wing with the higher lift will move upward, the wing with the lower lift will move downward.)

When the aircraft banks or rolls to one side, the balance of forces on the aircraft are changed and the aircraft moves in a new direction. The weight force is always directed toward the center of the Earth. In a wings-level cruise condition, the lift is perpendicular to the flight direction and opposes the weight. The lift acts nearly perpendicular to the wing surface. When the aircraft (and the wing) rolls to one side, the lift remains perpendicular to the flight path and the wing surface. A large portion of the lift still opposes the weight, but there is now a component of the lift that produces a side force on the aircraft. The side force is unopposed by any other force, so the aircraft moves in that direction in accordance with Newton's first law of motion (every object will remain at rest or in uniform motion in a straight line unless compelled to change its state by the action of an external force). The side force is a centralized force; it is always perpendicular to the flight path because it is a component of the lift. An object subjected to a centralized force moves in a circular path.

If the aircraft is rolled in the opposite direction, the plane turns in the opposite direction. Banking an aircraft to one side causes the aircraft to turn in that direction. The turning is not the result of a rudder input as it would be on a boat. The 1901 aircraft had no rudder. Airplanes are turned by banking or rolling. The rudder on an airplane is used to keep the nose pointed in the correct direction to eliminate a condition called adverse yaw, and to bring the thrust vector into the turn on high-performance aircraft.

The Wright brothers used wing warping for roll control on their 1901 and 1902 gliders and on the successful 1903 flyer. Modern airliners and fighter planes no longer use wing warping for roll control. They typically use either ailerons or spoilers that move sections on the wing of the aircraft.

The complexity of the mechanisms to control ailerons and spoilers on both commercial and military aircraft, and the radar reflection of ailerons and spoilers on military aircraft, have reinvigorated interest in wing warping.

The use of graphite fiber epoxy and other composite materials as replacements for metallic parts on airplanes and space vehicles has led to evaluation of aeroelastic tailoring as a method to reintroduce wing warping and wing morphing into the designs for next-generation airplanes and space vehicles.

Researchers are investigating biomechanical-derived fiber orientation of composites wings to enable strength and stiffness where and when needed. This technology is to provide warping elasticity in areas of the control surface and stimulation of the fibers to induce controlled movement without the use of mechanical devices such as linear or hydraulic actuators. In aerospace engineering, this means optimizing the aerodynamic, thermodynamic, and structural layout of an air vehicle. One way of achieving this is by using the concept of morphing. In the field of engineering, the word "morphing" is used when referring to continuous shape change—no discrete parts are moved relative to each other but one entity deforms upon actuation. For example, on an aircraft wing, this could mean replacement of a hinged aileron and/or flap by a structure that could transform its surface area and camber. The structure would transform in such a way as to not allow open gaps in and between itself and the main wing or lead to sudden changes in cross-section that result in significant aerodynamic losses, excessive noise, and vibration in the airframe (Thill et al. 2008).

A morphing skin can be envisaged as an aerodynamic fairing to cover an underlying morphing structure. A requirement for use in an aerospace application is that it must be able to change shape in at least one of two ways (Wiggins et al. 2004):

1. Change in surface area (e.g., flaps, slats on an aircraft wing), and
2. Change in camber (e.g., aileron, flaps, slats, winglet on an aircraft wing, or variable pitch propeller).

This shape change can be instigated by external or integrated actuators, which make the skin self-actuating or active and potentially "smart." An active structure can be defined as possessing the ability to change shape while maintaining a continuous form, whereas a passive structure, such as a hinged aileron, has discrete components that move relative to each other. A smart structure is able to sense external stimuli (pressure, velocity, density, or temperature change), process the information, and respond in a controlled manner in real-time (Noor et al. 2000; Weiss 2003). Overall, sensing, actuation, and control are embedded in a single multifunctional smart structure. Smart materials encompass a broad range of components that can respond mechanically (e.g., shorten, elongate, flex) to a variety of stimuli including electromagnetic fields, pressure, temperature and/or light. Note that it is often not obvious how to differentiate between the material and structural levels of any given system due to the hierarchical nature and multi-functionality of the components involved (Weiss 2003).

Many engineering concepts have been copied from nature. Nearly all load-bearing structures in nature are fibrous, which means that they are good in tension but poor in compression (John et al. 2005). There is a similar problem for man-made composite materials. Nature has four solutions (Thill et al. 2008):

1. Pre-stress fibers,
2. Introduce high volumes of mineral phases (matrix),
3. Heavily cross-link the fibers to introduce lateral stability, or
4. Change fiber orientation so that compressive loads do not act along the fibers.

Airline and Automotive Applications

Two areas where advances in composite materials will have benefit are in the interiors of automobiles and commercial airplanes. While the obvious use of nature's example for fiber orientation is wing warping (morphing), another application is in the realm of automobile and airline seating.

Metal framing in seats and mechanisms for seat control add considerable complexity and weight to land and air vehicles. The use of morphing composite materials for seating would add comfort and reduce weight. A smart seat structure would be able to sense external stimuli (pressure, velocity, density, or temperature change), process the information, and respond in a controlled manner, adding to passenger comfort. Sensing, actuation, and control would be embedded in a single multifunctional smart seat. Smart materials encompass a broad range of components that can respond mechanically to shorten, elongate, and flex to a variety of stimuli including pressure, temperature, and light. Airplane seats offer a lucrative opportunity for a smart composite seat application.

Airframes have led the market for the design and use of high-strength composite materials. The next expansion for their use in airplanes is emerging and will challenge manufacturers to meet demand. Aircraft interiors represent a larger market (by volume) than airframe structures for high-performance composites. Interior components account for as much as 40% of a commercial airliner's empty operating weight. Over the next decade, ≈1,600 new commercial transport aircraft will enter service. Each delivered airplane will require thousands of pounds of composite interior components to increase fuel efficiency and reduce operating costs for the airlines while improving passenger comfort.

More carbon-fiber-reinforced polymer (CFRP) is earning its way into the cabin. And there is a growing interest in recycled carbon fiber for applications such as seat backs and trays. Moving through the next decade, there will be thousands of tons of reclaimed carbon fiber sent to recycling for alternative uses. The research effort is intensifying to find fast, economical, and satisfactory methods to reclaim carbon-fiber material in a usable form. There is a great interest in returning the reclaimed material to the cabin.

Phenolic resins are the current resin systems of choice for interior applications and will continue their strong presence in the future. Thermoplastics will play a significant role in displacing metals in new aircraft cabins and might also begin to displace phenolics in some composite applications (Bullen 2013).

The new-build market represents about 6 million lb (2,722 metric tons) of composite components annually for the new aircraft scheduled for delivery between 2013 and 2023. By the time the Airbus A350 and Bombardier CSeries enter full-rate production, the OEM market could grow by at least 50% compared to 2012. Prepreg material requirements for commercial aircraft interiors will more than double in the carbon fiber and aramid fiber categories, and the carbon fiber/glass fiber gap will narrow during the forecast period. In addition to new aircraft, the aftermarket interiors segment will make a significant contribution to growth in the use of composites on commercial aircraft during the same forecast period (Composites Forecasts and Consulting 2013).

Aftermarket potential is driven by replacement cycles and economic conditions. Generally, passenger seating is replaced every one to two years. Paneling, class dividers, and other major components are turned over every four years. Complete cabin refurbishments take place every six to eight years. The replacement and refurbishment effort incentivizes interior component producers because there is continuous demand for their products after the airplane is delivered.

Seats represent one of the biggest near-term opportunities. New and replacement seating has the potential to consume 4–5 million lb (1,814–2,268 metric tons) of composites within the next five years. Switching to composite seats can save from 882–992 lb (400–450 kg) on a single-aisle aircraft. Composite materials can be used to produce a thinner seat, reducing the thickness by as much as 2 in. (50.8 mm). With the current spacing in the coach cabin, thinner seats mean that, on average, a new row can be added every 18 rows without any weight penalty (Bullen 2013).

Composite seat designers, such as Recaro and ZIM Flugsitz GmbH of Germany, have found that composite materials provide better passenger comfort through ergonomic design. Conformal seating and integrated electronics also add to the composite seat's aesthetic appeal.

Newer seat designs using high-strength composites offer a significant departure from the stale seat designs populating today's airplane. High-concept seat designs are being developed based on the idea of active seating to enhance the appeal, comfort, and functionality of seats. Ludekedesign (Zurich, Switzerland) designed and manufactured a seat with an Aerasknit® cover on a carbon-fiber shell. The reclining function is built into the fabric, eliminating the need for a mechanical recline. The Ludekedesign seat concept is still in the development stage but offers insight into the effort of OEMs to provide better customer comfort and aesthetic appeal while reducing airplane weight and adding revenue-producing seats.

The manufacturing potential over the next decade for seats based on projected airplanes entering the market is ≈10,230,000. This production number is based on new aircraft requirements and a two-year cycle of seat replacement. It does not include the market potential for refurbishment of seats currently in operation within the airline fleets.

Other potential areas for composites growth include service carts, brackets, trays and clips, cockpit flooring, and seat rails. Galley carts are a strong candidate for the application of high-strength composites. It is surprising to note the quantities that an average airplane requires. The general rule is an average of from 80–100 in the supply chain for each plane with three to four carts on the ground for every cart flying. The cart supply process includes removal, transport, refurbishment, repair, restock, and staging for redelivery.

The advantages of high-strength composite galley carts are longer life due to their impact resistance and reduced weight, which contributes to fewer crew, passenger, and service personnel injuries. Maintenance costs and spare parts inventory are also reduced because they have fewer parts and molded screws. Besides increased durability, their flexible, sturdy composite construction has excellent shock-absorbent properties. It also enables high read rates for embedded RFID chips for traceability purposes. In service, the carts require less energy and/or dry ice to keep contents cool due to improved insulation. Lightweight composite carts offer an attractive alternative to the bulky, heavy, and less aesthetically appealing carts presently in use.

Based on the number of airplanes due to be delivered over the next decade and a four year refurbishment rate, there is a market potential for ≈2,952,000 galley carts. Aircraft already in service would add to the requirement.

Challenges to the Use of Composites

While the market potential is large, the challenges that prohibit the use of high-strength carbon fiber for interior airplane components must be addressed. Material cost, manufacturability, and flammability are major inhibitors to the rapid proliferation of high-strength, carbon-fiber composite materials in the interiors of commercial aircraft.

In addition to composite material costs, recyclability of manufactured components has become a major worldwide concern for environmental compliance. Research efforts have demonstrated typically the same fiber stiffness on recycled composites as virgin material. Electrical properties are unchanged but there is some degradation in strength. Recycled fibers have the potential to replace virgin fibers in some applications, such as interior components, where strength properties are not as rigid as the exterior or structural components of the airframe. The potential for recycling material back into the aircraft as interior components aligns with the projected retirement of carbon-fiber composite materials from existing fleets of airplanes.

Recycling existing parts back into new interior components can reduce the cost of composite raw material when compared to virgin material by as much as 50%. There are strong economic drivers for carbon-fiber recovery and reuse on cabin articles. Several recovery methods have been developed. To date, MIT-RCF has reclaimed 1.5 million lb (680.4 metric tons) of carbon-fiber scrap from landfills. A test barrel for Boeing's 787 program was chopped up and recycled, and bicycle manufacturer Trek (Waterloo, Wis.) has implemented a recycling program for its carbon bike frames that has, thus far, amassed 140,000 lb (63.5 metric tons) of scrap.

Manufacturability is another factor that needs to be addressed. Aircraft manufacturers are low-rate producers of carbon-fiber parts. The process for manufacture of high-strength, carbon fiber parts has been a barrier for use of the material in the high-production-rate automotive industry, except on premium automobiles such as the Lamborghini. The need for transfer of high-production-rate manufacturing technologies to a material developed for low rates is essential to get the material into the interior components.

Seat manufacturers for the current designs are primarily metal and fabric fabricators with limited or no experience in the manufacture and process controls required for high-strength, carbon-fiber composites. Therefore, there is opportunity for new manufacturers to enter the market or combine with existing seat manufacturers to integrate and optimize the manufacture of composite interior airplane components.

One possible higher-production-rate solution is chopped fiber, liquid resin infusion using precise fiber charges in seat or cart compression molds. Unlike virgin material, recycled material emerges from the process as random discontinuous bundles of fiber. The process for straightening/aligning the fiber to match virgin material has not been discovered yet; it is estimated to be expensive if it can be accomplished. The fibers do not need to be straightened/aligned if used as a charge in a compression mold.

Material flammability is another issue that must be solved to enable the application of high-strength carbon fiber and incentivize its use for seats and galley carts. New flammability test methods for composites aimed at flame propagation have driven research to evaluate their use, processes, criteria, and standards. The new Méker burner test uses a device similar to a Bunsen burner, only the flame burns hotter and wider. It has the potential to be proven a more stringent and simpler test for aircraft certification.

The Flammability Standardization Task Group (FSTG), a subgroup of the FAA's International Aircraft Fire Test Working Group, was formed to collaborate and propose industry-wide standards and methods of compliance. This is due to FAA flammability requirements being interpreted differently by regional FAA organizations, other regulatory agencies, and industry suppliers and manufacturers. Before the widespread replacement of existing interior components can be accomplished, the inconsistences need to be addressed and corrected.

Conclusions

There is an opportunity to manufacture a wide variety of interior components on airplanes using high-strength, carbon-fiber composite material. The opportunity is incentivized by their lighter weight, increased strength, and ability to offer greater passenger comfort.

The limitations can be mitigated by high-rate-production tooling and processes, and recycling if the new stringent flame retardation standards can be met. The use of coatings and additives shows promise. If these issues can be addressed and mitigated, the horizon for consumption of high-strength, carbon-fiber composite materials for manufacture of airplane interior components could dwarf its use on the airframe (Bullen 2013).

Some of the research opportunities in process, which will further enable the use of composites on airplanes include:

- Developing a new flammability test method for composites;
- Next-generation honeycomb core;
- Pumpable, low-density void fillers for aircraft interiors;
- Composite prepregs that display fire resistance and adhesive properties;
- Flame-retardant adhesive technology for aircraft interior applications;
- Modified cyanate ester for air duct applications;
- Fire-resistant nano-coatings for foam and fabric using renewable and/or environmentally benign materials;
- VARTM structures for interiors;
- Aircraft seating design analysis and optimization;
- Aeras knit and carbon fiber;
- New galley carts through the extensive use of lightweight composites;

- Aircraft Fleet Recycling Association: recycling implementation, future goals, and initiatives that involve aircraft interiors;
- Combining thermoplastic technologies and materials to achieve nontraditional results for reduction of mass/weight;
- Carbon-fiber-reinforced, thermoplastic composites for complex-shape metal replacement in aircraft interiors; and
- High-flow, high-strength, OSU-compliant, carbon-fiber-filled thermoplastic composites for metal replacement.

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5

MAX LAUNCH ABORT SYSTEM (MLAS)

"Technology feeds on itself.
Technology makes more technology possible."
—Alvin Toffler

PROJECT CONCEPTS

Two major areas of focus for the MLAS project were vehicle operations and manufacturing. The concept for vehicle operations was described in Chapter 1. The manufacturing concept of operations was to bring together a diverse group of "best athletes" to develop, define, and perform the fabrication, assembly, and integration of the MLAS vehicle systems and components. Best practices for each identified manufacturing process would be performed at a manufacturing facility where the process was already in use and mature. The manufacturing facilities were evaluated based on shop rates and the availability of resources necessary to meet the schedule.

The necessary critical skills to perform the project tasks were defined. The critical skills list was used to identify the "best athlete" to perform each required task. A survey using internal and external databases composed of skill sets, aptitude, certifications, and performance measures was used to match requirements with individuals. Coordination with the operating unit was necessary to ensure the availability of individuals when needed. Shipment of needed assets, such as laser tracking systems, was also coordinated so they were available at the location where needed when the skilled individual arrived.

Management and supervisory personnel were chosen for each operation by identifying the best expertise. In example, assembly managers were identified with the critical skills necessary to motivate diverse groups of people and skill sets at a remote location for extended periods of time. They were also evaluated for their resourcefulness and innovation when confronted with challenges such as the absence of needed material and human resources.

All the major and minor critical path components were managed through a collaborative enterprise-central location in Huntsville, Ala.

MAJOR STRUCTURAL COMPONENTS DEFINED

The major structural components were composed of the forward fairing, coast skirt, boost skirt, fins, and motor cage with support struts. The forward fairing, coast skirt, and boost skirt were fabricated in quarter sections and joined together in the assembly process described in Chapter 7. A mock crew module simulator would be enclosed in the forward fairing. The quarter sections of the forward fairing, boost skirt assembly, and the coast skirt were joined and then stacked to form the completed MLAS structure.

The forward fairing (≈12,200 lb [≈5,534 kg]), crew module simulator (≈19,000 lb [8,618 kg]), and coast skirt (2,260 lb [1,025 kg]) weighed in at a combined ≈33,460 lb (≈15,177 kg). The boost skirt assembly composed of the structure (≈5,000 lb [2,268 kg]), motors (≈2,200 lb [998 kg]), and propellant (≈6,050 lb [2,744 kg]) added another ≈13,250 lb (6,010 kg) for an estimated vehicle design weight of ≈46,710 lb (21,187 kg).

The maximum thrust for the MLAS vehicle was 300,000 lbf (1,334 kN) with a maximum load of 6.3 g's.

INNOVATIVE USE OF COMPOSITES MANUFACTURING PROCESSES

The technologies described in this chapter are innovative in their application and use of composites manufacturing processes.

The use of high-strength, carbon-fiber composite material has intrigued NASA and space vehicle designers for decades. High-strength, carbon-fiber composite materials offer design flexibility as demonstrated by the composite crew module (CCM). Features such as weight reduction, stiffness, and strength as compared to aluminum are attractive to space vehicle designers. However, the reticence to use composites on space vehicles by NASA and space vehicle design engineers issues from their high comfort level with existing materials. The intense vibration that vehicles must withstand, their large sizes compared to airplanes, and the operating environment of space are some concerns.

Driving the change to composites for space vehicle components is their lighter weight and evolution of more robust manufacturing techniques. The evolution spurred by MLAS and other simultaneous manufacturing development efforts included the out-of-autoclave cure (OAC) of composites and in-situ manufacture of a large, composite sandwich core, unified structure.

Enabling the move to more efficient methods of manufacture was the divergence from brick-and-mortar, highly controlled environments and expensive-to-buy and -operate equipment, such as autoclaves. The demonstration of lean manufacturing facilities using reconfigurable, flexible, transportable ovens, cleanrooms, and processes invigorated the interest in composites as an affordable and viable alternative to traditional metal components. Lean manufacturing facility concepts and the benefits of high-strength, carbon-fiber composite material also created a synergism that incentivized the material's use for other products. The investment, cost of operation, and complex, highly controlled processes thought to be needed for any production of parts using high-strength, carbon-fiber composite materials were demystified. Up until the design, development, and manufacture of MLAS, the barriers to entry for new manufacturers of parts using carbon-fiber composite materials were highly restrictive. The barriers are now reduced so producers other than from the aerospace, transportation, ship, and wind turbine industries can look to the material for benefits to improve or enhance their capabilities and product offerings. The viability for extension of composite material uses includes sporting goods, bicycles, seats, automotive parts, and even bridge components.

VACUUM-ASSISTED RESIN TRANSFER MOLDING

Vacuum-assisted resin transfer molding (VARTM) is a well understood process. Figure 5-1 shows the basic VARTM process used to produce structural parts of the MLAS. The VARTM overarching process involves a one-sided mold, dry fabric preforms applied to the mold, and uses a tackifier or spray tack adhesive to hold them in place. The mold is then vacuum bagged and infused with a low-viscosity resin from the edges or over the surface with a distribution media to penetrate the dry fiber. It is then cured at room temperature or in an oven.

What made the MLAS application of the VARTM process unique was the innovative manufacturing process performed at a facility that normally produced ship parts. The boost skirt, coast skirt, and forward fairing quarter panels were made on wooden molds in an uncontrolled environment by mechanics unfamiliar with aerospace products. Some of the cultural and technical differences created challenges, but the experience demonstrated that understanding the process was essential and skills did not necessarily need to be product specific. Figure 5-2 shows the resin infusion and bagging process of a quarter-panel using VARTM.

The low-cost, large-scale VARTM process used fiberglass fabric with vinyl ester resin and 1-in. (25.4-mm) -thick foam core. Parts were infused under full vacuum at climate-controlled ambient temperature in four, 90-degree segments for each section. Single-shot infusion and visual inspection was performed.

Dry glass was placed on the tool's surface. The core details were located and glass was placed on top of the core. The parts were then vacuum bagged and infused with resin. After cure at room (ambient) temperature in an open shop environment, reinforcing ring

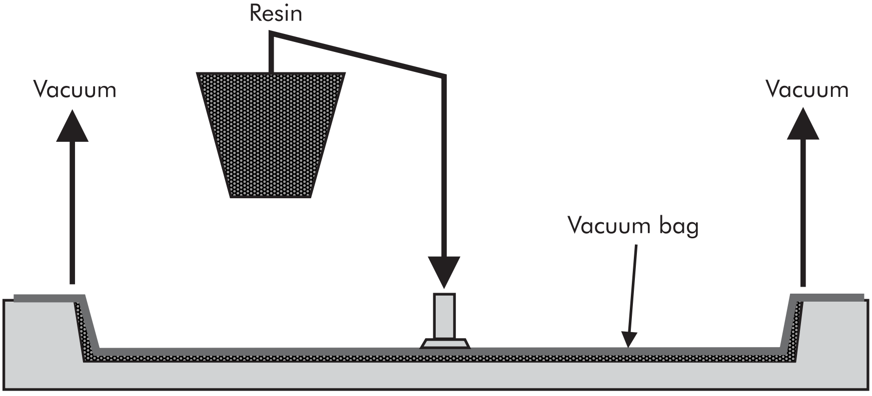

Figure 5-1. Basic VARTM process.

Figure 5-2. Resin infusion and bagging for a quarter-panel using the VARTM process.

frames were added using wet ties. After completion, the parts were separated from the mold, cleaned, trimmed, boxed, and shipped to Wallops Island, Va. for assembly.

The use of VARTM for the major structural flight components of MLAS provided a model that validated the process for extensibility to other flight and transportation products. Eliminating the complexity of composite part fabrication opens up the manufacture of composite parts to a broader supply base by reducing the costly barriers to entry that other complex methods require. The VARTM manufacturing process reduces tooling cost and facility investment in items such as autoclaves or ovens.

PARAPLAST® WASH FILAMENT WINDING

Paraplast is attractive as a material to facilitate the fabrication of high-strength, carbon-fiber composite parts. It separates (washes away) without residue or contamination of the part; and it has a coefficient of thermal expansion that matches the solidification point of the composite material as it cures in an autoclave. Therefore, the inner mold line of a part can be accurately predicted.

To produce aerospace ducting for military airframes, Paraplast material was used as a mandrel. Mechanics wrapped high-strength, carbon-fiber prepreg around the Paraplast mandrel. The raw part was then vacuum bagged and cured in an autoclave. Once cured, the Paraplast was washed away, leaving a hollow part.

The downside in the early years of Paraplast was that its pour temperature approached the usable peak temperature of the mold materials that were available. Molds often warped during the pour process. So the IML diameter was in conformance but the center line of the duct would deviate from the design geometry resulting in mismatches between adjoining parts. The rise of computer-aided design (CAD) and numerically controlled (NC) machinery enabled the fabrication of molds made from metal, such as aluminum, directly from engineering data. Paraplast material could be poured into the cavity of the mold without impact to the geometry of the mandrel. Parts produced with CAD and NC machines using higher-temperature materials enabled conformance to engineering specifications.

The link between engineering design and part fit further improved when direct manufacturing technology advanced so that prototype parts could be manufactured directly from CAD data to provide fit analysis. Additive manufacturing technology emerged, such as stereolithography. This allowed fabrication of rapid prototype parts, which were used to refine the engineering data by examining for fit-up and providing feedback through the digital thread. The fit-up analysis was used to adjust engineering data, such as duct geometry, to match the as-built cumulative variance specified for the assembled airframe. The resultant molds provided precise Paraplast mandrels that manufactured precise parts. The highly evolved process was used in conjunction with other elements resident in the MLAS digital thread including finite element analysis to produce optimal performance parts precisely to engineering design. Unique to the filament winding process was the utilization of a wood lathe to wind strands of composite material around the Paraplast mandrel. The part was then cured using an out-of-autoclave cure (OAC) process. Thus a highly evolved digital thread was completed using the most efficient and effective manufacturing process, hand manufacture of the part OAC (see Figure 5-3).

In Figure 5-3, note that the composite material is being wrapped around the Paraplast mandrel and the metal detail that facilitates attachment to the MLAS structure and thrust plate. The clevis and composite strut are bonded together during the cure process. Figure 5-4 shows the completed struts mounted in the MLAS vehicle.

OUT-OF-AUTOCLAVE CURE (OAC)

The increased use of composite materials in a variety of structures has provided manufacturers with greater design flexibility for the production of highly loaded structural members with complex

Figure 5-3. Paraplast® mandrel mounted in the lathe and in the process of being wound. (Courtesy NASA)

Figure 5-4. Completed struts mounted in the MLAS vehicle. (Courtesy NASA)

geometries. The main constraint on the ability to fabricate composite structures is the availability, acquisition cost, operating cost, and complexity of autoclaves to cure the components (Snider 2008). The development of out-of-autoclave materials and processes decreases the cost of entry into composites manufacturing and enables new opportunities for product designers. It has enabled the fabrication of composite structures with nearly identical properties to their autoclave-cured counterparts.

The processing techniques and tooling methods for out-of-autoclave cure of autoclave material was demonstrated on fins for the MLAS vehicle. Destructive and non-destructive testing was performed on a process validation article. An initial qualification and scalability plan was developed based on the resulting data. The manufacture and test of flight hardware demonstrated the repeatability and scalability of the process. MLAS stiffness-critical fins required aerospace-grade materials. Figure 5-5 shows the MLAS fin assembly components.

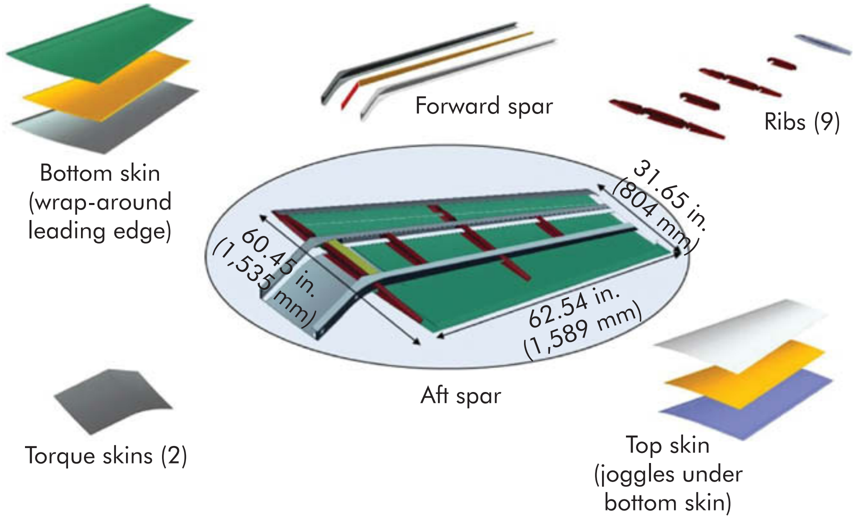

Figure 5-5. MLAS fin assembly. (Courtesy NASA)

MLAS used bulk graphite, outer-mold-line tooling and was CAD -surface-model driven for design flexibility. Therefore, part design was not final before the tool build. The honeycomb-core-stiffened skins used out-of-autoclave processing by forced degassing cure, and the assembly was room-temperature bonded.

The vacuum degas processing (VDP) of MLAS fins used vacuum and an oven to promote degassing and elimination of absorbed moisture prior to gel. The cure process was tailored to keep the pressure above the moisture saturation line. The fins were processed using an elevated temperature that was below the cure temperature to bleed off moisture (water boiling point). Once the moisture was bled off, the temperature was elevated to cure the part(s). Compaction under vacuum bag pressure was provided simultaneously, followed by a higher-temperature, freestanding or supported post-cure.

The reduced cost of a curing oven compared to an autoclave increases the ability of a small business to enter the composites manufacturing market, and thereby increases the available supply network. The OAC process was supported by other low-cost, flexible manufacturing innovations such a Sopers retractable oven and cleanroom. The oven was expanded when needed and used to cure the part. After use, it was retracted until needed again, sparing intrusion into the manufacturing space.

The OAC process has been successfully demonstrated with currently qualified aerospace materials (8552, 977-2, 977-3, MTM45-1) and is compatible with FM300-2 adhesives and standard honeycomb core materials.

VDP significantly reduces the risk of bag failure compared to autoclave cures. Further, it has the potential for compatibility with a wider range of conventional, premium-strength, toughened, pre-impregnated materials. VDP can accommodate a variety of automated material placement methods and is compatible with sandwich structures.

VDP does have its limitations, however. It is not compatible with many resin systems, particularly those with short cure times. High-viscosity systems can inhibit moisture/volatile migration or elimination. There is also a tendency for higher void content when using fabrics as opposed to tape. Good vacuum is critical to the process; site location elevation where the process is performed may limit the achievable vacuum levels.

AUTOCLAVE CURE

The autoclave-cured composite crew module (CCM) shown in Figure 5-6 demonstrates the potential for high-strength, carbon-fiber composites use on inhabited and uninhabited space vehicles, including satellites. The material benefits designs, offering the capability to open up the interior space. The lighter weight, larger interiors, and fewer assembly points provide greater crew comfort for inhabited vehicles, and greater payload capability for satellites.

TECHNOLOGY TRANSFER

The technologies born out of the United States space program have demonstrated their extensibility to other uses and products. While it is not true that Velcro® had its genesis in the U.S. space program, many other technologies spun off from the push into space. Scratch-resistant lenses, temper foam, freeze-dried food, solar energy, pollution remediation, and structural analysis

Figure 5-6. Composite crew module. (Courtesy NASA)

software are only a few of the technologies developed and matured through their application in space exploration.

Similarly, many of the MLAS manufacturing technologies and related technology development efforts have spawned or are candidates to spawn their extended use for other applications. Their extensibility is not limited to space vehicles. Many have applicability to dissimilar industries and products.

Automotive Industry

The auto industry has struggled to find a way to incorporate high-strength, carbon-fiber composites into vehicles for good reason. Some of the manufacturers of high-end vehicles have and continue to use the material. Carbon-fiber composites are well established in limited-edition cars. All but the doors and roof of some Lamborghini bodies are made of composites materials. And Lamborghini's Murciélago LP 670-4 SuperVeloce incorporates carbon composites in its floor, transmission tunnel, and outer skin, for a total of roughly one-third composite materials by weight (Supercars.net 2010). The development of materials and processes to enable their use in high-volume vehicles is the challenge.

Fuel efficiency and low-carbon-emission regulations are playing a major role in raising demand for lightweight automotive composite components to replace metal parts (Stewart 2012a). Barriers to growth include:

- The high cost of carbon fiber,
- Existing production techniques that result in higher manufacturing cycle times (and low-volume production), and
- Concerns over providing a waste disposal/recycling system for carbon-composite parts.
- Lack of general engineering experience among OEMs who are reluctant to move away from the metal-based assembly lines.

The MLAS program demonstrated the low-cost manufacturing processes and technologies needed by the auto industry to spin the use of high-strength, carbon-fiber composites to high-rate-production cars. Out-of-autoclave cure using low-cost, high-strength, carbon-fiber prepreg composites can be developed to integrate well with the metal work currently dominating high-volume auto production.

Automobile producers have experience with carbon-fiber manufacturing. General Motors introduced its seventh generation Chevrolet Corvette® at the North American International Auto Show in Detroit in January 2013. The use of composite materials included carbon fiber in the hood and roof panels; sheet molding compound (of a lighter density than previously used) in the fenders, doors, rear quarter panels, and rear hatch panel; and carbon nano-composite, an advanced blend of traditional composite material and carbon fiber, for the underbody panels. For the first time, carbon fiber was brought to an entry-level vehicle.

One area opening up for consideration of high-strength, carbon-fiber composites on cars is seats. A recent study from research firm GFK Automotive found that Americans who are intending to buy a car in the next year are considering small cars in bigger numbers than ever before (Vlasic 2008). Smart cars and Fiat® cars offer fuel economy at the expense of space. Thinner seats designed for comfort using high-strength, carbon-fiber composites material can add inches of leg room while improving impact properties.

Wind Energy

VARTM manufacturing technology is used to produce composite blades for wind-generated electricity.

As wind turbine blades grew in size, the need for higher-strength materials became evident. The existing materials and manufacturing processes were not adequate to withstand the greater loads, strains, vibration, harsh weather, and stress encountered by the larger blades.

Large blades manufactured using previously acceptable materials and processes began to fail with catastrophic results and have caused increases in injuries and fatalities. Wind turbines present significant safety challenges and serious accidents have resulted from the expansion of safety zones and imposed limitations. The wind energy industry is one of the fastest-growing consumers of fiber-reinforced plastics in the world. Production challenges are compounded as the scale of wind turbines continues to climb. Blades, among the most complex parts to mold, now exceed 262.5 ft (80 m) in length and are getting longer (Stewart 2012b).

By far, blade failure was attributable to the largest number of incidents. It can arise from a number of possible sources, resulting in either whole blades or pieces of blades being thrown from the turbine. Pieces of blade are documented as travelling up to 1 mile (1.6 km). In Germany, blade pieces have gone through the roofs and walls of nearby buildings (Caithness Windfarm Information Forum 2013).

Fires are also a concern. As blades have increased in size, they have strained the bearings, shafts, and gears of turbines. The blades are not balanced individually or dynamically balanced as an integral part of the operating system. The resulting vibration causes friction that is transferred to the electrical-generating components of the turbine.

Some turbine nacelle fires cannot be extinguished because of their height, and are sometimes left to burn themselves out. In such cases, they generate toxic fumes and can cause secondary fires below. However, newer wind turbines are built with automatic fire extinguishing systems similar to those provided for jet aircraft engines.

The autonomous Firex® system, which can be retrofitted to older wind turbines, automatically detects a fire, orders the shutdown of the turbine unit, and immediately extinguishes the fire completely (Info4Fire.com 2011).

Technology transferred from the MLAS program could be used as a model to determine the mass properties of the blades and provide data for the system to be dynamically balanced. Since vibration is the prime contributor to the catastrophic failure of blades, turbine fires, and premature wear, the application of mass properties analysis and vibration reduction would significantly reduce blade failures, fires, and extend the life of wind turbines (Adams 2011).

Aerospace

Aerospace has begun to see the economic advantages to the use of composites for aircraft interiors. There is an opportunity to manufacture a wide variety of interior components using high-strength, carbon-fiber composites material. The opportunity is incentivized by the material's lighter weight and increased strength, while contributing to greater passenger comfort.

The limitations can be mitigated by high-rate production tooling and processes, low skill work instructions, and recycling if the new stringent flame retardation standards can be met. The use of coatings and additives shows promise. The horizon for consumption of high-strength, carbon-fiber composite materials for manufacture of airplane interior components could dwarf its use on the airframe.

The MLAS program provides manufacturing solutions that incentivize low-cost solutions for seat, galley cart, and interior component production and assembly. To reinvigorate the small manufacturer base in the United States, divergent manufacturers, digitally linked, could collaborate to produce interior components for a specific airplane. Since the VARTM and OAC composites manufacturing processes do not require large amounts of capital investment, small manufacturers could fulfill airplane or airline-specific component orders for a specific airframe. The distributed manufacturing base would lower overhead and be more flexible to support the unique attributes of each airplane. A digital thread similar to the one for MLAS, enhanced by current apps and communication technology, would facilitate low-cost, highly effective "small shop" manufacture of high-quality interior components for airplanes.

Emergency Tools

Emergency personnel use struts to stabilize vehicles, buildings, and rocks when disasters strike or accidents happen. In a tornado or other weather event when buildings collapse, the debris is stabilized with a combination of tools including struts to protect those trapped beneath the debris. When an automobile or truck accident occurs where the car is toppled on its side or roof, struts are used to stabilize the vehicle before work can begin to extract trapped people.

Most struts used today are made from steel or aluminum. The issue with these life-saving devices is that their individual weight limits the number that can be hand carried into a disaster area. Several trips may be needed to the disaster site as first responders retrieve struts.

Struts made of high-strength, carbon-fiber composite materials offer an alternative to the heavier steel or aluminum in use. They offer the same stabilizing properties and strength at reduced weight. The reduced weight enables faster response by increasing the number of stabilizing struts a first responder can carry.

The low-cost manufacturing method of hand filament winding, coupled with OAC cure, provides a cost-competitive alternative to the heavier metal struts.

Transportation

Another use for high-strength, carbon-fiber composite materials is emergency/rescue vehicle bodies. Due to the response scenario where these vehicles must "run" through red lights, they are subject to a higher percentage of side impacts from inattentive or unaware motorists who go through the opposite green light.

High-strength, carbon-fiber composite materials have demonstrated impact protection at much lighter weights than the aluminum or steel side structures resident in current emergency/rescue vehicles. VARTM formed parts can replace doors and frames to improve the safety of the individuals racing to rescue others.

Trucks, buses, and rapid-transit systems have the potential to leverage MLAS-related technologies and realize advances in performance and safety. These vehicle producers have not yet leveraged the advantages of high-strength, carbon-fiber composite materials to reduce weight, improve safety, and increase fuel efficiency.

A current class 8 truck (commonly called an "18 wheeler") operating on United States roadways has a tractor weight of 14,000–23,000 lb (≈6,350–10,433 kg). The empty weight of its trailer is 12,000 lb (≈5,443 kg). Trucks account for 10% of fatal accidents, one-third of emissions pollution, half the wear, damage, and aging of roads and bridges, contribute to noise pollution at 84 dB, and consume 10% of the nation's fuel. In 2006, an estimated 15.5 million trucks operated in the U.S. Of this figure, 2 million were tractor trailers (class 8) that travelled ≈139.3 billion miles (≈224.2 billion km) (Truckinfo.net 2006).

Buses contribute an additional load on roads, the environment, and safety. In 2004, there were 458,229 school buses operating in the United States, traveling 4.1 billion miles (6.6 billion km), and consuming 556 million gal (2.1 billion L) of fuel (Laughlin 2004). In 2012, data shows that school-bus-related accidents send 17,000 U.S. children to hospitals (U.S. Department of Transportation 2012).

The use of VARTM and other MLAS-related technologies, if incorporated into truck and bus designs, can lower fuel cost and improve safety while reducing road wear repair costs. An example is the advanced technology transit bus (ATTB). The use of VARTM with high-strength, carbon-fiber composites and other innovative manufacturing technologies has contributed to its success. Northrop Grumman produced the ATTB using aerospace-type high-strength, carbon-fiber composite materials, construction techniques, and defense conversion technologies. The ATTB program began with the objective of developing a lightweight, low-floor, low-emission transit bus that would use proven advanced technologies developed in the aerospace industries (Best Manufacturing Practices 2007; SpecialtyVehicles.net 2011). The vehicle was designed to meet federal, state, and local (Southern California) axle weight and clean-air requirements. The ATTB's curb weight is 10,000 lb (4,536 kg) less than an equivalently configured conventional transit bus.

Northrop Grumman also developed full-scale structural and mobile test beds for its ATTB program. The structural test bed was used to validate the design of the ATTB's composite structure. The testing program included a side impact crash test with a 4,000-lb (1,814-kg) car traveling at 25 mph (40.2 kmh), which resulted in only cosmetic damage to the test bed.

An additional advantage to the ATTB's composite body was reduction of maintenance cost resulting from the corrosion resistance of the material and fewer assembly points. The light, high-strength, carbon-fiber composite material can be molded into seamless shapes. There are no bolts or fasteners required, which lowers the chance of corrosion and failure points.

RFID Use to Monitor Material Life and Health

High-strength, carbon-fiber composite material is a superior conduit for the read rate and manufacturing inclusion of radio frequency identification (RFID) technology.

The expansion of carbon-fiber composites into the domain of products other than airplanes has been limited due to several issues related to the materials' properties before and after cure. Out-time for raw material is a critical manufacturing process control point for high-strength, carbon-fiber composites. As soon as the material leaves the freezer for cutting and kitting, the roll of prepreg begins aging (curing). Temperature variations in the room where the material is stored compounds the estimates for the remaining material life. Higher temperatures in cutting rooms age the material faster. The aggregate time and temperature that raw material has been out of the freezer contributes to a reduction of the useful life of the remaining raw material. NASA and other potential users have concerns about its use in larger structures. Processing high quantities of prepreg at once could result in expired material prior to completion of the layup and cure processes. The application of fresh (newest) material and increases in the rate of application could diminish the risk.

The application of RFID technology for MLAS-related projects provided a data-driven assessment of the critical time and temperature components of the material to mitigate the risk of it expiring before processing was complete. RFID tags embedded in the raw material provided an absolute value for the time and temperature components for age assessment. The data was used in an algorithm to determine the remaining useful life of the material and which parts could be manufactured in the remaining time. The manufacturing assessment algorithm had a safety setback to ensure a margin for safe manufacturability.

Another concern that has inhibited the expansion of high-strength, carbon-fiber composites is impact. Hollow structural parts could have internal damage resulting from impact to the external structure during manufacture or use. The probabilistic method to investigate impact damage of composite parts is visual based upon observation of an indentation. A more reliable and accurate determinant of impact damage is to measure impact energy. Emergency response teams and automobile manufacturers have been reticent to use high-strength, carbon-fiber composite struts for this reason. Unseen damage to a part or component could cause catastrophic failure during use. An unseen/unknown impact to the outside of a composite strut could degrade the strength of the strut from internal fracture.

During MLAS, projects were funded to assess the viability of RFID technology to monitor composite structures for impact. Tests were performed to determine which technologies could detect, accurately and repeatedly, impact energy in composite material. Those technologies were then leveraged to establish baselines and thresholds to demonstrate how composite design structures could perform their intended function with the desired confidence and at lower weight and cost.

The outcome of the research was an inexpensive system that could determine the size and location of an impact that would affect the strength properties of a strut. Acoustic emissions are captured from rapid release of energy due to impacts while accelerometers capture the material's displacement. Radio frequency technology detects changes in resonance frequency as a function of distance. Therefore, a part, such as a strut, can contain an integrated structural health monitoring (ISHM) system imbedded for active detection of any event and its location, which could degrade its performance prior to use. Since MLAS, the system technology for ISHM has evolved.

Wireless communication technology enabled the development of nanowire and nanostructure-based sensor systems. Smart phone (and/or Wi-Fi®) advanced wireless communicating devices and ISHM software are combined in one unit.

The system employs unique dry-nanotechnology-based electrodes and textile-based electrodes as active sensors and neurosensors. An associated wireless and cloud-based system is used for ISHM data collection, data analysis, and data dissemination and monitoring of various structural disorders including strain disorders and impact events. Designed primarily for "lights-out" monitoring, the devices collect and transmit an array of data with unique RFID allocated for the manufacturer and user (confidentiality is maintained). The prototypes developed during MLAS and the associated programs provide real-time monitoring over wireless communication devices such as smart phones.

The salient features of the system that differentiate it from other related products are:

- The nanosensor component uses either gold nanowire-based electrodes, textile electrodes with a nanosensor, or a combination of both to capture data and critical integrated vehicle structural health signals.
- The use of dry nanosensor leads to improve contact surface area.
- Coupled with a low-power microcontroller and Bluetooth® module (ZigBee®, Wi-Fi, and other communication protocols as appropriate), the sensor data can be streamed to commercial off-the-shelf cell phones and handheld devices.

The specialized software system for cellular smart phones collects sensor data over Bluetooth and relays the data over 3G, Wi-Fi, WiMax® or any outgoing connection with RFID data transmission capability. It does not require an additional custom handheld device for data relaying. Apart from the cost benefits of using an off-the-shelf cell phone, the software system provides other distinguishing features:

- It employs filtering algorithms on the cell phone to mitigate issues due to motion and other artifacts, rendering clean data.
- It provides a visualization interface on the cell phone so that users can see the salient features of current activity such as movement, heat, impact, and vibration.

- It tags the data with the location of the user. The location (latitude and longitude) is key for both backend services and the user in case of an ISHM emergency.

The software on the phone will run simple machine learning algorithms to perform preliminary anomaly detection. In case of an ISHM emergency, it can either alert the user and recommend solutions or make an automated call to the designated response team member with the component's location. Manufacturers and product users can access vital ISHM information anywhere and anytime within the networks, which can be set for global-level active monitoring. The ZigBee-based Wi-Fi system is capable of handling separate parts of an assembly at a given time.

The geo-tagged data is transferred to a cloud cluster and stored in a secure database. An SD card is installed in the cell phone for data storage. For expert diagnostics, a backend service is available, where the expert can log into the system and visually look at past or real-time data. Machine learning services are available to detect anomalies in the data collected in the past. In the event that the machine learning algorithms detect abnormalities in the data, a service can make phone calls or send text messages to designated experts.

The technology provides additional benefits other than for structural health monitoring. For example, the devices report earned value management data, calibration alerts, foreign object inclusions, and material out-time.

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6

MLAS QUALITY ASSESSMENT OF PARTS

"Anyone who has never made a mistake
has never tried anything new."

—Albert Einstein

INTRODUCTION

A mentor, Dr. Hall told me that complex projects are puzzles composed of simple pieces. On August 27th, 2008 at Wallops Island, Va., critical pieces of the MLAS project fell apart. Ten of the 12 MLAS flight fairing panels showed evidence of low bond strength. The flight panels were delivered prior to knowledge of the poor bonding condition (see Figure 6-1). The two boost skirt panels fabricated using the co-infusion process where no adhesive was required appeared to be solid.

Coupon testing of the other 10 panels showed bond strength as low as 6 psi (≈41 kPa). The requirement was 100 psi (≈689 kPa). Testing was performed the last week in September by the Northrop Grumman Corporation Test and Evaluation Group. Upon extraction of 2 × 2-in. (50.8 × 50.8-mm) coupons from the flight panels, noticeable dis-bonds were present along with the smell of vinyl ester resin. Coupons extracted from the bonded area between the outer mold line and core at NASA Wallops Island, Va. on October 3, 2008 were gooey when probed around the coupon cutout areas (see Figure 6-2). As a result of this condition, 10 flight panels were scrapped. A three-to-four-month slip to the launch date was estimated due to new panel fabrication at a rough order of magnitude cost to the program of $800,000–1,400,000 (≈€640,000–1,120,000). After the shock

Figure 6-1. The flight fairing panels arriving at NASA's Wallops Island, Va. facility. (Courtesy NASA)

subsided, a scientific and systematic forensic engineering process was begun to determine the cause and corrective action.

FORENSIC ENGINEERING

Dr. Edmond Locard (1877–1966) was a pioneer in forensic science and engineering who formulated its basic principle, "Every contact leaves a trace." This is known as Locard's exchange principal (Noon 1992). Forensic engineering (FE) involves the investigation of materials, products, structures, or components that fail or do not operate or function as intended. Vital to the forensic engineering process is investigating and collecting data related to the materials, products, structures, or components that failed. The process involves inspections, collecting evidence,

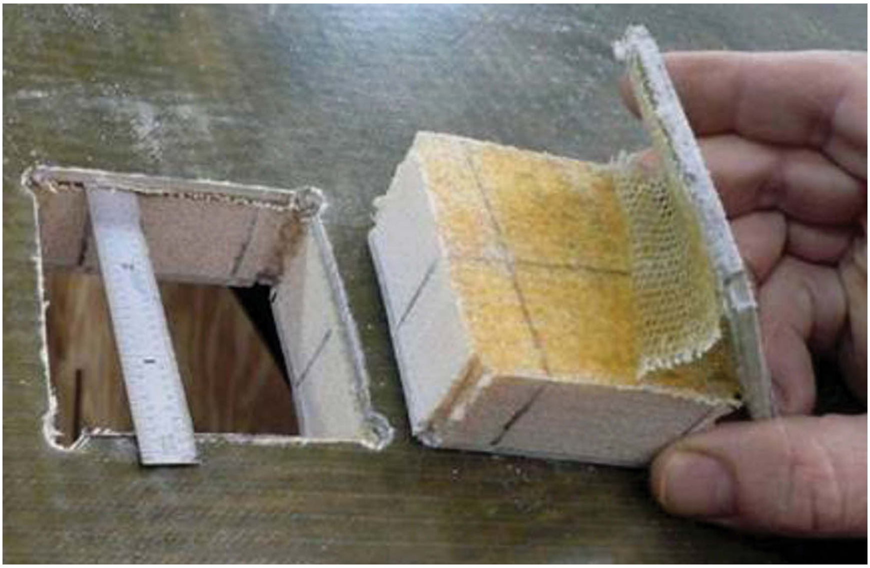


Figure 6-2. The first excised piece removed from the delivered panels. (Courtesy NASA)

measurements, developing models, obtaining exemplar samples, and performing experiments. Critical to forensic engineering is testing and measurement conducted by an independent team in independent testing laboratories (Noon 1992; Ericson 1999). FE evolved as a legal tool for failure reconstruction specifically designed to help with litigation. However, it has also been recognized as a valuable analysis tool for engineers and scientists to find the cause(s) of malfunction or failure.

NASA has been one of the prime drivers for the use of forensic engineering as an analysis tool to determine failure cause and corrective action. In the early Apollo command module, NASA used forensic engineering tools to identify the wide range of lethal design and construction flaws. The investigation was triggered by the Apollo 1 cabin fire that occurred during a launch pad test on February 21, 1967, which killed all three crew members. As a result of the investigation and subsequent discovery of the flaws, the manned phase of the project was delayed for 20 months while the problems were corrected.

FE uses failure modes and effects analysis (FMEA) and fault tree analysis to examine product or process failure in a structured and systematic way. FMEA and fault tree analysis techniques rely on accurate and precise reporting of the failure modes involved (Edwards and Lewis 2007; Vesely et al. 2002).

Information on product failures has not been widely published in academic literature. Government, companies, and people do not like to publicize their failures. Therefore, there is not much opportunity to research previous experience using the methods, tools, and techniques of forensics engineering. However, notable exceptions are *Engineering Failure Analysis* and the *Journal of Constructed Facilities*, published by the American Society of Civil Engineers, Technical Council on Forensic Engineering. There are also a growing number of books associated with the subjects of forensic engineering and forensic science.

The MLAS team used established forensic engineering methods, tools, and techniques to evaluate and determine the cause of the bonding problem that scrapped the flight fairings. The resulting data and information were used to develop a plan to ensure the successful fabrication of the replacement flight panels. The forensic engineering approach to the MLAS flight fairing bond failure was familiar to the four NASA engineers assigned to the investigation team. Therefore, the FE methods and tools were easily integrated as part of the MLAS forensic engineering assessment model.

The application of forensic engineering methods, tools, and techniques are complicated in a high-stress production environment. The tools of forensic engineering analysis require a thorough and systematic process that runs contrary to the “push forward” culture of manufacturing and product delivery. Investigating and collecting data related to the materials, products, structures, or components that fail requires a detailed plan and execution of the plan can result in dead ends. Inspections, collecting evidence, measurements, developing models, obtaining samples, and performing experiments are crucial to the process. Precise calculation of the time required to perform these activities is difficult since much evidence can be lost as time increases between the time of manufacture of the product and its failure.

Further compounding the FE investigation task is the social stigma attached to failure. Investigators encounter a defensive reaction on the part of people who were involved with manufacture of a failed component. The collection of valid and usable data by the investigating team members during FE activities must be tempered with sensitivity to reactive response from threatened individuals.

When large, costly, and visible failure occurs, there is a natural tendency to drift away from the analysis to determine the cause and toward the determination of *who* is responsible for the failure. The investigative team members must be cognizant of the culture they are entering and tailor their investigative approach to its elements. Operating an FE investigation within a culture that corrects failure by replacing people is difficult.

Most often, FE investigation teams are composed of engineers and scientists who are not sensitive to the culture they are entering. They focus on the scientific/engineering aspect of the investigation. Ignoring the resident culture and company leadership can create friction, impeding efforts and delaying data collection and testing. Taking the time to explain the purpose of the FE investigation to leadership at the location where the investigation takes place makes the process easier. Gathering the individuals who will be interviewed and explaining to them the intent and purpose of the investigation is important. Clear communication that the intent of the FE investigation is to find the cause of the failure and not to assign blame will help ensure success. Perception that the FE investigation team is hunting for people rather than the failure's cause can delay and even defeat a thorough investigation and result in flawed conclusions.

Clearly communicating to the leadership at the location about the FE investigation's impact to current operations is also essential to a successful outcome. Having completed their production activities and shipped the product, they have moved on. Unplanned disruption to the rhythm of production flow is unwelcome, even when they know it is the result of their own actions. Providing a plan that includes who the FE investigation team will need to interview, the support (including facilities) needed, and the approximate time the investigation will take including follow-ups, helps soften the resistance to the investigation. As part of the initial briefing to the resident leadership, clear identification of who will receive the final report should be provided.

MLAS FLIGHT FAIRING BOND FAILURE INVESTIGATION

For MLAS, the cultural differences between the FE investigating team and the manufacturing facility where the failed flight fairings were manufactured were significant.

The Gulfport, Miss. manufacturing plant was a shipbuilding facility. The NASA and Northrop Grumman investigation team members were space and aerospace engineers. The two cultures represented divergent approaches to manufacturing: Tough and rough met precise and refined, unified through a common vacuum-assisted resin transfer molding (VARTM) manufacturing process.

The top-down shipbuilding style of manufacturing at the Gulfport facility where the MLAS vehicle flight fairings were fabricated was alien to the investigative team. Many of the people, processes, and methods operating at Gulfport were divergent from the aerospace or space environment and culture even though the universal moniker of VARTM was common to both. Compounding the cultural difficulties was the view that the MLAS project was not shipbuilding. Shipbuilding was the primary function of the Gulfport facility and the U.S. Navy was its customer. Revisiting an "alien" project to conduct FE and disrupting the flow of its primary product to the U.S. Navy caused frustration. Production had shifted to other projects, engineers had been reassigned, material had expired and been disposed of, tools meant to be temporary were stored in the open, and plans were archived.

The MLAS FE investigation was further complicated by the nature of the product. The launch of MLAS or any space vehicle requires a launch window with mission specialist personnel onsite. Most of the personnel possess the highly specialized skills necessary to launch and recover a rocket-propelled vehicle. In demand, mission specialists must be scheduled to coordinate with the needs of other launches requiring their services. In addition, ships (for vehicle observation and recovery) and other equipment needed to be scheduled and available for the launch.

Launch windows can be narrow. As a result, the schedule, which outlined the steps and timing for the team's formulation, forensic engineering approach, identification of cause, corrective action, and delivery of new flight fairings hardware had to be closely coordinated with NASA personnel. Further, the schedule commitment of the forensic engineering team had to be maintained within the narrow launch window.

Adding to the FE investigative challenges was the geographically diverse locations of the relevant contributors to the design and manufacture of the MLAS flight fairings. The design team was located in Huntsville, Ala.; the technical program leadership team was located in El Segundo, Calif.; the NASA team was located in Wallops Island, Va.; and the manufacturing team was located in Gulfport, Miss.

Teaming

The MLAS FE investigative team was led by George Bullen and was composed of engineers and investigators from NASA, Northrop Grumman Integrated Systems, and Northrop Grumman Shipbuilding. The NASA-assigned group of four was the MLAS chief engineer, composites structures engineer, root cause/quality engineer, and VARTM process engineer. The Northrop Grumman Integrated Systems Group of six was composed of manufacturing (three including group leadership), quality engineer (RCCA facilitator), NGIS stress/DDX structures engineer, MLAS mission systems engineer, and reviewing leader. The Northrop Grumman shipbuilding team members were composed of two VARTM manufacturing engineers who were familiar with the project.

The team leadership's first order of business was to establish contact for collaboration and form a concept of operations, team charter, and timeline for the first team engagement onsite at the Gulfport, Miss. facility. The Gulfport facility was chosen because it is where all activities for the manufacture of the MLAS flight fairings had taken place. While it was a minor consideration that possible damage may have occurred in transport of the flight fairings from Gulfport to Wallops island, the materials, tools, personnel, their manufacture, and packaging for shipment took place at the Gulfport manufacturing facility.

Concept of Operations

The team was composed of three groups. Group one was resident at the Gulfport manufacturing facility. Its task was to investigate; collect data; design, organize, and oversee testing; collect and evaluate the resulting data; and compile a preliminary and final report. This group was composed of George Bullen (group investigation leader, manufacturing), the quality engineering RCCA facilitator, the NASA root cause/quality engineer, the NASA VARTM process engineer, and two Gulfport manufacturing engineers.

The second group of individuals remained at their normal workplace and supported the FE effort through regular meetings, providing test samples as needed in offsite laboratories, reviewing data, and supporting the efforts of the onsite group one team. Group two also travelled to the Gulfport manufacturing facility "on call" as requested by group one.

Group three was composed of unidentified individuals who were used as needed. They were experts called in to support the effort where testing or investigation revealed a particular skill set was lacking. An example was the need for a laser tracker team (and equipment) to be flown in from El Segundo, Calif. to support evaluation of the VARTM flight fairing layup tools.

Team Charter

The team's charter provided clear communication of the roles and responsibilities assigned to each team member. There was a clear action path for each individual. The assignment of tasks to individuals prior to implementing the investigation added value that included prevention of redundancy and a quick startup. Pre-assigned tasks eliminated redundant actions by two individuals where neither knew the other was performing the same task. Clearly defined roles and responsibilities minimized the team's time on site. The assignment of roles did not prohibit the cooperative nature of the team; rather it facilitated carrying out the plan. The team's charter specified the frequency of daily, weekly, and monthly meetings to support communication within and outside the team. A list of supporting personnel, equipment, material, tools, facilities, and budget estimates necessary to perform the investigation was also included.

Preparation

To prepare for the investigation, a series of teleconference meetings was attended by all team members. The meetings were to engage the local leadership at the Gulfport manufacturing facility to acquaint them with the investigative activities and solicit their support.

The team supplied the estimates for the needed facilities at the Gulfport manufacturing facility such as desks, computers, materials, access requirements, meeting rooms, site maps, and operating hours. In addition, a list of Gulfport employees (by category) needed to perform the investigation through interviews and testing support was supplied to the Gulfport leadership.

To maximize its time on-site, group one needed to know the safety requirements and operating criteria unique to the Gulfport manufacturing facility. As an example, hard hats and steel-toed shoes are a requirement that would have slowed the team's investigation if they discovered they could not access the Gulfport plant without them. They were acquired in advance.

Prior to arrival, the team members were given site maps to familiarize themselves with the Gulfport manufacturing facility. This provided the location of the various manufacturing activities that produced the defective flight fairings, thus highlighting the areas where testing and evaluation would be performed as part of the investigation.

The plant operating rhythms including start and stop times and overtime requirements helped the team align their arrival and investigation with the Gulfport manufacturing facility's operation. Union representatives were consulted to understand work relationships and guidelines for interaction and support of the Gulfport labor force.

Before the arrival of the team, the manufacturing investigation team leader made a preliminary trip to the Gulfport manufacturing facility to ensure all the necessary preparations had been made for the team's arrival and execution of the plan.

Planning

Based on the information gathered from the preparation phase of the investigation, a plan was developed. The team also met to discuss and develop a plan of action once they were onsite at the Gulfport manufacturing facility. A cause-and-effect diagram was used to identify the areas of focus for the team members once they arrived. Figure 6-3 shows the results of the cause-and-effect diagram with the areas of focus. It was populated from phone interviews with individuals familiar with the build of the MLAS failed flight fairings. Interviews also included suppliers of the Plexus adhesive and resin for the VARTM infusion. The cause-and-effect diagram lists the areas that had a high probability for contributing to the failure and key focus areas to be captured in the development of the fault tree.

Timeline

The plan was overlaid with the facilities layout and relevant personnel roster to build two timelines.

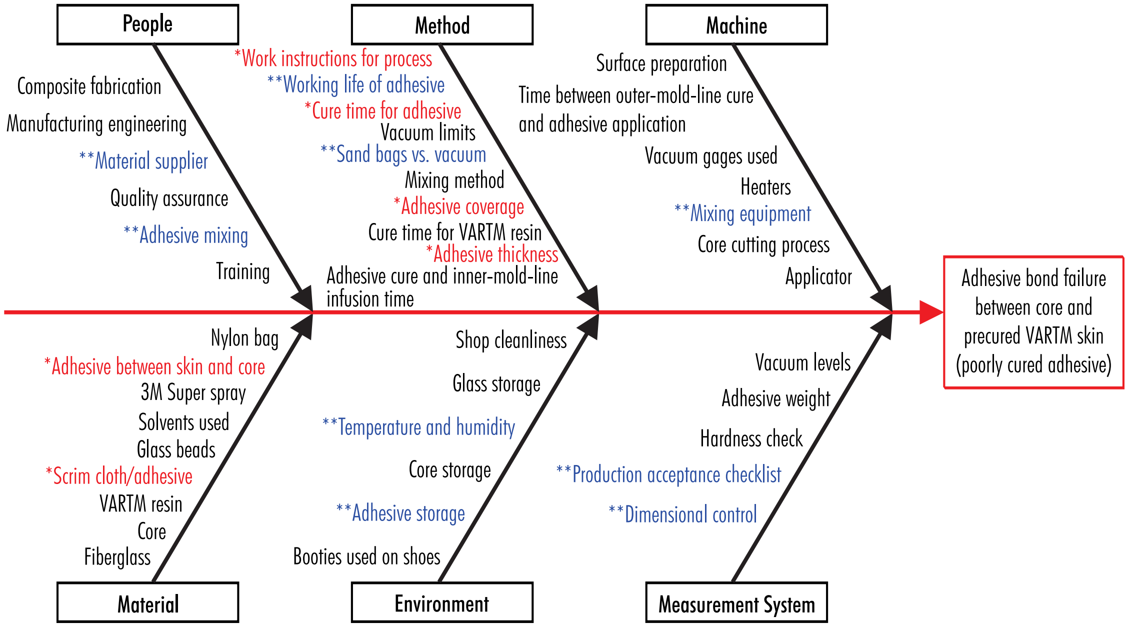
The first timeline examined the events that led to the failure. Cautionary measures were taken to ensure that defining the trail that led to the MLAS flight fairing bond failure was not interpreted as a search for blame or a rush to judgment. However, the forensic engineering investigation had to include an examination of the decision model that was in place to properly evaluate the process and its outcome. Figure 6-4 shows the timeline that led to the decision to use the three-step adhesion bonding process for fabricating MLAS flight fairings using VARTM, which was considered the better method.

The decision was weighted and the pros for Plexus adhesive were identified:

- It was widely used in maritime structures;
- It was widely used at Gulfport;
- Supplier and in-house data showed excellent properties;
- Availability of the adhesive product was good;
- It appeared to have a working life compatible with familiar processes;
- There was decreased risk due to previous experience with this adhesive in the forward fairings, especially in the motor trough area; and
- The most attractive attribute was the ability to align a progressive build based on the engineering release.

The cons were increased weight, cost, and a longer build schedule.

The second timeline developed as part of the planning phase was the path forward. This was the timeline of greatest interest



*High probability of failure in these areas, which become the primary direct causes to be investigated

**Key focus areas that should be captured in the development of "5 Why" fault tree

Figure 6-3. Cause-and-effect diagram.

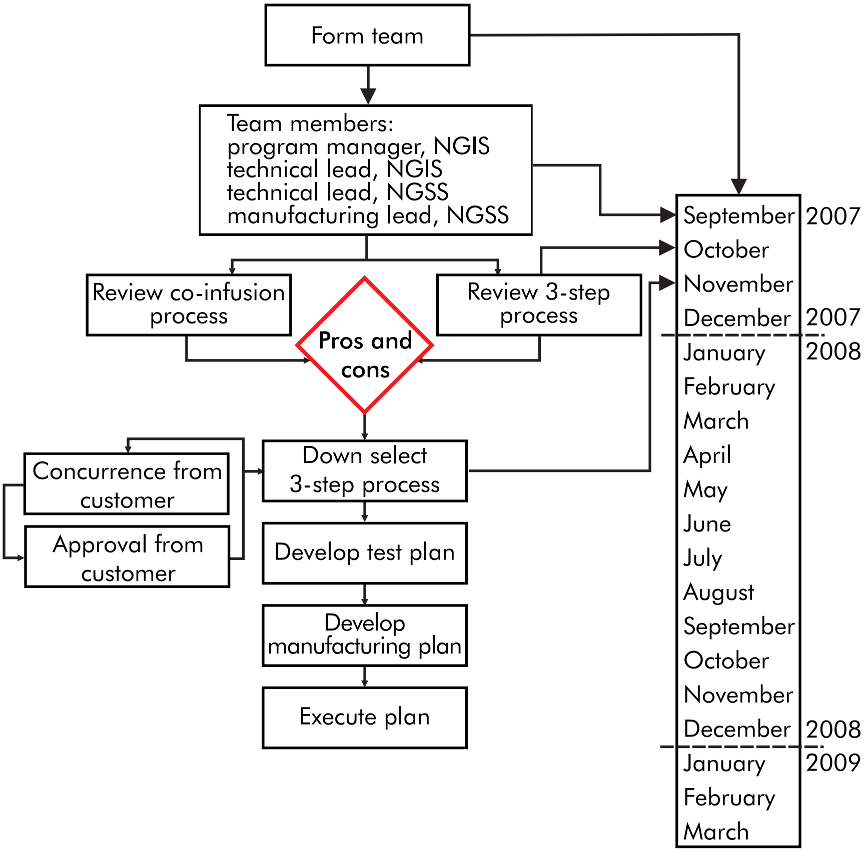


Figure 6-4. First timeline.

since it laid out a manufacturing recovery plan, the timing for new panels, and identification of a new launch window. Figure 6-5 shows the timeline for evaluation, determination, recommendation, and implementation for the corrective action necessary to complete MLAS.

It should be noted that tool design improvements were a part of the recovery plan integrated into the forensic engineering investigation tasks. The two-step approach used the assumption that the two good panels that had been co-infused would become the baseline for future MLAS flight fairings.

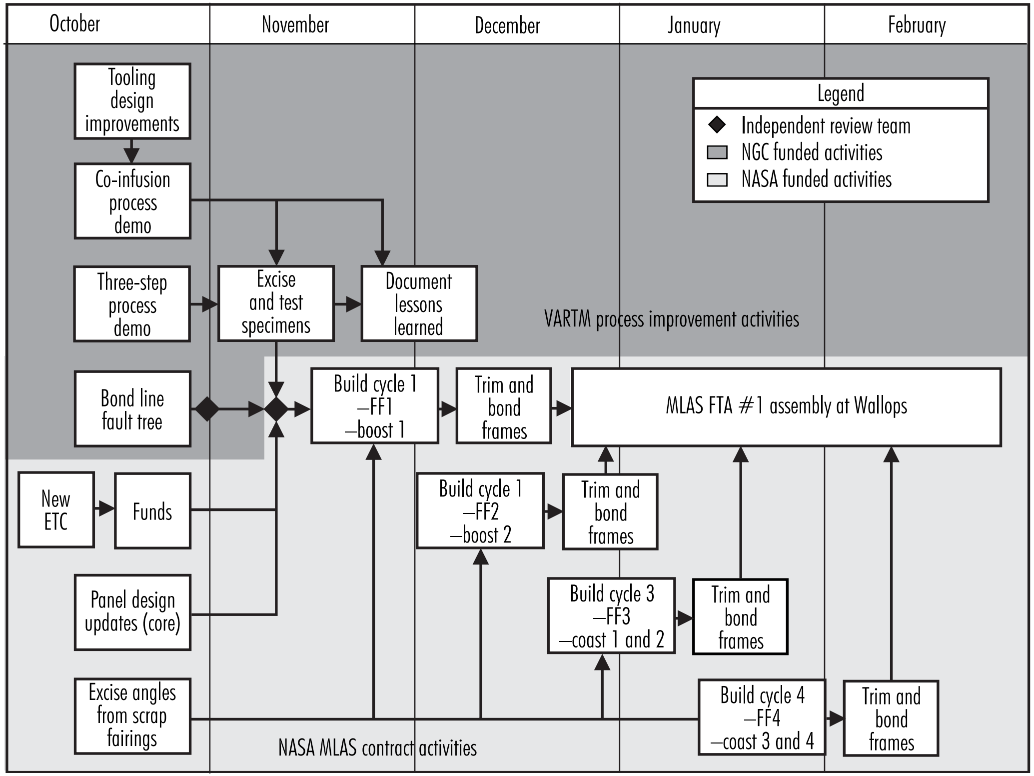


Figure 6-5. Second timeline.

Execution

Execution of the forensic investigation plan began by building a high-level schedule for the bond line incorporating the recovery tasks and responsibilities. Figure 6-6 shows the schedule and identifies the person responsible, accountable, and authority (RAA) for each task. Names have been removed for confidentiality.

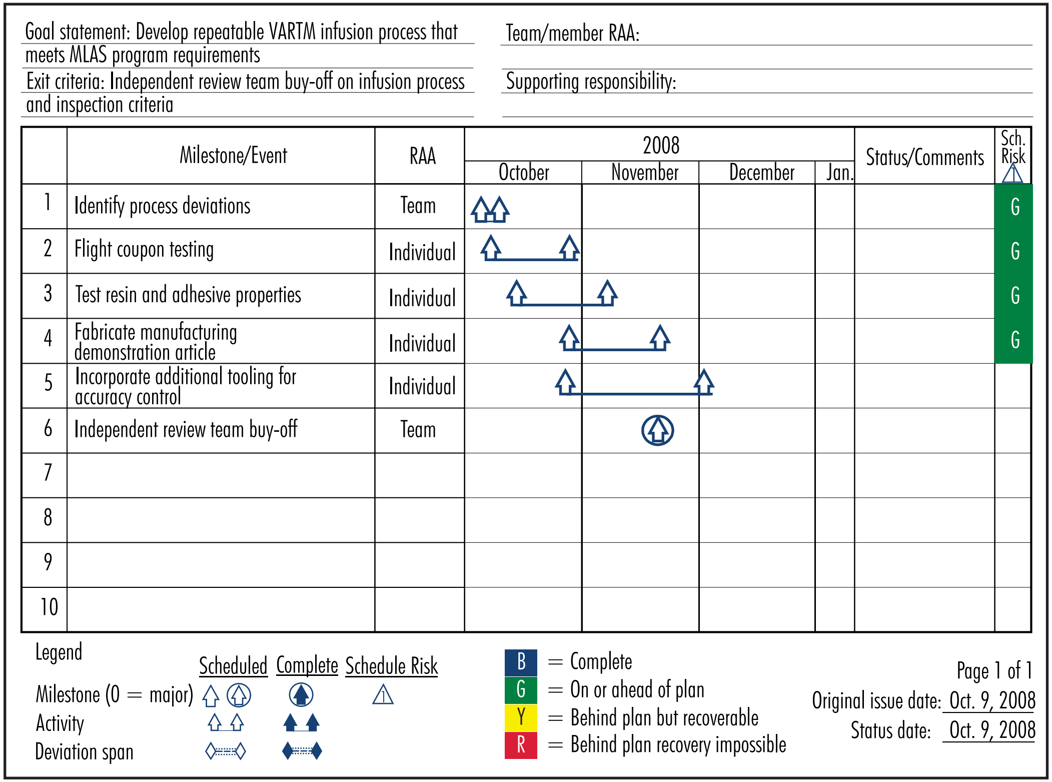
Figure 6-7 shows the fault tree developed for the investigation and evaluation of the bond failure on the MLAS flight fairings. A digital file, the user could click on a box to get a detailed fault analysis for that item. For example, clicking on item 1.5 in Figure 6-7a would take the user to a quad chart with further information (see Figure 6-8) for "Adhesive not properly stored prior to use."

Collecting Data

As the data was collected and analyzed, the outcomes began to point to a particular manufacturing difference between the initial testing of the three-step process and the actual manufacturing method used to produce the panels. The foam core was cut into squares to conform to the shape of curves in the surface. The squares were held together by scrim, which was bonded to the squares. An analogy would be mosaics where the small pieces of tile are held together by scrim bonded to the tile. A solid piece of core would not be capable of being shaped to the same degree as the core squares.

When the testing was performed to determine the compatibility of the core to the adhesive, the core was always placed against the cured material. The Plexus adhesive was applied to the side of the core opposite the scrim. When the investigation team's tests were run with the Plexus adhesive against the scrim, as it was during the manufacture of the flight fairings, the same dis-bonding condition resulted. While Plexus had been used at the Gulfport manufacturing facility before and workers were familiar with the product, it had not previously been used in core bonding for the three-step process.

In addition, the initial test specimens did not have Plexus adhesive applied to the scrim side and the original production plans did not include Plexus to scrim bonding. The scrim was placed and bonded using Plexus adhesive without a clear understanding that the adhesive should have been applied only to the side without



Goal statement: Develop repeatable VARTM infusion process that meets MLAS program requirements

Team/member RAA:

Exit criteria: Independent review team buy-off on infusion process and inspection criteria

Supporting responsibility:

	Milestone/Event	RAA	2008				Status/Comments	Sch. Risk △
			October	November	December	Jan.		
1	Identify process deviations	Team	⇧⇧					G
2	Flight coupon testing	Individual	⇧——⇧					G
3	Test resin and adhesive properties	Individual	⇧——	—⇧				G
4	Fabricate manufacturing demonstration article	Individual	⇧	——⇧				G
5	Incorporate additional tooling for accuracy control	Individual	⇧	————⇧				
6	Independent review team buy-off	Team		⇧				
7								
8								
9								
10								

Legend

	Scheduled	Complete	Schedule Risk
Milestone (0 = major)	⇧ ⇧	⬆	△
Activity	⇧ ⇧	⬆ ⬆	
Deviation span	◇⋯◇	◆⋯◆	

B = Complete
G = On or ahead of plan
Y = Behind plan but recoverable
R = Behind plan recovery impossible

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Status date: Oct. 9, 2008

Figure 6-6. High-level schedule for bond line.

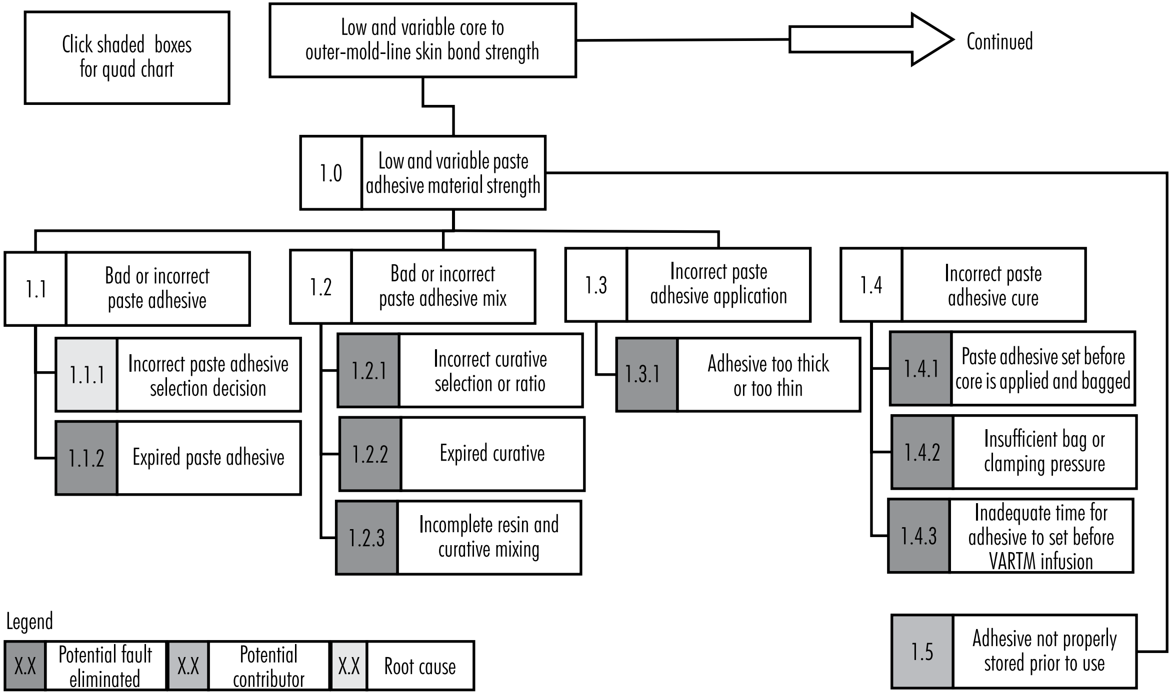

Figure 6-7a. Fault tree for MLAS bond failure.

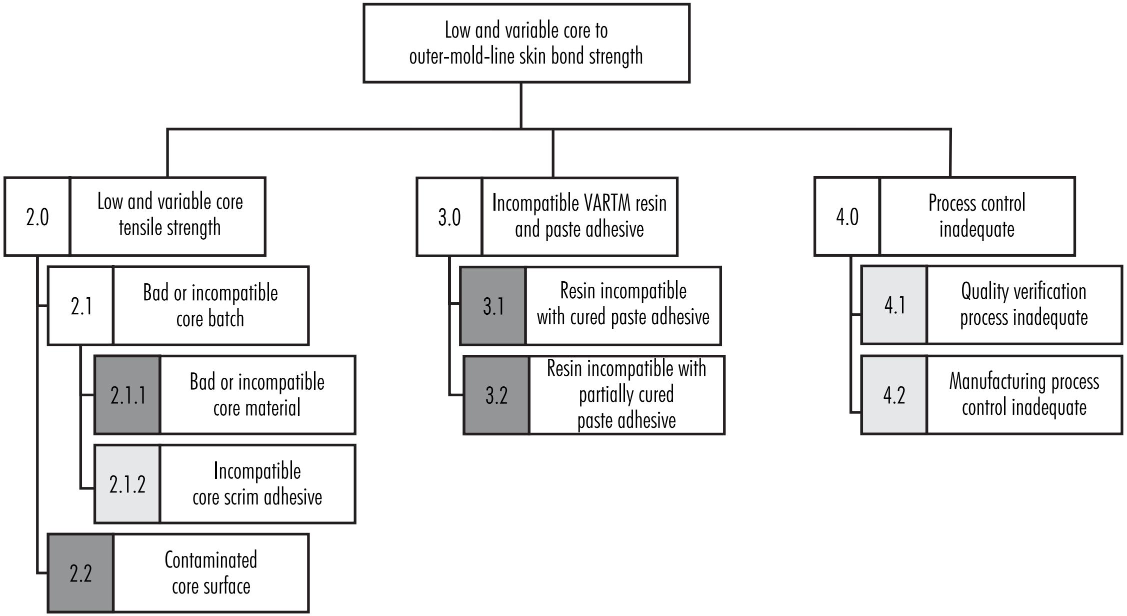

Figure 6-7b. Fault tree for MLAS bond failure (continued).

1.5 Adhesive not properly stored (closed)

Potential root cause description

- Plexus may have exceeded vendor’s recommended shelf life due to storage temperature acceleration
- This could cause the adhesive to prematurely age and behave poorly when mixed, creating a variable, non-uniform bond on the MLAS fairings

Closure status

1.5	Adhesive not properly stored prior to use

- Containers located
- Standard industry practice used but did not meet supplier recommendations to meet 55–75° F temperature
- The remaining adhesive used in the production process was reported to be fully cured in the bucket
- The remaining adhesive used in the post test panel process had uncured areas in the bucket

Closure approach

- Locate shipping records of Plexus adhesive used for MLAS fairing fabrication
- Identify if transportation was refrigerated (yes/no)
- Findings on transportation shipment way points and method of storage
- Identify receiving dock duration prior to transport to “cold” storage
- Determine time of exposure to sunlight

Open items for closure

- None

Figure 6-8. Quad chart.

scrim. It also became clear that although the initial tests of the bonds with the Plexus adhesive on the side without the scrim met the required strength margin, they were below expectations.

A remake of one boost skirt (9.3 × 13 ft [2.83 × 3.96 m]) and additional 2 × 2-in. (50.8 × 50.8-mm) test specimens were fabricated using the three-step process. The adhesive was applied with a trowel and the core was applied scrim side down. The core was pressed down with a vacuum bag. After three days, the adhesive had not cured, even after heat was applied. Normally, there is a four-hour cure time for the resin. The resin in the mixing bucket had fully hardened a few hours after application. During the flight fairing fabrication process, it was noticed by the Gulfport manufacturing team that the core was installed scrim side down. Upon noticing this mistake, work was stopped and the customer was notified. The customer gave consent to proceed. Violation of the original manufacturing controls, which designated that the non-scrim side have adhesive applied, led to the dis-bonded condition of the delivered flight fairings.

Defect Determination (Cause)

The determination for the cause of the defect was the interaction between the adhesive holding the scrim to the foam core and the Plexus adhesive. A test study of various adhesives indicated significant variation between the results from tests conducted at the supplier, ITW Plexus, and at the Gulfport manufacturing facility.

There were not any tests performed to validate the manufacturing process change when the flight fairings were manufactured with the scrim against the adhesive. Further, testing was not performed when the process deviated from the original plan (scrim up vs. scrim down). The root-cause failure was not identified as a risk prior to selection of the three-step process; therefore, it was not considered in the decision model. Analysis of the data revealed that the initial testing did not evaluate sufficient parameters to provide the needed information prior to selecting the three-step process.

Defect Resolution (Corrective Action)

Based on the investigation team's recommendations, the cobond process replaced the three-step process as the method of manufacturing the flight fairings. The decision matrix that was used is shown in Figure 6-9. The advantages of the co-bond process included:

- It eliminated the suspect Plexus adhesive from the manufacturing process;
- The replacement co-bond process was used for the majority of structures at the Gulfport manufacturing facility;
- It was a mature, low-risk alternative to the three-step process; and
- It saved time and process steps when compared to the three-step process.

While there were no identified significant risks inherent in the co-bond process, the change caused some issues when manufacturing the more complex large motor trough on the forward fairings. In addition, the switch to the co-bond process required additional testing to validate its applicability to the forward fairings.

Summary

The use of new materials and processes never-before used for a space launch vehicle comes with risk. Their manufacture at a facility that had never-before built anything remotely resembling a space or flight vehicle compounded it. Further, when the materials, processes, and the manufacturing facility are located hundreds of miles from the controls, management structure, and leadership tasked to provide oversight, it becomes a recipe for a failed enterprise. The success of the MLAS launch is testimony, however, that it can work. The materials and manufacturing processes used to produce the MLAS proved the composite material's structural ability to provide the necessary engineering strength.

When things go wrong, the natural tendency is to rush to judgment, assign blame, make more parts, and hope for the best. This course of action, if followed, ensures continued frustration and failure. An objective team using proven scientific methods, such as forensic engineering and its tools, can be used after failure to develop a successful path forward.

Teaming, preparation, planning, and establishment of a timeline are essential first steps. Coordination with the leadership

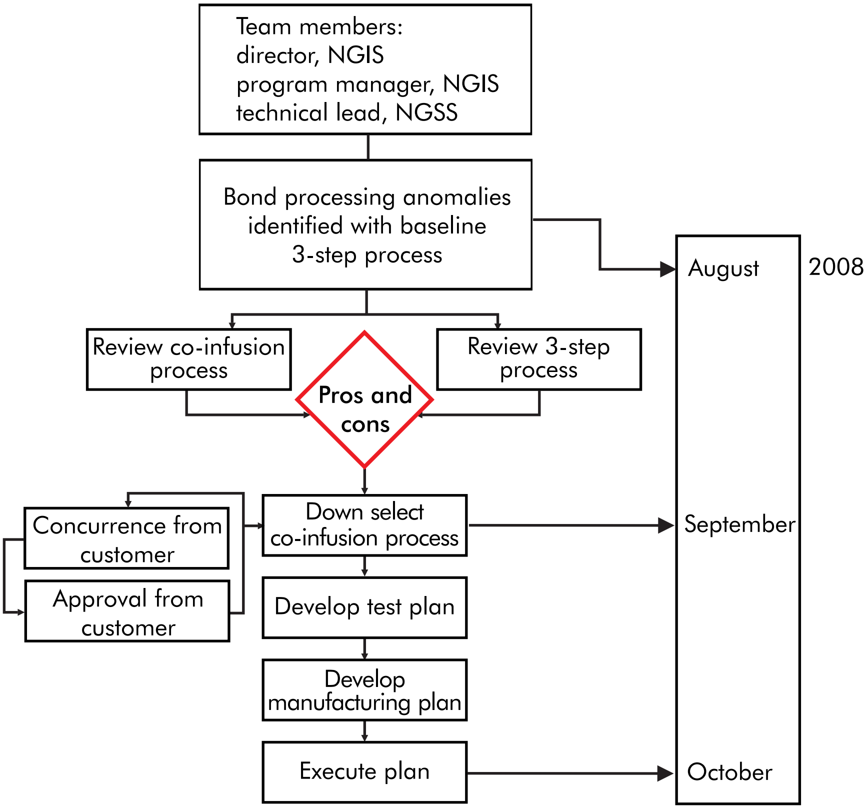

Figure 6-9. MLAS co-infusion process decision matrix.

where the investigation will take place is also essential to a successful outcome. The cooperative teaming agreement in the form of a team charter maximizes the use of resources by establishing the assignments, responsibility, and authority of individuals.

The pressure to find a cure for the failure is intense. Team members must be chosen for their abilities to withstand the pressure and politics to find an apparent cause and move on. The apparent cause is most often just a symptom of the failure and not the cause itself. Pressure can be reduced by clear and concise communication at regular intervals and the formulation of an accurate and attainable timeline for corrective action.

Given the numerous opportunities for things to have gone horribly wrong, it is testimony to the dedication and expertise of those involved with the manufacture of the MLAS flight fairings that they only had the bond failure event during the fabrication process. The lessons learned and application of remedies to mitigate the failure effects on the product will be a benefit to the cost and quality of future VARTM parts manufactured at other factories that produce dissimilar products. It would be a mistake to reject the process, materials, tools, and methods because of the struggles that occurred when they were first applied.

Lessons Learned

The first lesson learned was that manufacturing process controls used at a shipbuilding facility do not translate to the same process controls used for space or aerospace vehicles. The approach to shipbuilding is "rougher" than the aerospace counterpart in respect to controls, methods, planning, and execution. The word *precise* means something quite different when used in reference to building a ship than in reference to building an airplane or space vehicle. Therefore, an infusion of training to align the two processes and discover areas of commonality and gaps that need to be filled is essential to success. The measurement equipment, tooling facilities, or even hand tools are not the same at a shipbuilding facility. They may have to be supplied.

Secondly, continuous on-site oversight needs to be provided. The aerospace/space team members need to be present at every step of the manufacturing process to monitor and ensure alignment with the needs of the program. Absent oversight, dominant resident manufacturing processes will realign to what is known. The known process will be assumed when there is not an expert to facilitate and maintain the discipline of the process.

The third lesson is that little stuff can have big consequences. It is reasonable to think that simply turning a piece of core around and gluing down the opposite side would not cause a problem. But reasonable assumptions have often led to the demise of large enterprises. In the day-to-day battle of aligning and assigning priorities, some knowledgeable and competent people decided that flipping the core was, "no big deal." When you think about it, a person would logically assume that the scrim side should have the adhesive. Always stop and evaluate the effects of every change in the manufacturing process, no matter how small. A small dog can have a big bite.

Quality Improvement

Most manufacturing models will have a forensic component that monitors early failures to improve quality or efficiencies. The forensic methods for manufacturing operation fault analysis were adapted from what is primarily used in the legal and insurance businesses for determining cause for assignment of damages, awards, and liability contribution to the failure. Forensic engineering was and is still used to determine the cause and corrective action for a failure during the operation of a completed product. The Federal Aviation Administration (FAA) uses forensic engineering to determine the cause of a crash, and then to make recommendations for correcting the "fault" to prevent future failures.

For the MLAS project, the forensic component began with in-process assessment of the product. Major components were evaluated if form, fit, or function problems, or failure occurred during the manufacturing process. This differs from forensic engineering used to determine the cause for failure during product use. The use of forensic engineering during manufacture also differs from in-process inspection. In-process inspection determines conformance to engineering design and specifications. Forensic engineering addresses the escaped defects that passed through the quality gate. In-process fault determination and corrective action using forensic engineering tools provides greater product reliability. Scientific assessment and correction of failure-causing defects are made during the manufacturing phase. The use of forensic engineering tools throughout the entire manufacturing process increases the product's robustness. By proactively detecting and correcting engineering-derived defects found during manufacture, the product is less likely to fail during operation.

Development of integrated structural health monitoring (ISHM) devices has enabled the digital thread to extend into the manufacture of products. The devices tracked, monitored, and recorded data during the MLAS manufacturing process. The high-fidelity data was retrieved and rapidly inserted into the analysis models for fault and correction determination. For the team, the devices provided access to manufacturing data remotely for collaborative analysis. The devices were also set to alert the team if preset limits, such as temperature and vibration resulting from impact, were experienced during manufacture or transport. These devices were the genesis for current textile-based health monitoring systems that provide data proactively during the manufacturing process for data on demand or trigger alerts.

The integration of ISHM and forensic engineering in-process during fabrication and assembly enhance the ability of manufacturers to provide superior products. ISHM and forensic engineering tools provide predictive and proactive means to prevent finished product failure during use.

MANUFACTURING INDUSTRY USES

The use of forensic engineering and ISHM during manufacturing eliminates the need to subjectively assess product fault events. When these tools are used during the manufacturing process, defects that could cause product failure during use can be detected and corrected before they are fielded as finished products. The use of ISHM can detect many causal events during fabrication and assembly, such as unintentional impact or foreign objects, which could lead to failure. Location and event data can be assessed using forensic engineering tools to determine the cause, correct the fault, and prevent future occurrences.

There has been heightened interest in ISHM as an integrated manufacturing tool to identify, correct, and enhance product quality. It has been driven by manufacturers' desire to reduce in-process defects that escape quality checks and to detect design-inherent defects that manifest themselves during the build process. The data is digitally coordinated with the manufacturing build plan to improve product reliability and reduce liability from product failure.

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7

MLAS VEHICLE ASSEMBLY

> *"Success usually comes*
> *to those who are too busy to be looking for it."*
> —Henry David Thoreau

INTRODUCTION

The Max Launch Abort System (MLAS) assembly method was derived from the materials and processes used for its structural parts, which were manufactured using high-strength, carbon-fiber material. The evolution of assembly methods that resulted in the determinant assembly process was aided by the use of digital data.

Some of the pieces of the assembly required rework as the result of failure of the core bond in the forward fairing quarter sections. The use of the determinant method of assembly was negatively impacted by the remake of parts because the wooden tools, when needed for a second set of parts, lacked the fidelity of their first use. The quality and mold line fidelity was impacted by disposal of the tools in an outdoor area of Mississippi that was environmentally harsh and degraded the tools. This impacted the trim and fit-up at final assembly requiring multiple stacks and de-stacks to align the components of the assembly. The decision to use a determinant method of assembly was the culmination of an evolutionary tooling process based on the tradition of all-metal airframes.

At some point along the journey to become a fully functioning product that meets the expectations of the customer, parts must be assembled and joined together. The joining must be robust enough to survive in the environment for its intended use. The assembly must have a quality level that meets or exceeds specifications. It must be produced in quantities that satisfy customer demand.

Further, it must be delivered in a timely manner at an agreed schedule. Parts that come together for assembly and joining arrive from a variety of locations. Their arrival is timed to coincide with the assembly requirements for their inclusion in the product's progression. Escape and in-process defects discovered during the manufacturing process can stop production flow.

Space and aerospace parts represent a large investment in time, toil, and treasure well above most products such as automobiles. A single aerospace part such as the skin for the F/A 18 E/F vertical stabilizer costs in excess of U.S. $70,000 (€50,750). The precision and critical nature of the joining of the parts causes seemingly small errors to have large impacts. As parts are joined along the assembly path, the collective investment increases, making the impact of error, defects, and failures progressively more costly. As the product approaches the end of its manufacturing journey, the impact of discovered escape defects or in-process defects can dramatically affect the reputation and profitability of a producer. A defect can escape detection either because the test patterns applied do not expose the effects of the defect, or the defect does not interfere with correct operation under the operating conditions of the tests (McCluskey 2001). Escape defects that are located in flight-critical areas can have catastrophic results. Space and aerospace vehicles are the most complex and costly products and represent a highly visible and dramatic image when catastrophic failure occurs. People often die as a result of part or component failure due to defects undiscovered during the manufacturing process.

The attention to assembly is well deserved as the airframe assembly process accounts for 65% of the cost of the airframe, 80% of defects, and 80% of lost time injuries during manufacture of an airplane (most studies done to collect this type of data are of a proprietary nature).

A HISTORICAL PERSPECTIVE OF METAL PART ASSEMBLY

I entered the aerospace manufacturing and assembly domain in 1965 as a jig and fixture trainee at the North American Aviation training center located at the corners of Aviation Boulevard and Imperial Highway in El Segundo, Calif. After six months of classwork, I was sent to report to my supervisor in the tooling building across El Segundo Boulevard. As I entered the new world that was to occupy my life for the next 50 years, the sights, sounds, and smells of the hay-day of aerospace tooling was impressive and overwhelming. At the time commercial and military aviation assembly tooling were mixed together under the roof of North American's building 101. There were fixtures at varying stages of completion packed together everywhere. The Cold War and the Viet Nam war were in full swing and commercial aviation was emerging into the jet age with an assortment of new airplanes.

Jigs and fixtures were the royalty of the manufacturing process needed to hold the airplane parts and pieces in place while the mechanics drilled and filled holes to fasten them together. These tools began small as subassemblies were fastened together until they were complete and could be moved to mate fixtures. The mate fixtures added more pieces and joined the smaller subassemblies together in progressively larger sections until a complete airplane emerged. Several iterations of the same jig or fixture were being built resulting from the rate at which airframes were needed and the ability of a single tool to produce the rate. For example, if four airframe subassemblies were needed per week and the tool could only produce one per week, then five or six tools were produced. The extra fixtures were needed to accommodate the out-of-service requirements for tool calibration and maintenance.

Watching the assembly methods of the 1960s, 1970s, and early 1980s would reveal the need for hammers, pry bars, and rework departments to bend and coax the metal parts into the details of the assembly fixtures until they could be fastened together. The part and piece manufacturing methods of the time were derived from hand-built tooling that inherently contained a great deal of variability from engineering requirements and from part to part.

As a component of my training, I was sent to the blue blocking operation where female molds were painted with blue die and then lowered onto a metal-forming male die that would eventually be used to manufacture an airplane skin or part. I would grind down the blue high points until 80% contact was called "good enough." Multiple-rate tools to make the same part, produced by many people, resulted in part variability because my 80% contact area might not be the same as one of my fellow blue block mechanic's 80% contact area.

Compounding the die process and its variability were the parent master models for the female bluing molds. They were of plaster and made from templates using height gages and compasses as their measuring mediums. Figure 7-1 shows a master model and measuring tools of the time. With use the plaster deteriorated and grew or shrank from humidity, temperature, and wear. Nonetheless, this manufacturing method was sufficient to produce acceptable aircraft because metal was forgiving. It could be bent into shape to fit into the holding details of the jigs and fixtures. But some parts were so bad that they had to be sent to a rework department called "check and straighten" before they reentered the assembly process to be bent into the fixture's holding details. Figure 7-2 shows a typical small subassembly fixture of the 1970s with removable positioning details.

Figure 7-1. Master model and measuring tools.

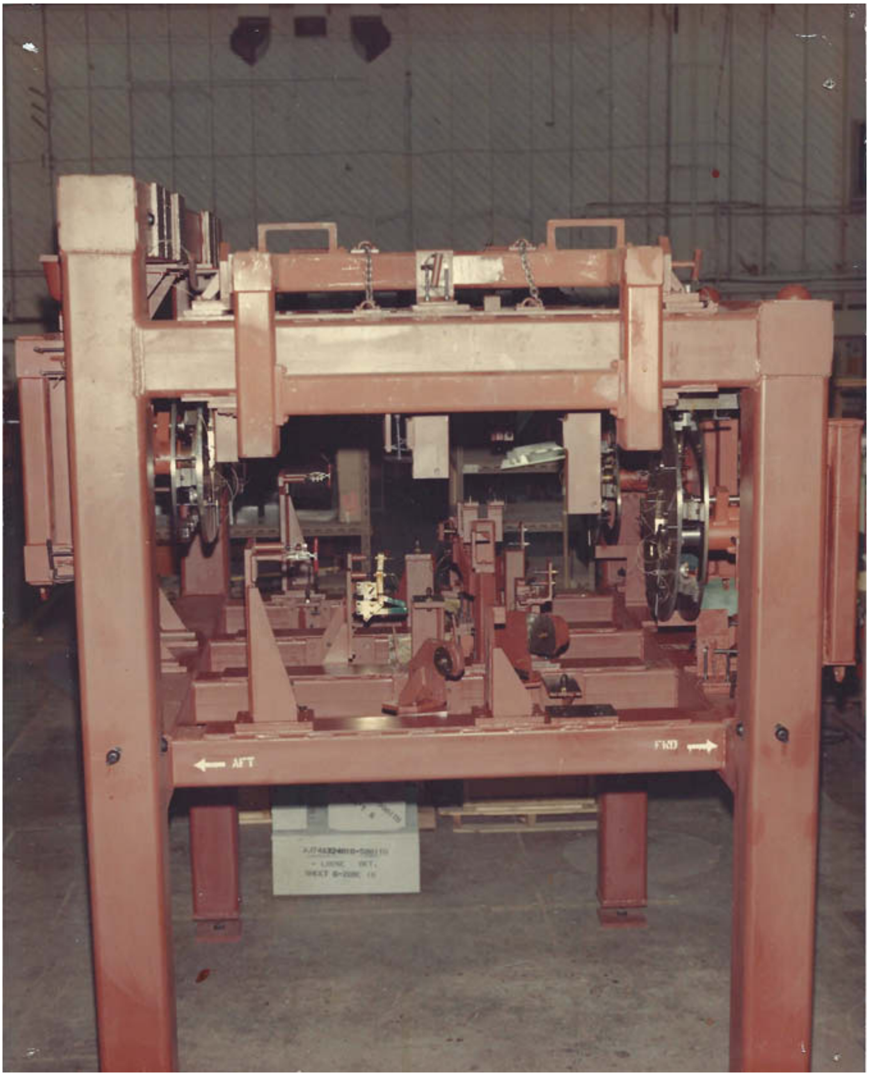

Figure 7-2. Typical small subassembly fixture of the 1970s with removable positioning details.

EVOLUTION OF ASSEMBLY METHODS

When composites began to emerge as viable and attractive alternatives to metals because of their attributes of stiffness and light weight, it became apparent to the tooling industry that the previously acceptable methods of assembly were not going to work for the new material. The very stiffness that was attractive to the airframe designers defeated the entire "close-enough" metal fabrication and assembly philosophy. Parts fabricated from composite materials resisted beating, prying, and bending, so new methods of tool fabrication and assembly fixtures would have to be developed.

Fortunately, as composites emerged as the material of choice for airframes, numerical control (NC) machines and laser measuring devices also entered the picture as new tools for the fabrication of masters, molds, and fixtures. NC machining reduced the variability of masters and molds. The NC machine's tool paths were driven by data derived from engineering specifications, so the molds and masters were a more accurate representation of the desired dimensions. Repeatability and accuracy in the tooling translated into consistent, repeatable, and predictable parts.

Assembly fixtures were improved when they began to have their part positioning details produced by NC machines. The master gages used to position and calibrate their location also began being made from NC machines. Laser positioning technology evolved into sophisticated systems for jig and fixture construction and calibration. This further improved the tooling and, therefore, the parts positioned and held for joining and assembly. All of this led to a continuance of the fixture-as-king assembly process developed during World War II and brought to a high art form by the mid-1990s.

NC machines and improved metrology systems like laser trackers mitigated the stiffness challenges for fabrication and assembly tooling. However, a new demon emerged from parts built from composite material, which would drive manufacturing technology to find a solution. Whereas the skin thickness of a metallic part is uniform as a product of its manufacturing method, a part made of composite material varies in thickness based on the number of plies used in its fabrication. A .375-in. (9.525-mm) thick part can vary from .345–.405-in. (8.763–10.287-mm), with thickness variability increasing in proportion to the part's thickness.

With the advent of stealth requirements that drove precision conformance to provide steps between skins, this manufacturing challenge drove cost into the assembly process. As each part nested against the substructure, the outer mold line (OML) of the skin could not rise above or fall below the adjoining skins. The first mostly composite skin airplane was already expensive before large numbers of mechanics had to crawl over the completed airframe sanding down gaps to meet design requirements, further increasing cost. As a result of this painful experience, the designers "fixed" the problem by throwing the challenge to manufacturing and driving the tighter requirements for steps (and gaps) into the fabrication and assembly processes. They specified as-manufactured requirements for steps (and gaps) as part of the fabrication and assembly processes to preclude the need for sanding.

It was becoming clear that the old monolith assembly tools with all their girth and weight were going to have to give way to a new, more flexible tooling method.

INNOVATIVE ASSEMBLY PROCESS

As the precision of automobiles has increased to approach that of airframe components, and the airframe manufacturing process has become more repeatable, the natural manufacturing intersection of these two products has merged.

Tooling Advancements

With the use of more composite material parts on airframes, manufacturing technology groups in Europe and the United States began to have epiphanies linking their attributes to newer manufacturing technology, such as NC machining, which required a revision of the old large monolithic tooling approach to airframe assembly. The first step was the implosion of parts to reduce assembly steps and part quantity. ("Implosion" refers to the combination of many small parts that require assembly into a single part, sometimes referred to as a *unified structure*.) This process was already embraced by the automobile industry and had resulted in fewer assembly points, higher quality, lower cost, and increased customer satisfaction. It also enabled the use of robotics for the assembly process. Precise and repeatable parts are exactly what robots require to be successful.

Higher-quality parts made from stiff materials that resisted changing shape once formed awakened a new vision for the assembly of airframes. The vision was the elimination of old-style tooling. It would be replaced by determinant part alignment and positioning using the key features of highly accurate parts and accomplished by automation or mechanization. Thus the large, heavy, and robust assembly fixtures required a redesign. Loaded with positioning details whose function was to bend metal parts into conformance until their job was replaced by fasteners, the stiffness of composites made such fixtures obsolete. Bulkheads, ribs, and spars made with highly precise NC machines could replace many of the locating details, further reducing the assembly tool's bill of material. As a result, the new large box tools are naked of clutter when compared to the fixtures of the past.

Overall, the individual quality and precision of manufactured parts, pieces, and components of the end product had increased substantially since the old days of metal forming and hand-driven machining processes. However, several challenges blurred the vision of an airplane or space vehicle robotically assembled using repeatable parts with interlocking features. One was the variability of the thickness of composites parts and another was the variability between the parts produced, which were the building blocks of the airplane.

Additional challenges were emerging as airplane manufacturing specifications included stealth requirements that began to stress the last vestige of the hand-built manufacturing process. Large assembly tools were no longer capable of addressing the tighter tolerances nor could they compensate for the variability of combined metallic-composite assemblies.

Large assembly tools are composed of a heavy steel welded structure. Steel is used to reduce the coefficient of thermal expansion of the fixture and its collective positioning details. The steel structure begins its life as an empty box, heat-treated and stress-relieved to promote a stable platform for positioning the details of an assembly. Within the box of the steel structure, a complex array of removable details is attached to the steel structure. They facilitate the positioning and holding of parts until they are fastened together and become strong enough as an assembly (or subassembly) to be removed and transported to the next position for joining with the mating subassembly. Attached to the assembly tool structure, the details are made removable. Once the assembly has been completed within the tool, the details can be disassembled and stored so the finished assembly can exit the tool.

The removable details are designed to be less than 35 lb (≈16 kg) so humans can attach and remove them. The jigsaw puzzle composed of removable details presents a tool design challenge. Sometimes this has resulted in embarrassing errors as large sections of airframes have been completed only to discover that the assembly could not be removed from the tool. This necessitates cutting out the part and destruction of the tool that had created it. The phenomenon of discovering that the removable details were incorrectly designed, which prevents their removal and the removal of the airframe assembly, is called "jig locked."

Removable details are critical to the dimensional outcome of the finished assembly and its ability to attach to the next assembly in the manufacturing process. They are typically constructed to meet a ±.01-in. (±.254-mm) tolerance criteria for positioning parts. Large master gages are constructed and lowered into the box assembly fixture for locating and attaching the removable details during the assembly tool fabrication process. The positioning tolerance inside the assembly tool is ±.002 in. (±.0508 mm) for the master gage and the master gage itself is constructed to a tolerance of ±.002 in. (±.0508 mm). All of the tooling's stacked tolerances add a variability potential to part positioning within an assembly beyond a typical part's tolerance of ±.014 in. (±.3556 mm). Compounding the added variability of tooling to the collective workpieces of an assembly was the lack of on-assembly (in-process) control of assembly tool conformance. Tools were and, in many cases still are, reliant on annual reinsertion of the master gage into the assembly tool to check and validate the removable tooling details' location conformance. Otherwise, workpieces will continue to be placed and held in position by the details until a problem with fit at the next assembly step is discovered.

Precision Machining and Determinant Assembly

The evolution to machining and trimming parts using precision machines optimized by volumetric error compensation algorithms (VECA) and operating in temperature-controlled rooms began producing parts with very little variability. The accuracy and precision of multi-axis machines are profoundly affected by their volumetric accuracy. The volumetric accuracy of a machine depends on numerous factors, including geometric and kinematic errors, motion-induced errors, deformation of structural members due to static and dynamic loads, and thermally induced errors. To alleviate the influence of these factors, passive on-line software has been developed to control volumetric error compensation in the machine envelope. The system operates by an interpolation algorithm with shape functions for error prediction and uses a recursive online software compensation scheme (Wang and Ehmann 2008). Figure 7-3 shows the software compensation scheme for a volumetric compensation algorithm (VCA) or VECA system.

Precision machining of component parts and trimming of skins has led to a new tooling model where determinant assembly (DA) is driven by interlocking parts that align with each other using key features. The essence of the DA philosophy is that indexing one part or assembly together yields three primary benefits over indexing

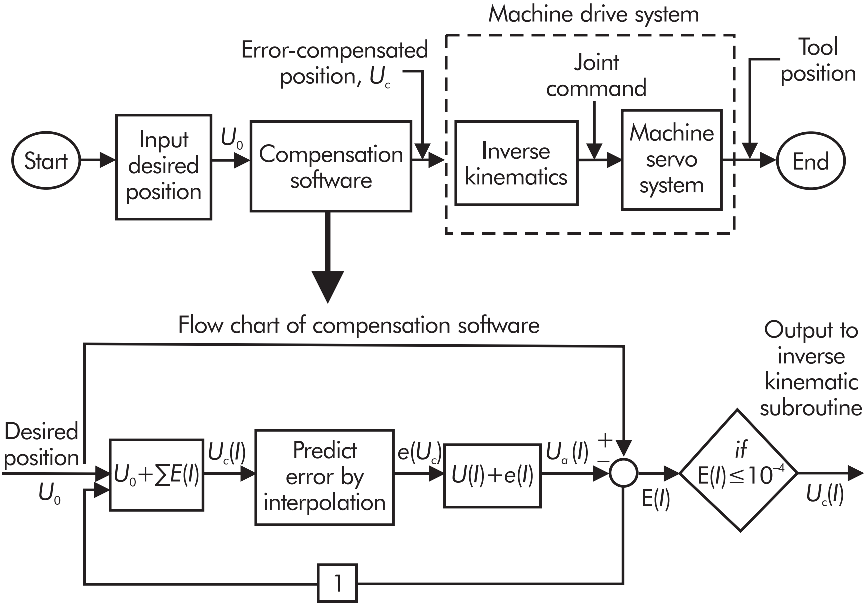

Figure 7-3. Software compensation scheme for a VCA or VECA system.

the two parts or assemblies to a tool: improved accuracy, increased flexibility, and reduced cost (Williams et al. 1997). Accuracy of the part-to-part relationship is improved because the tolerance chain is typically shorter and each tolerance is smaller in magnitude than tool-based indexing systems. Tool tolerances are usually biased and fixed while part-to-part indexing tolerances are randomly distributed and centered around the mean. This enables the manufacturing engineer to take advantage of statistical tolerance combinations for determinant assembly processes, which typically are not available for tool-based assembly processes.

DA is more flexible because changes to assemblies often can be accomplished by modifying the feature locations in the part's NC program. This is contrasted to conventional assembly tooling where a physical component of an assembly fixture must be relocated or a new index fabricated and installed on the assembly fixture.

Determinant assembly yields cost advantages. Engineering change costs are typically lower; non-recurring tooling costs are significantly lower because many of typical parts of the assembly fixture are precluded by part-to-part indexing. The biggest cost savings is derived from reduced recurring expenditures, a result of the superior fit of parts and assemblies built using the DA process. Not only is less assembly rework required using DA, but basic direct and indirect factory labor is significantly lower for these closer-tolerance assemblies. As a result, the customer receives a higher-quality product at a lower cost and within a better delivery schedule.

THE CLOSED-LOOP DIGITAL THREAD

While metal parts are manufactured with less variability than their hand-built and manually machined predecessors, they still contain enough variation when combined to created assembly challenges. Parts made with composite materials add to that challenge by their thickness variability. Airframes, wings, control surfaces, and tails are all built as progressive assemblies from the inside out, arriving at the final outer-mold-line (OML) configuration as a product of the collective variation of their component parts. Parts made from composite materials are fabricated with their tooled surface as the exterior or air-flow surface (OML) of the airplane.

As a result, the rough untooled surface is fastened against a metal substructure that contains variability as a result of its collectively assembled parts and the thickness variation of the other composite parts attached to it. The exterior (OML) variation causes step variation from piece to piece as the airplane parts are fastened together. This drives complexity into the assembly process as various methods are employed to mitigate the steps between OML parts. Thus the final step in the assembly of airplanes consisting of skinning-out the structure turned from being predictable with metallic skins to being unpredictable with composite skins.

The digital thread has provided a powerful design and manufacturing distribution medium for transferring data out and into the supply chain. Until recently it stopped at the end of the manufacturing process when quality assessment tools compared as-manufactured parts with design-specified conformance criteria. The digital thread and its full potential to improve manufacturing product is recognized in the return of the data back up the supply chain for optimal assembly efficiency and precision. Management of as-manufactured part measurements and intersecting data at the mating points to optimize subassemblies and assemblies for precise fit is now recognized as the second-generation goal of the digital thread. The return of data back up the supply chain optimizes fit and function at an increasing value as the end product becomes more complex with a larger number of performance-critical parts. Complex assemblies are enhanced by part measurement data that is optimized at each mating assembly for the best fit and dimensional outcome.

Geometric Dimensioning & Tolerancing

Geometric dimensioning and tolerancing (GD&T) is a system for defining and communicating engineering tolerances. It uses a symbolic language on engineering drawings and computer-generated, three-dimensional solid models that explicitly describe the nominal geometry and its allowable variation. It tells the manufacturing staff and machines what degree of accuracy and precision is needed on each controlled feature of the part. GD&T is used to define the nominal (theoretically perfect) geometry of parts and assemblies, the allowable variation in form and possible size of individual features, and the allowable variation between features.

GD&T is recognized as the front-end methodology for adequately dimensioning and tolerancing parts which, when assembled, result in a fully functioning product matching the end assembly's desired dimensional requirements. The issue with GD&T is the lack of an adequate feedback system to monitor each manufactured component and map its interaction with other parts as they collect into a finished assembly. The digital thread has optimized the outward distribution of the GD&T-specific knowledge and data base for parts and assemblies to assure that components meet specifications. Optimization of the GD&T model for part and assembly best fit and dimensional conformance would use the digital thread as a closed-loop feedback system. There would be a constant data stream interacting and adjusting the parts along the manufacturing chain. The end result would be assemblies produced to a new conformance model whose dimensional intersections are optimized between mating parts.

The purpose of GD&T is to describe the geometric requirements for parts and assemblies. Proper application of GD&T during the MLAS product definition process ensured that the geometry defined on the drawing led to parts and assemblies that had the desired form, fit (within limits), and function as intended.

ASSEMBLY FIT AND FUNCTION

The NASA Engineering and Safety Center (NESC) had several partners during the coordinated effort to develop and conduct the demonstration and perform the assembly work. Besides Northrop Grumman Corp., NASA personnel based at Wallops Island conducted structures and mechanism assembly as well as flight test support (Bullen 2010).

The Role of Determinant Assembly

Determinant assembly is accomplished by integrating part indexes into the product definition process. Digitally designed subassemblies and assemblies with DA features are used to create NC programs that machine these features into the part. As early as 1995, Boeing and Northrop Grumman commenced a reengineering program for the majority of the Northrop Grumman-supplied fuselage panels. It included the creation of CATIA® data sets with DA features. Northrop, along with its suppliers, completely revamped its 747 manufacturing and tooling plan to take advantage of the determinant-assembly-enhanced digital product definition. To maximize the leverage obtained from this investment in quality, Boeing committed to building completely new major assembly jigs based on the DA philosophy in its Everett facility.

It is important to note that some portions of the fuselage were outside the scope of the Northrop Grumman effort. In these areas, Boeing needed a method to bridge the gap between the determinant-assembly indexing systems and the conventional-tooling-based indexing systems. To bridge the gap, planar laser systems similar to those provided by AIT (Advanced Integration Technology, Inc.) for other Boeing airplane programs were required. The planar laser technology allows highly accurate integration of conventional and determinant-built assemblies. The resultant tooling is a combination of gageless (determinant assembly) and virtual (planar laser) tooling (Williams et al. 1997). Figure 7-4 summarizes the objectives, tooling requirements, implemented solutions, and benefits of the Fuselage Assembly Improvement Team.

Alignment and Measurement

MLAS was a benefactor of the progress made toward gageless tooling that integrated composite structures into a building block approach to assembly. Parts were assembled as stand-alone, self-locating interlocking pieces. The interlocking part alignment was aided by laser alignment systems. The use of these systems was critical to the success of the precision assembly process. In the laser indexing system, MLAS features were located using laser measurement feedback instead of hard tooling. At the MLAS assembly center located at Wallops Island, Va., a rotating laser continuously swept 360° and struck targets located in a structure. A retro-reflective pattern on each target face returned a pulse signal to a photodiode receiver in the laser head. The pulse signal varied based on where the laser struck the target face. Processing the return signal, the laser determined where the target was in space relative to its “zero” or centerline position.

	Determinant Assembly	Conventional Assembly	
Assembly technique	Snap-together parts Part-to-part indexing	Parts-to-tool indexing	
Tooling characterization	Gageless tooling	Hard tooling	Soft tooling
Tooling requirements	Free-form manipulation	Indexing	Indexing
Benefits	Precision, speed, flexibility (versus non-automated tooling)		Less constraining Less routine (versus hard tooling)
FAIT program solution	Precision automated motion	🚫	Laser measurement

Figure 7-4. Objectives, tooling requirements, implemented solutions, and benefits of the Fuselage Assembly Improvement Team.

The laser alignment approach to assembly enabled the MLAS project to accomplish its manufacturing objectives of accuracy, flexibility, and cost effectiveness. Precision panel positioning and control supported the unique requirements of determinant assembly. Skin coordination holes in the quarter sections of the vehicle coast and boost skirts, as well as the forward fairings, were aligned. Additional benefits of the technology were ease of assembly and manufacturing flexibility. Laser measurement technology enabled the highly accurate integration of conventionally and determinant-built assemblies in MLAS. The replacement of hard tooling with laser indexing freed up critical shop-floor space, decreased tool routine requirements, and eliminated part constraints during assembly.

The precise assembly of MLAS was critical because the vehicle did not have a guidance system to correct errors in flight. It was a launch-and-leave system that relied on the precision of its assembly aligned with the thrust of the motors to maintain proper trajectory. Therefore, the mass properties of all the combined components had to be weighed, measured, and constantly aligned during the assembly process using precision measuring instruments. Without proper alignment of all the pieces and parts of the assembly to the centerline of thrust, the vehicle would tumble or veer off course. In addition, the fins had to be aligned precisely with the vehicle as it was stacked and assembled. The fins of the coast skirt had to be clocked 45° from the fins located in the boost skirt to be positioned between them at their precise midpoint.

The MLAS assembly team also used laser alignment technology to facilitate the calculation and precise installation of motors and motor mounts. Figure 7-5 shows alignment of the assembly. Figure 7-6 shows the use of laser technology to pinpoint precise assembly locations and obtain accurate data to align the mass properties for a successful launch.

Other hard-point details were used to facilitate proper alignment during the assembly and launch of the MLAS vehicle. They included alignment stacking pins and frangible joints. Four drag plates were used to facilitate the separation of the boost skirt from the rest of the vehicle after the rocket thrust stopped.

Figure 7-5. Installation, assembly, and alignment of the motors into the motor-mount cage of the MLAS vehicle. (Courtesy NASA)

Figure 7-6. Use of laser technology for alignment of the assembly. (Courtesy NASA)

The assembly process included the stacking and unstacking of the MLAS vehicle to ensure that the separation and fitting would realign and not bind. Assembly also included the 27.6-ft (8.4-m) diameter conical ribbon parachutes for the coast skirt, 27.6-ft (8.4-m) diameter conical ribbon parachutes for reorientation of the capsule simulator and fairing, and two more 27.6 ft (8.4 m) parachutes to slow descent until splashdown.

TECHNOLOGY TRANSFER

NASA, Northrop Grumman, and the other MLAS team members realized early-on that the program would require the expertise of senior scientists and engineers who had participated in previous inhabited space launch vehicle programs. The complexities of a functioning assembly needed to draw on the experience of individuals who had been successful to leverage the knowledge base for MLAS.

It is rare enough when a new product is developed for aerospace use where a new engineer or scientist is given the opportunity to participate and work with senior professionals who have taken the development-to-reality journey at least once. Today, the opportunity for exposure to a new program may occur only every 20–25 years. As a result, 50-to-60-year-old engineers and scientists work with 20-year-old, entry-level engineers.

New design and development programs for space vehicles are even rarer. The space shuttle began its manufacturing journey nearly 40 years ago. So, the available expert knowledge base of engineers was in their 70s and in some cases their 80s when MLAS and Project Constellation began. Human space journeys to the Moon were enabled by manufacturing technology experts from the 1960s who were now in their 80s. It may seem that an "old-dog's" experience and expertise would be antiquated. However, there is a common thread of unchanging rules, physical laws, and scientific principles that is absolute for travel and especially human survival in the hostile space environment.

While much has been written about the lessons learned, the exposure to and leverage of the knowledge from the authors of the works became critical to the MLAS design, development, and manufacturing plan. Integration of university interns and junior-level engineers and scientists was, and still is, a necessary component for robust technology transfer. The MLAS program coalesced into a young energetic group of individuals who became invigorated by the opportunity to work with the astronauts, scientists, and engineers who had been in space, designed and built the space station, and who were part of every U.S. space program in the last 50 years. Together they applied the new tools, technologies, and materials of the modern age. This mentoring partnership was the primary and most valuable deliverable for the transfer of technologies and processes that came out of the MLAS and Constellation projects.

Technology transfer and extensibility is often seen as the identification of dissimilar applications for processes and technologies designed, developed, and applied for a specific purpose. The newly developed processes and technology and their potential for other uses is overshadowed by the need to disseminate the acquired knowledge. The necessity of engaging young scientists and engineers from the beginning of the development and design process becomes critical as new product design and development evolves.

The MLAS team was comprised of over 150 engineers, researchers, and analysts from across NASA and industry. The NASA component of the MLAS team capitalized on the opportunity to share lessons learned from past experiences and pass on corporate knowledge. Apollo-era veterans were brought in as mentors and advisors to junior engineers with five to 10 years of experience. The mentors provided the MLAS team with first-hand knowledge acquired while building a human-rated spacecraft. The junior engineers, referred to as resident engineers by NASA (based on the concept of medical residencies), received hands-on experience through the entire design, build, and test life cycle. The multi-generational nature of the team was enriching and helped to meet the goal of expanding NASA's experience base in fast turnaround design and development projects.

From the industry's perspective and, especially from Northrop Grumman's perspective, working on MLAS offered the opportunity to bring young engineers and scientists together to learn and grow through participation in a rare event. Senior leadership and engineers identified highly motivated individuals for participation in MLAS and Constellation projects. They became embedded and resident with NASA and Northrop senior personnel. The ratio for senior-to-junior-level engineers varied according to the specific task and ranged from one-to-one to five-to-one with the latter being in favor of junior individuals to their mentor. Feedback from the experience was highly favorable across the global enterprise. Returning engineers rose to leadership positions. Technology and processes learned from their experience became distributed across the enterprise. As the modern era increasingly focuses on technology as the substance of today's society, the MLAS team recognized the human component of technology transfer and its ability to be a multiplier for the spread of manufacturing technology to other applications.

At the end of the MLAS, Composite Crew Module, and Constellation projects, the extensibility and technology transfer resided in the human knowledge base. The digital thread, innovative technologies, determinant assembly, and advanced materials and processes stand alone in isolation without the human ability to transfer and disseminate the knowledge of their advantages. The real value has come from the participation of dozens of young engineers and scientists who now transfer their knowledge and experience through industrial leadership, contributions at conferences, and teaching at universities.

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8

MLAS TRANSPORTATION, PACKAGING, HANDLING, AND SHIPPING

"All things are difficult before they are easy."
—Thomas Fuller

INTRODUCTION

Just like most products, all land, sea (surface and subsurface), air, road, and space vehicles must be transported, packaged, handled, and shipped (TPHS) during and after their manufacture. MLAS quarter sections for the boost skirt, coast skirt, and forward fairing were large and structurally sensitive enough to warrant special consideration for their TPHS. Their functional design strength was dependent on the collective assembly of their components. Therefore, their packaging included special shipping instructions, shipping fixtures, packaging, and optimized roadway consideration to avoid weather and excessive bumping and vibration. The roadway for their transport ran from Gulfport, Miss. to Wallops Island, Va. and was intentionally mapped to avoid road construction and extreme weather. Each component needed to arrive in the condition it left Gulfport to ensure the integrity of the completed vehicle assembly. Truckers accustomed to using come-along winches and straps slung over the top of the shipping fixtures and containers had to be instructed to re-route their straps through specially designed strap slots in the shipping containers to avoid damage to the MLAS parts.

The complex nature of the vehicle and criticality of the mass properties had to be maintained throughout the TPHS process to assure that it arrived at the launch point as it had left the assembly center. Successful vehicle launch was dependent on stringently following the defined TPHS criteria.

Transportation, packaging, handling, and shipping are crucial to the success of the manufacturing process. Transportation operations are responsible for the efficiency of moving products. Progress in techniques and management principles has improved delivery speed, service quality, operation costs, logistics, and energy savings. *Logistics* is defined as the process of moving and handling goods and materials from the beginning to the end of production, to the sale process, and final waste disposal to satisfy customers and add business competitiveness (Tseng et al. 2005).

Transportation-caused product damage, liability, cost, and impact to manufacturer reputation have invigorated the development of technologies to measure and monitor the treatment of cargo while in transit. There are tracking, position, and operator fatigue monitoring systems widely available and in use. However, in-transit monitoring of the product's environment at the detail level has lacked the fidelity and sophistication necessary to assess impacts and damage liability in shipping. There are a number of emerging technologies to monitor and measure the vibration and road trauma that can negatively impact products as they are transported from their point of manufacture to point of distribution or use. These technologies also provide the manufacturer with a means for managing the entire TPHS journey. They communicate the essential data and alerts for part and component health monitoring to transportation and factory management.

One technology incorporates impact indicators on packaging. The highly visible devices activate when an impact level exceeds a predetermined level. Mounted on a packaging container, the device visually alerts everyone involved in the package handling process that additional care is required. The technology involves several types of impact indicators for packaging:

1. A single-use device is available with several levels of sensitivity and designed to be affixed directly to a package.
2. A single-use, go/no-go device is used to determine if fragile products have been dropped during transit or in storage. The indicators are field-armable, tamper-proof devices that turn bright red when an impact beyond a specific threshold has occurred.

3. Resettable, reusable indicators intended for large crates and shipments weighing over 500 lb (227 kg). These devices can record the direction and angle of impact.

ENVIRONMENTAL CONSIDERATIONS

Another area for consideration is temperature, humidity, and altitude variations that transported products experience along their journey. Products are often manufactured far from their point of consumption or use. Temperature inside or under the covering for the product can vary from 130° F (54.4° C) to –20° F (–28.9° C), and from 90% humidity to 10% humidity. Sometimes the temperatures can change rapidly. Leaving the desert floor in Phoenix, Ariz. when the temperature is 110° F (43.3° C), it is not uncommon to drive the 144 miles North to Flagstaff, Ariz. and arrive 2.5 hours later to experience a temperature of 32° F (0° C). Parts made from high-strength graphite composites materials to exacting specifications, in highly controlled environments, fabricated on robust tools made from materials to control the coefficient of thermal expansion for dimensional integrity, are now transported cradled in handling fixtures often made of aluminum or wood.

COST OF PRODUCT EFFECTS

Most manufacturers consider TPHS complexity in their manufacturing plans, including liability for damage or failure when calculating the delivered cost of their product(s). For example, as wind turbine blades and their support towers have grown larger and routinely exceed 131 ft (40 m), TPHS has become a challenging component for their manufacture and delivery. The transport of wind turbine blades in the United States now accounts for one third of their delivered cost. Road-size restrictions make transportation of wind turbine towers with a diameter of more than 14 ft (4.3 m) difficult. Figure 8-1 shows the challenge of maneuvering a large wind turbine blade on one roadway in the United States. Figure 8-2 shows the impact to the environment when a road has to be cut through a forest to deliver large wind turbine blades. Swedish analyses show that it is important to have the bottom wing tip at least 98 ft (30 m) above the tree tops, but a taller tower requires a larger tower diameter (Emme 2011). A 3 MW turbine may increase output from 5,000–7,700 MWh per year by going from 262 ft (80 m) to 410 ft (125 m) tower height (Wittrup 2011). A tower profile made of connected shells rather than cylinders can have a larger diameter and still be transportable.

MANUFACTURING PLANNING

Transportation, packaging, handling, and shipping play a connective role among the several steps that result in the conversion of resources into useful goods in the name of the customer. It is the planning of all these functions and subfunctions into a system of goods movement that minimizes cost and maximizes service to the customers that constitutes the concept of business logistics. The system, once put in place, must be effectively managed.

TPHS are critical to the quality and conformance of the end product. They are major considerations when developing a manufacturing plan and determining production breaks. Inadequate consideration for TPHS in manufacturing planning and design can negatively impact the delivered product at the next assembly station in the manufacturing flow or when delivered to the end user.

A subassembly must be robust enough upon completion in its fabrication station to maintain its dimensional integrity at the next fabrication station. The method and tools used to move the

Figure 8-1. Large wind turbine blade on the road.

Figure 8-2. Environmental impact of transporting wind turbine blades to a wind farm.

subassembly also must be taken into consideration as to how they impact the process and the subassembly. Lift points have to be calculated to consider stress on the assembly and the center of gravity. Some of the most expensive and complex products still require cranes to move ahead in the assembly progression. The Northrop Grumman produced center section of the F/A 18 E/F represents approximately 40% of that aircraft's build effort. To complete the assembly process for the center section of the airplane, there are 255 crane moves. Designing, building, calibrating, tracking, maintaining, and certifying chains, straps, and handling fixture lifting tools (HFLT) are complex and challenging. The diverse array of tools, the need to shut down shop areas while product is moved overhead, the dangers of damage and impact during movement, limited access to cranes, and other inefficiencies have led to a new vision for handling and transporting large, complex, and expensive assemblies during the manufacturing process.

TOOLING

The cost and effort to move assemblies to completion through a traditional box assembly line has further incentivized the change to open-architecture tooling. Traditionally, after an assembly was complete, the tool positioning details had to be removed to release the subassembly or assembly from their grip. The compact nature of the assembly tool, the surrounding work stands and racks for tools, materials, and parts often made it difficult to ascertain whether all the positioning and workpiece holding tooling details had been removed. As a result, a crane might strain against an assembly in an effort to lift it while unseen details held it fast to the assembly tool. In many of these cases, something had to give. Either the tool or the part suddenly won the retention battle, breaking loose the assembly with at best minimal damage. At worst, the assembly and the tool are damaged and need repair. Even when the damage is minimal, a complete evaluation of the assembly must be performed. Documentation of the event must include the cause and corrective action. These efforts stop the assembly progression and disrupt production flow. In every event, the tool must be taken out of service for calibration and damage assessment.

The other limiting factor to progressive box-type assembly fixtures is they are designed to be close to the workpiece assembly. This approach minimizes the distance from the robust steel frame that carries the load of the structure and the workpiece to minimize deflection. The tight confines of the assembly tool minimize the positioning detail length, deflection, and complexity, but compound removal difficulty. When the crane is affixed and activated to neutralize the load, all pins are removed, and the hope is the assembly will not “jink” around inside the steel box as it is released. It is gingerly removed and then inserted into the tight fit of the next assembly fixture frame with caution, worry, and anxiety until the holding pins are inserted and the crane detached and removed.

DETERMINANT ASSEMBLY

The complexities of a process developed over decades to facilitate the assembly of metallic parts was challenged by composites’ parts stiffness and thickness variability, driving manufacturers to look for a new approach to assembly. Compounding the complexities were new bonding, shimming, and sealing materials needed for the new composite parts to engage with dissimilar metallic materials. The new materials were consumed at the point of use, temperature sensitive, and had a limited shelf life. Most of the new materials were frozen and required freezers located near their points of use where they were mixed and consumed.

The change to eliminate large box structures in favor of determinant, open-floor assemblies came when new, mostly composite airframes became overly complex and burdensome to manage using the old assembly processes developed for metallic airframes. The new open-architecture assembly approach leveraged the stiffness of composite parts and precision machining advances such as volumetric error compensation algorithms. A new assembly tooling model that used the parts themselves as key components to position subassemblies and assemblies evolved through the early part of 2000. It operated on a clean and open manufacturing floor that was absent the clutter of large assembly tools and their associated removable details. Figure 8-3 shows the MLAS forward fairing assembly being lifted to position onto the next assembly without use of a mating fixture. Figure 8-4 shows the clean look of an open-architecture, determinant assembly line that uses laser-assisted positioning.

The advent of a determinant assembly (DA) program and the subsequent production of accurate fuselage subpanels created the need to position subpanels accurately and repeatably during the fuselage assembly process. Automated positioning and alignment systems were installed throughout major fuselage assembly areas of airframe manufacturers to enable DA techniques. The benefits of the DA assembly approach and automated precision tooling were flexibility, accuracy, ease of assembly and associated speed, reduced downtime for tool maintenance, and improved shop-floor ergonomics. Additional benefits to DA were derived from a significant reduction in the need for control of the thousands of tools required for traditional assembly methods.

ASSEMBLY AUTOMATION

As DA took hold, the use of automation was enabled by the increased dimensional conformance and consistency of manufactured

Figure 8-3. Forward fairing assembly using straps and crane to position onto MLAS vehicle. (Courtesy NASA)

parts. Aerospace manufacturing engineers began to revisit high-rate automobile manufacturing facilities to re-evaluate their automation approaches to vehicle assembly. Both automobile and airplane manufacturers had long histories of looking to one another for synergy in leveraging technology. The inhibitors to incorporate automotive technology were aerospace's comparatively low rates of production and the automotive industry's comparatively less precise specifications for assembly. By early 2000, the two divergent assembly processes and specifications for assembly had merged to the point where automotive assembly automation could be applied to aerospace products.

One example of the outcome to the new aerospace/automotive blended assembly approach is the Northrop Grumman integrated assembly line (IAL) for the F-35 located in Palmdale, Calif. IAL represents a significant shift in the way airframes are assembled. The IAL has achieved a 450% increase in throughput

Figure 8-4. Open-architecture assembly line.

over the traditional assembly method (Weber 2013). The IAL maximizes robotics and automation, providing additional capacity and assembly capability, while meeting engineering tolerances that are not easily achieved using traditional tooling and manual methods. The IAL design uses a systems-engineering approach to integrate tooling and structure transport, system automation, automated drill and countersinking cells, and to coordinate tooling mechanization across multiple build centers.

The IAL evolved from a continuous, sequential, universal rail system that moved parts and assemblies of the F-35 between workstations. The “moving line” for material handling reduced the use of traditional overhead cranes and large assembly tools.

To address reliability, quality and safety concerns, aerospace manufacturers have talked about using robots for many years. However, most efforts have been hindered by accuracy issues and low production volumes. As previously mentioned, the industry has continued to rely on large, monument-style assembly jigs and traditional fixed automation, such as large gantry systems and product-specific fixtures. Unfortunately, gantry machines are expensive. And, they typically have limited throughput and require a large footprint.

Unlike gantry systems and other islands of automation, robots are more flexible and can be quickly deployed at a fraction of the cost of custom-designed machines. Other benefits over fixed automation include process repeatability, increased uptime, reduced scrap, reduced maintenance costs, and a reduction in jig and fixture requirements.

The IAL represented a breakthrough in using robots to improve assembly throughput and cycle times in the production of low-cost, flexible airframes. It was inspired by automation systems used by American automakers and was developed with the help of KUKA Systems North America, LLC. A team of Northrop Grumman engineers made several field trips to Detroit to see how automakers tackle assembly line automation.

Although challenged to achieve significant affordability goals, the IAL offered the opportunity to eliminate standalone islands of automation and develop an assembly line as an integrated system. Engineers from KUKA and Northrop Grumman worked together to design and install a fully optimized assembly line rather than just a conglomeration of independent tooling stations. KUKA leveraged its expertise with high-rate assembly lines, while Northrop Grumman focused on its extensive tooling knowledge. To begin, Northrop Grumman had to make fundamental changes to its business model and cast away old methods. For instance, in the past, the company had built at least 80% of tools in-house.

For the integrated assembly line, the new airframe assembly tools included automatic laser welding and automated panelization systems, in addition to multifunctional robotic end-effectors for drilling, sealant application, and fastener insertion. The IAL featured 13 articulated robots and an automated guided vehicle (AGV) system. The engineering structure and the tool were moved from station to station. This enhanced the ability to keep tight tolerances. It also reduced flex, improved quality, and greatly reduced the possibility of injuries or accidents.

The increase in automation allowed very precise tolerances to be maintained with drilling systems. In fact, one of the highlights of the IAL was a robotic drilling system for inlet ducts. It used nine-axis robots to drill thousands of holes in a challenging, small internal space. A vision guidance system allowed the robot to enter the narrow openings in the F-35's contoured air-inlet ducts, which are critical to the performance of the jet engine. The composite duct was integrated with the center fuselage by attaching aluminum frames that required hundreds of mechanical fasteners. The assembly process required the drilling and countersinking of 500 holes per duct. Each air duct was approximately 9 ft (2.7 m) long, but only 20 in. (508 mm) in internal diameter. Despite the ergonomically challenging space constraints, the operation was initially done manually. Assemblers would crawl inside the duct and use hand tools.

By using articulated robots, Northrop Grumman engineers reduced a 52-hour manual process to a 12-hour automated process and also reduced floor space. Three robotic cells drilled three different sections of the inlet ducts: aft, forward right side, and forward left side. They required 2,000 holes per set. Because each of the 500 drilling points had a unique safe-radius area, a laser tracking system located the correct position within a narrow tolerance. A laser inspection system was also used to evaluate the quality of each hole.

Another highlight of the U-shaped automated assembly line was the fleet of AGVs that transported work in process to assembly cells. Traditionally, overhead cranes were used to move fuselages. However, this created delays as the crane was acquired, areas were cleared for safety, chains and handling fixtures were attached, and the subassembly was moved. Each move with an overhead crane took about one hour and required a crew of up to eight people who helped stabilize the fuselage with tethers as it slowly moved from one part of the assembly line to the next. With the AGVs, a similar move only took about 20 minutes.

Three AGVs had a 38,000-lb (17,237-kg) capacity, while the other two units carried 75,000-lb (34,020-kg) loads. All the vehicles were battery-powered and equipped with obstacle-detection sensors to prevent collisions. The self-loading AGVs were capable of omnidirectional docking maneuvers. This eliminated tooling misalignments and ensured routing flexibility. It also assured that the vehicles interfaced correctly with various workstation dock designs, which varied in height depending on whether work was being done on the upper or lower section of a fuselage. The low-profile, height-adjustable AGVs were equipped with inertial guidance technology that enabled them to travel along a virtual free-range path rather than follow specific floor tape patterns. This eliminated the problem of blocked lines of sight or targets, and damaged floor tape.

An RFID-based control and indication server continually communicated with servers onboard each AGV. When a vehicle arrived at a workstation, an assembler took over control. He or she lowered the AGV's deck, guided the vehicle under a supported tooling structure, and raised the deck to lift the tooling so that the fuselage could be moved to the next work-cell for further assembly. All IAL cells and the AGVs were integrated together through a central control and indication server. Assemblers used touch-screen terminals to manage all production processes.

Despite all the recent investment by aerospace in automation, people still play a vital role in assembling the center fuselage of the F-35. For instance, wiring harnesses, pneumatic lines, and other components are manually installed. The workers' reactions to automation have been mixed, but most people view it as a positive departure from the traditional assembly processes, especially when they see the benefits to quality and ergonomics. For instance, using robots precludes the need for someone to sit in a hot, cramped inlet duct and drill hundreds of holes. Indirect savings from automation incorporated into the IAL line included an 85% reduction in lost-time injuries due to the stress of hand drilling. There has also been a 90% reduction in defects and an increase in hole quality.

DOD REQUIREMENTS FOR ASSET MANAGEMENT SYSTEMS

TPHS and asset management have been identified as essential, elemental responsibilities of a product or service supplier to ensure customer satisfaction of quality, timely delivery, and sustained lifecycle. The Department of Defense (DoD), with foresight, is focusing on the benefits of cradle-to-grave asset management from suppliers to the war fighter. Further, the DoD recognizes that there are multiple suppliers, both foreign and domestic, that will be sharing assets to support the war fighter locally and remotely (in-theater, within the continental United States, and outside the contiguous United States). The Department of Defense's strategy (iterated within DoD standards and defense federal acquisition regulations) is to delegate implementation and maintenance of these requirements to prime contractors. The contractors must comply with respect to their defense assets. In turn, they are held accountable to ensure requirements are understood, and within compliance, by their subcontractors.

There is a transformation taking place, yet again, within logistical asset management systems for the DoD and those supplying the DoD. What used to be known as store-and-forward, a mass-based supply chain, has clearly been identified as slow, inefficient, and costly (in both financial terms and in asset availability to the war fighter). The initial transformation was from mass-based supply chains (utilizing huge warehouses and depots) to a more lean approach by implementing just-in-time (JIT) provisions. This has proven more efficient and cost-conscious for the logisticians, especially base-confined supply chains. However, there are still shortcomings in providing appropriate and timely delivery to the end-user war fighter in forward-deployed, combatant operational theaters (not to mention the significant amount of unused, unidentified inventory). One inhibitive shortcoming is the timely delivery of required assets. One way to address timely delivery is to reduce long lead times and to have a real-time, accurate representation of the current supply status. Another shortcoming is the inability to manage assets across the dynamic DoD supply chain (including all services, prime contractors, and subcontractors).

All United States services (Army, Navy, and Air Force) are becoming more light and mobile to address the ever-changing, unconventional warfare tactics associated with the war on terror. To increase mobility, forces must deploy light and be quickly supplied at the point of adversary interaction. Performance-based logistics (PBL) is the current DoD policy utilized during this transformational period for the supply chain. To support the light and mobile war fighter requires the transition from JIT to sense-and-respond PBL.

Technology Mandate

Though effective, PBL is still lacking performance in some key areas: real-time alertness, cost-effective delivery, and reliability of assets. To provide more accurate data, real-time effective data capture, asset integrity, and system integration, the following technologies will be utilized:

- Unique identification (UID), uses an item-level identifier, which allows personnel to know "what" the asset is;
- radio frequency identification (RFID)—both passive and active (includes real-time locating systems [RTLS]),
- sensors and health management systems,
- prognostic and predictive maintenance, and
- true enterprise integration solutions.

RFID is a data communication technology that will allow personnel to know "which" assets, at a case/pallet level, have entered or left a defined area with a single scan. A real-time, autonomous asset tracking system, RTLS is normally implemented at a container level (a global positioning system [GPS] would be implemented as a transportation locator for vehicles). RTLS can track movement in and out of defined areas, as well as locate within an area where an asset is with a single query. These are the level-based applications. However, there are assets that due to size, movement, and utilization could implement RFID/RTLS on an item-level as well. Suppliers can gain tremendous information from the analysis of RFID/RTLS information for asset genealogy and value-stream mapping.

Currently, each company has their own way to do business internally. They have their own systems for identification, serialization, tracking, and delivery of assets/products. Within these databases the most explicit relationship is one-to-one, referring to the ability to link one action to another without the possibility of redundant data, but with the assurance of accurate data. If you are able to house a system of systems where data transfer occurs from one system to another without losing data or modifying, incoherently, the data, then you have created a seamless integration.

Where seamless integration is most beneficial is when a part's genealogy must be traced. For example, when an asset's capability is in question due to environmental conditions, workload stress, or poor maintenance, traceability is important. There are times when an off-site "quick fix" may be utilized to fix a part. However, this "quick fix" could comprise of modified maintenance or the outright purchase of a new one. When such an approach is implemented, the product's genealogy and integrity is lost for any type of forensic testing. Forensic testing and part genealogy are used in improvement processes to better the quality, life, and survivability of supplier products. A major concern about a "quick fix" approach (besides the obvious waste of money) is that by only acknowledging a failed part you are ignoring the reason for failure. It is the reason for failure that most engineers want to understand. If a product can be delivered, maintained, and data allowed to be captured and analyzed throughout the lifecycle of that part, then suppliers have a much better idea of how to improve products, procedures, and applications. This is where the technologies such as UID, RFID/RTLS and other health monitoring systems are a true benefit to the supplier. They enable a supplier to have in place a mechanism to better manage assets and produce a more effective product. The technology also allows for tracking assets throughout the supplier's supply chain, ensuring the most efficient use of resources, which can save the supplier money.

Understanding the Technology

Now, the question is not what should be implemented (UID, RFID/RTLS technologies have emerged and are going to be required by the DoD), but instead, how should these technologies be implemented? Before a supplier goes feet-first into this problem, there should be an understanding of what each technology actually entails. The power of combined RFID and UID is resident in their ability to identify a location of a pallet of one type of part or product; and within the pallet, locate a specific part/product or group of parts/products that may be differentiated by production date or age. This is called *nested visibility* and is shown in Figure 8-5.

Unique identification (UID) is the process by which an asset is assigned an item unique identifier (IUID). The IUID can be constructed in two ways: 1) A commercial and government entity (CAGE) number concatenated with product number; and 2) A CAGE number concatenated with product number concatenated with part number. The complete data field requirement is stated in the military standards (MIL-STD-130M [item] and MIL-STD-129 [package]). Marking quality requirements are outlined in the International Organization for Standardization (ISO) 15415, Inter-Agency Consultative Group (IACG) 9132.

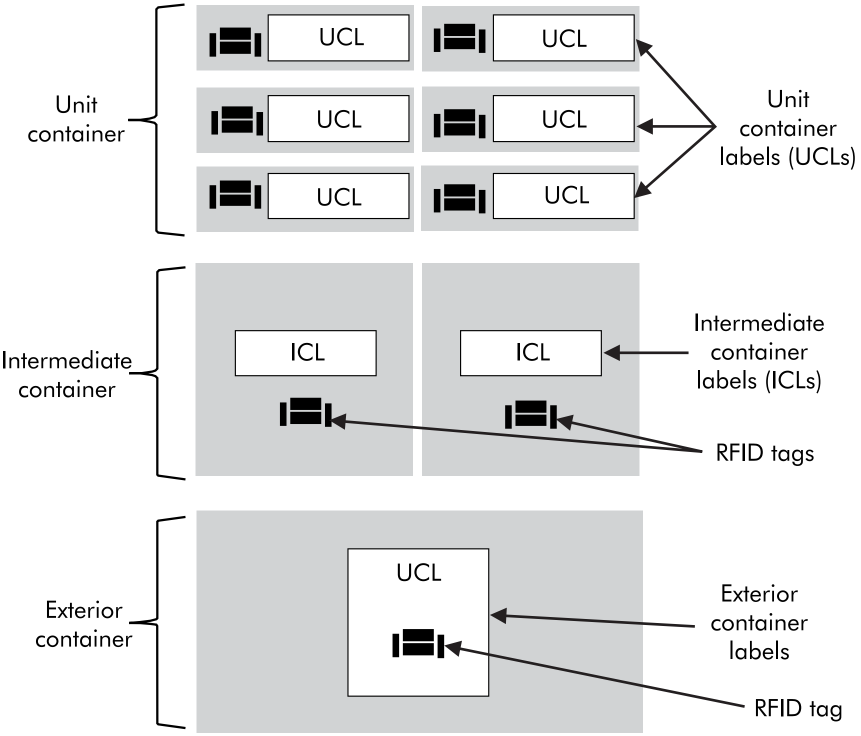

Figure 8-5. An RFID example of nested visibility to the unit container level.

Current data standards are addressed in ISO 1033. An enterprise would be responsible for setting the IUID construction type (either 1 or 2), the technical information required for the asset, and the method of marking.

There may be some confusion when talking about RFID and UID. RFID is a system that uses a unique identification (UID) associated with a specific product or part. This information is on a tag affixed to the product or part. Figure 8-6 shows an RFID tag that would be programmed with a UID number specific to a product. It would contain batch numbers and other information to differentiate it from identical products produced during different runs or on different dates.

It seems more likely that the DoD will go toward a variable data field to accommodate those suppliers whose part and product numbers differ greatly in size from other suppliers. A 2D bar code

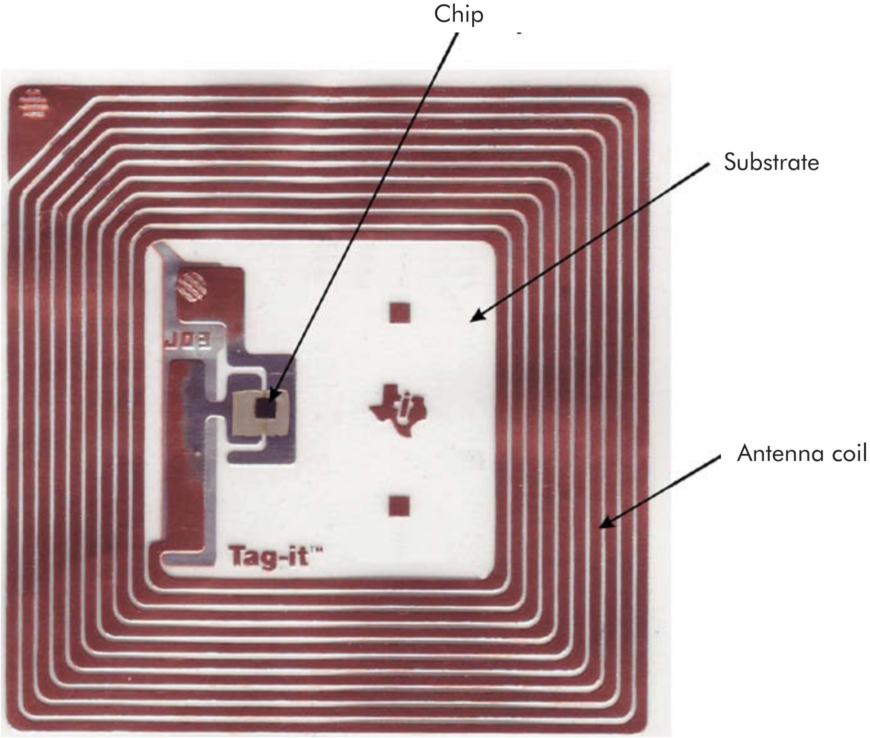

Figure 8-6. Example of transmission tag.

matrix is the technology utilized in storing the IUID on a particular asset valued at $5,000 or more. This is the lowest common denominator for all DoD suppliers, foreign and domestic. The business process of how to identify assets requiring an IUID and how to request/register an IUID will be determined by the prime contractor on a program-by-program basis. It is the responsibility of the prime contractor to assure the DoD that all subcontractors are within DoD compliance as stated in the Defense Federal Acquisition Regulation.

The UID initiative is not meant to create a global database; instead it is meant to enable the ability to link back to a specific supplier in support of a part's genealogy. The concept of item marking is not new. One-dimensional bar codes have been doing this for years. There already is a system in place with serial numbers. However, the problem with current serialization is that they are only unique within their enterprise or commodity. XYZ manufacturer could use the same serial number as ABC company. Concatenated together, the enterprise identification and serial number creates a truly unique identifier.

Suppliers would be required to mark all assets with a value of $5,000 or greater; however, they would only be required to utilize RFID/RTLS on those assets leaving the facilities. Nonetheless, the implementation of RFID/RTLS offers a huge cost savings and the company would see tremendous return on investment regardless of a mandate being in place or not.

With respect to the integration of RFID/RTLS, the Generation 2 Passive RFID Data Standard (from the EPC Global Consortium) will require research to ensure that tag reader and tag manufacturers are complying with this international standard as well as the ISO 18000 (parts 1–7) air interface standards. RTLS suppliers will need to comply with the INCITS 371.1 and 371.2 (two different, but acceptable, air interfaces) as well as the International Committee for Information Technology Standards (INCITS) 371.3 (Application Programming Interface—API).

Technology Implementation

While the DoD has begun to embrace the concept of combined RFID/UID to efficiently track and distribute goods, other industries and services have begun to include the combination of RFID and UID to maximize efficiencies throughout their supply chains. Two areas where RFID/UID tracking have been embraced are in the food distribution and medical fields.

Food distribution begins at the point of harvesting or slaughter. By identifying the exact time and temperature of the harvest or slaughter, better spoilage management and product placement can be realized. Without RFID/UID, batches are identified with a date stamp. A bunch of bananas picked in the morning may lay in the sun all day waiting for the bin to be filled for transport to a storage location for shipping. With RFID/UID, the same bunch of bananas has a time and temperature stamp that provides information for its placement on the shelf by the distributor or retailer. A bunch of bananas picked in the morning is placed on the shelf closer to the consumer because it has a shorter shelf life. In the banana example, a nested override setting with primary visibility switched on would alert distributors and retailers about established ordered criteria for sequenced distribution and placement to maximize product life.

It is good business to develop and implement RFID/RTLS solutions to better manage assets and in parallel use the technology to better enable value-stream mapping and improve business processes and work flow. Figure 8-7 outlines what is involved in a technology transition plan for RFID/RTLS.

Currently, there is a significant amount of "guesstronics" in place with regard to technology implementation. But by utilizing advanced planning systems (APS), this can be mitigated and real-time, accurate data for better solutions to multiple problems can be realized. There must be an infrastructure in place to capture and transmit the data back to the decision makers. UID, RFID/RTLS, and GPS are the enabling technologies that can capture and transmit data while maintaining its integrity. It is in the interest of each service and business to research and develop the best deployment methods for these technologies, which support and optimize business practices and processes. When creating an asset management system consideration must include:

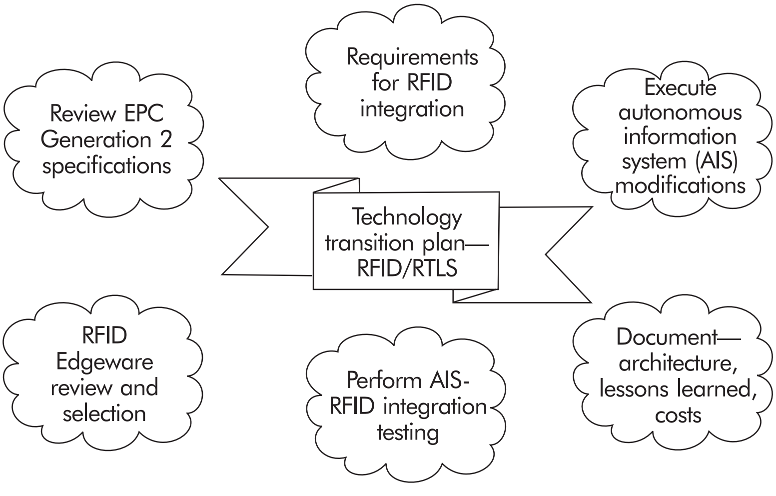

Figure 8-7. Technology transition plan for RFID/RTLS cloud model.

1. Business processes and policy,
2. Infrastructure,
3. Organizational preparedness,
4. Automatic identification technology (AIT) for data collection, and
5. Autonomous information systems (AIS) to link legacy systems with new databases and systems.

Essential for success, management decision making surrounding integration of RFID/RTLS technology must include consideration of its capability to withstand future growth and expanding partnerships. Software and hardware considerations to enable integration should only be pursued once all business process and goals have been identified and understood. It will become an inter-divisional, inter-sector, and inter-enterprise business endeavor.

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9

MLAS PROJECT MANAGEMENT AND ANALYSIS

"Freedom from the desire for an answer
is essential to the understanding of a problem."
–J. Krishnamurti

POST-OPTIMALITY ANALYSIS

Post-optimality analysis (POA) is used to determine the applicability of optimal sensitivity information in refinement and improvement of the vehicle's design after use. An optimal sensitivity analysis refers to "what-if" computations performed once the initial optimization problem is solved by tools used in the design and build phase of a vehicle (Braun et al. 1993). The computations may be used to re-characterize the design space using modeling, simulation, and analysis with applied margins for manufacturing variability and processes. Specific changes in the original solution can be inferred as the result of constraint or parameter variations without re-optimizing an entire system, vehicle, or assembly.

Testing

In destructive testing, tests are carried out until the specimen's failure. This is done to gain an understanding of its structural performance or material behavior under different loads. These tests are generally easy to carry out. In contrast to nondestructive testing, they are easier to interpret and yield more information.

Destructive testing is most suitable, and economical, for objects that will be mass-produced, as the cost of destroying a small number of specimens is negligible. It is usually not economical to do destructive testing where only one or very few items are to be produced (for example, in the case of launch vehicles).

Full-scale non-destructive testing of airframes and their components with automated loading control, continuous monitoring of airframe loads and states, and strain measuring provides an alternative to destructive testing. However, it does not provide the fidelity for failure analysis and absolute failure limits that destructive testing can provide.

Virtual test simulation with finite element models for designing and drawing-up recommendations on airframe improvements provides a front-end estimate of performance. Finite element analysis of local strength and calculation assessment can estimate the full-scale airframe elements' fatigue life. Solving problems of elastic-plastic strain and skin creep under unconstrained motion along with finite element analysis of significant nonlinear deformation and static aero-elasticity of flexible structures can predict, with a high degree of certainty, a vehicle's ability to perform as designed without degradation of the vehicle's systems, airframe, or components. To analyze complex material structures, metallographic studies can be made to determine the effects of fracture processes. Quantitative analysis of metallography and fractography can be performed using digital image processing.

To validate the computer models and analysis, the following tests may be performed:

- static and cyclic tensile, compression, and bending tests of samples at normal and high temperature,
- static and cyclic crack-resistance tests of material samples,
- creep rupture strength tests, and
- corrosion resistance tests under load.

Analyzing the MLAS Parts and Components

Retrieval of the MLAS boost skirt, coast skirt and forward fairing assemblies, and mock crew module were necessary to performing post-optimality analysis. Figure 9-1 shows the retrieval of the post-launch MLAS assemblies. Transportation of these components back to Wallops Island was essential to evaluating the design allowances, new materials, and manufacturing processes used in their manufacture. A future, fully operational, optimally designed vehicle would result.

Figure 9-1. MLAS post-launch assemblies retrieved and loaded on ship/barge. (Courtesy NASA)

Performing post-optimality analysis on the MLAS parts and components was important because the vehicle had been designed to be a one-shot success. The new materials and processes used in the manufacture of the composite parts were imbedded with safety margins to allow for a successful outcome. And the focus on a successful MLAS launch and performance had overshadowed many considerations for weight that would be incorporated into a fully operational design for application on top of a launch vehicle.

POA combines the evaluation and improvement of design and technology with consideration of operational factors. The analysis of recovered material samples and airframe elements included tests simulating factual operational conditions such as load spectra, temperatures, and environmental impacts.

The recovered MLAS vehicle components and parts permitted collection of post-optimality information generated through first-order computations. They were to be used to accurately predict the effects of design, constraint, and parameter perturbations on the optimal solution (Braun et al. 1993). A design is validated when the post-optimality assessments show that the design estimates and materials and manufacturing processes have produced a vehicle that results in variations of only a few percentage points over the practical range of the true solution. Further, when the post-optimality assessment is used to obtain a design, materials, and manufacturing process solution, the optimal sensitivity information plays a key role in improving the efficiency of the design process itself.

Iterative Design

Aerospace and space vehicle design is an iterative process that requires the integration of numerous disciplinary analyses such as aerodynamics, structure, propulsion, performance, manufacturing, and cost. Usually, low-rate initial production orders for complex products, such as air and space vehicles, are used to "settle" the manufacturing processes and design elements. A slow ramp-up prevents premature commitment in treasure and toil to a not-ready-for-prime-time design and manufacturing plan. A slow ramp up allows a new plan to consider:

- Discoveries during the manufacture of the first few airplanes,
- Design changes at the customer's request,
- Performance optimization changes,
- Feedback from operations and maintenance of the first units, and
- Errors.

The term, *low-rate initial production* (LRIP) is commonly used in military weapon projects/programs to designate the phase of initial, small-quantity production. The prospective first buyer and operator get to thoroughly test the weapons system over a protracted amount of time to evaluate the producer's performance/conformance to the stated requirements before contracts for mass production are signed. LRIP is also applied in fields other than weapons production, most commonly in complex non-weapon military equipment programs, such as airplanes and ship building, and even toys.

Manufacturers use LRIP as a production test-phase to develop the assembly line models that will eventually be used in mass production. Therefore, LRIP is commonly the first step in transitioning from highly customized, hand-built prototypes to the final, mass-produced, end product. In practice, either the production capability or the weapons system itself is unready during the LRIP phase. This can mean that systems produced during LRIP are built significantly different in terms of technique and cost owing to the immaturity of the production line. For instance, changes to the weapons system's design usually necessitate a large degree of hand assembly and trial and error during the prototyping stage. Typically, the cost of each LRIP system unit is greater than the final mass-production unit's cost. This is because the LRIP cost includes both the R&D and setup cost for production. However, the goal is that this additional cost will be amortized over future assembly production.

Immaturity in a system's design or its method of production discovered during the LRIP phase can result in additional LRIP phases to verify corrections/improvements or to determine project cancellation. Figure 9-2 shows the F-35 LRIP progression through many iterative phases. Such a complex product must be produced through a series of evaluations and refinements.

Spiral Development

Highly complex and expensive systems such as the F-35 can require tens of thousands of changes during their initial LRIP phases. This is even with the advent of modern simulation software, engineering, computer models, large data bases of historic information, game theory, and direct digital manufacturing.

The complex array of parts, pieces, systems, and components operating in extreme conditions and encountering unforeseen events and circumstances incentivizes post-optimality assessment for optimized design, manufacture, and product performance. The time to set up the design problem, model the disciplinary interactions, and obtain an optimal solution is significant. The post-optimality analysis and assessment, the LRIP approach to complex product development, and maturity through the phases of technology readiness levels (TRL) and manufacturing readiness levels (MRL) to transition to (full rate) production (TTP) uses a version of the Boehm spiral model for software development (Boehm 1986, 1988).

The spiral model was originally a risk-driven process model generator for software projects. Based on the unique risk patterns of a given project, the spiral model guides a team to adopt elements of one or more process models, such as incremental, waterfall, or evolutionary prototyping. It is now used for projects

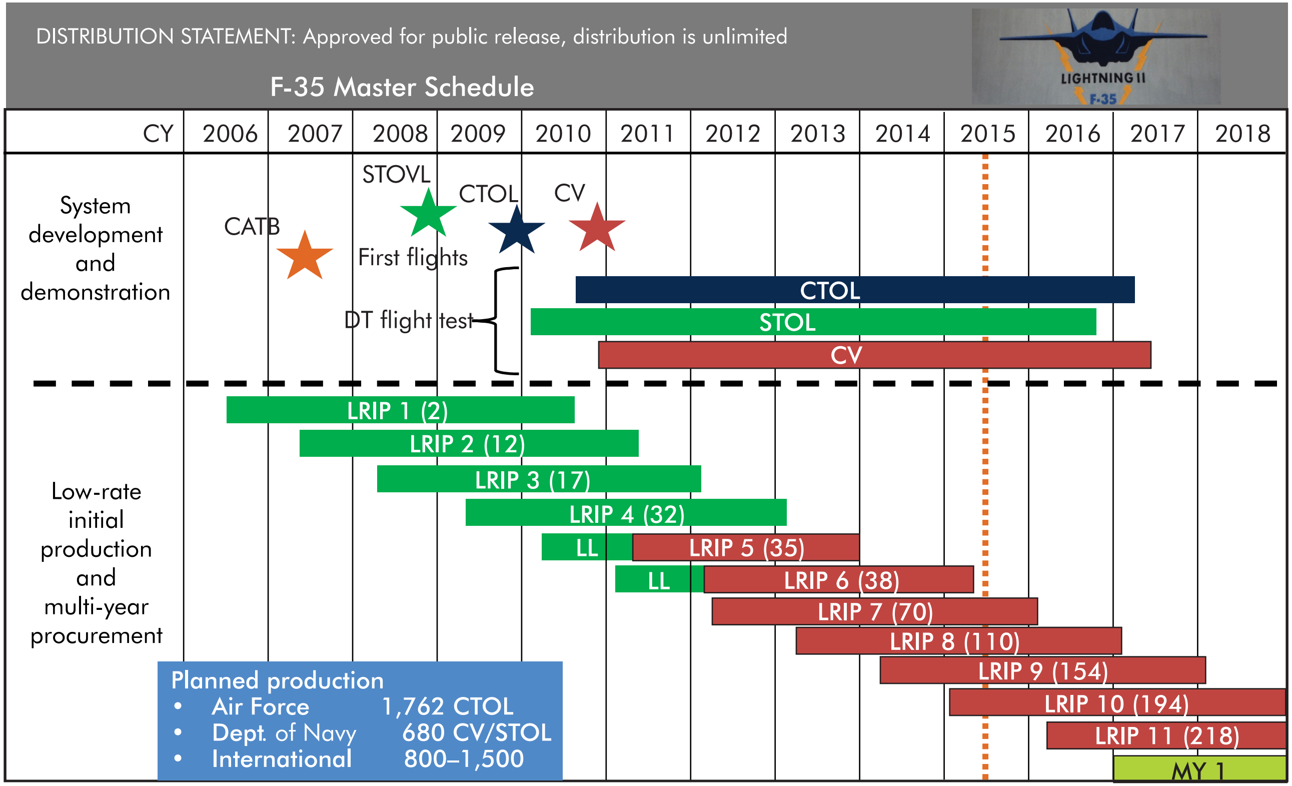

Figure 9-2. F-35 master schedule.

other than software. It has been adapted to air and space vehicles and is migrating to the development of next-generation hydrogen and electric automobiles. The Boehm spiral model shown in Figure 9-3 is used as the baseline model for complex products for design and manufacturing maturity development. Boehm's early papers use the term "process model" to refer to the spiral model as well as to incremental, waterfall, prototyping, and other approaches. However, the spiral model's characteristic risk-driven blending of other process models' features is present: "Risk-driven subsetting of the spiral model steps allows the model to accommodate any appropriate mixture of a specification-oriented, prototype-oriented, simulation-oriented, automatic transformation-oriented, or other approach to software development."

Boehm later described the spiral model as a "process model generator," where choices based on a project's risks generate an appropriate process model for the project (Boehm 2000). Thus,

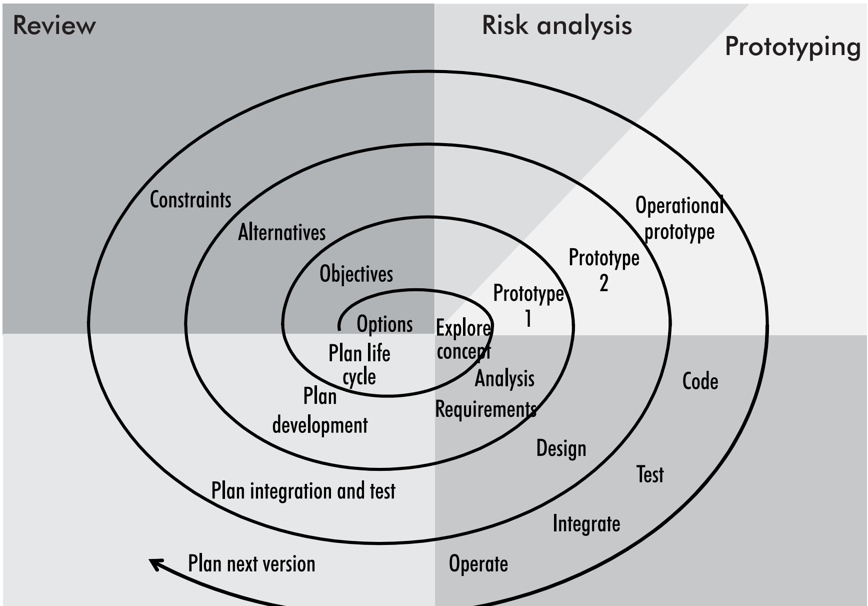

Figure 9-3. Boehm spiral model.

the incremental, waterfall, prototyping, and other process models are special cases of the spiral model that fit the risk patterns of certain projects.

Boehm also identifies a number of misconceptions arising from oversimplifications in the original spiral model diagram. The most dangerous of these misconceptions includes that the spiral is simply a sequence of waterfall increments; that all project activities follow a single spiral sequence; and every activity in the diagram must be performed, and in the order shown. While these misconceptions may fit the risk patterns of a few projects, they are not true for most projects, such as air and space vehicles, or other complex development projects, such as electric or hydrogen automobiles. To better distinguish them from "hazardous spiral look-alikes," Boehm lists six characteristics common to all authentic applications of the spiral model approach to software development:

1. Concurrent rather than sequential determination of artifacts.
2. Consideration in each spiral cycle of the main spiral elements: critical-stakeholder objectives and constraints; product and process alternatives; risk identification and resolution; stakeholder review; and commitment to proceed.
3. Using risk considerations to determine the level of effort to be devoted to each activity within each spiral cycle.
4. Using risk considerations to determine the degree of detail of each artifact produced in each spiral cycle.
5. Managing stakeholder life-cycle commitments with three anchor point milestones: life-cycle objectives (LCO); life-cycle architecture (LCA); and initial operational capability (IOC).
6. Emphasis on activities and artifacts for system and life cycle rather than for software and initial development.

Figure 9-4 is an example of a "hazardous spiral look-alike" that violates the invariant (Boehm 2000).

Defining artifacts concurrently is an essential element of spiral development that enables optimization of the product's TRL, MRL, and TTP. Sequentially defining the key artifacts often lowers the possibility of developing a system that meets stakeholder "win conditions" (objectives and constraints). This invariant excludes hazardous spiral look-alike processes that use a sequence of

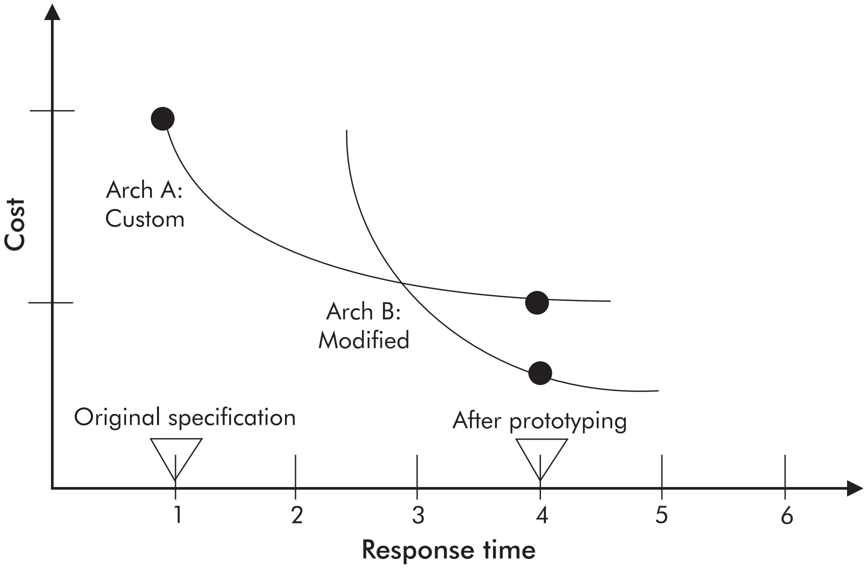

Figure 9-4. Sequential engineering buries risk. Sequential determination of the key artifacts will prematurely over-constrain, and often extinguish, the project's ability to develop a system that satisfies the stakeholders' essential success conditions (Boehm 2000).

incremental waterfall passes in settings where the underlying assumptions of the waterfall model do not apply.

Some hazardous spiral look-alike processes exclude key stakeholders from certain sequential phases or cycles. For example, system maintainers and administrators might not be invited to participate in definition and development of the system. As a result, the system is at risk of failing to satisfy the win conditions.

The application of roadmaps for product development integrated with earned value management (EVM) systems and criteria often defeat the dynamics necessary during the spiral development of new complex products. The application of EVM, while desirous for products transitioned to production or nearing maturity, often stymies effectiveness and efficiencies in the early stages of a product's development cycle. Incorporated into the EVM architecture are self-defeating assumptions for new product development and growth towards higher TRL, MRL, and TTP maturity levels. EVM assumes the requirements are knowable in advance of implementation; the requirements have no unresolved, high-risk implications, such as risks due to cost, schedule, performance, safety, security, user interfaces, organizational impacts, etc.; the nature of the requirements will not change very much during development or evolution; the requirements are compatible with all the key system stakeholders' expectations, including users, customers, developers, maintainers, and investors; the right architecture for implementing the requirements is well understood; and there is enough usable calendar time (time horizon) to proceed sequentially (Boehm 2000).

In situations where the EVM assumptions do apply, it is a project risk not to specify the requirements and proceed sequentially using EVM and roadmaps to provide performance factor visibility to the project. The waterfall model thus becomes a risk-driven special case of the spiral model, which has to be established before proceeding with a selected methodology, process, or model.

EARNED VALUE MANAGEMENT

The basic premise of *earned value management* is that the value of a piece of work is equal to the amount of funds budgeted to complete it. According to the Department of Defense, "Earned value management is an essential program manager and technical lead tool for supporting proactive decision making."

As part of EVM, the following information is used to assess schedule and cost performance throughout the project.

- *Planned value*: The approved budget for the work scheduled to be completed by a specified date, also referred to as the *budgeted cost of work scheduled*. The total planned value of a task is equal to the task's budget at completion—the total amount budgeted for the task.
- *Earned value*: The approved budget for the work actually completed by the specified date, also referred to as the *budgeted cost of work performed*.
- *Actual cost*: The costs actually incurred for the work completed by the specified date, also referred to as the *actual cost of work performed*.

The foundational principle of EVM does not depend on the size or complexity of the project. However, the implementations of

EVM can vary significantly depending on the circumstances. In many cases, organizations establish an all-or-nothing threshold; projects above the threshold require a full-featured (complex) EVM system and projects below the threshold are exempted. Another approach gaining favor is to scale EVM implementation according to the project at hand and skill level of the project team (Sumara and Goodpasture 1997; Goodpasture 2004).

MLAS was a highly dynamic project requiring flexible and high-risk manufacturing processes (for a launch vehicle) performed at geographically dispersed locations. It was a research project that had multiple suppliers; this made it a project unqualified for the stability requirements of an EVM system. The results of a survey by the Project Management Institute are shown in Figure 9-5. While 76.47% of the respondents felt that EVM was suitable as a standard for project performance measurement of engineering projects, only 1.18% felt it was suitable for research projects (Cable et al. 2004).

The use of EVM for MLAS was not suitable. Project portfolio management (PPM) was used to manage the dynamics and complexities of the project across multiple disciplines in geographically diverse locations.

There is good news and bad news to not using EVM for MLAS or any other research project where forensic post performance analysis is needed to optimize a design once the primary mission of the project is accomplished. The good news is that absent EVM, the research project and highly creative people and processes sustain continuity throughout the program. They are free to do what they do best, be creative and take risk, unencumbered by the confines of a system that desires stability. The bad news is that when the pieces are recovered and evaluation and analysis begins, the effort is complicated by the absence of a detailed record that EVM tools can provide.

PROJECT PORTFOLIO MANAGEMENT

Project portfolio management is the science of applying a set of knowledge, skills, tools, and techniques to a collection of projects to meet or exceed the needs and expectations of an organization's investment strategy (Pennypacker and Sepate 2003).

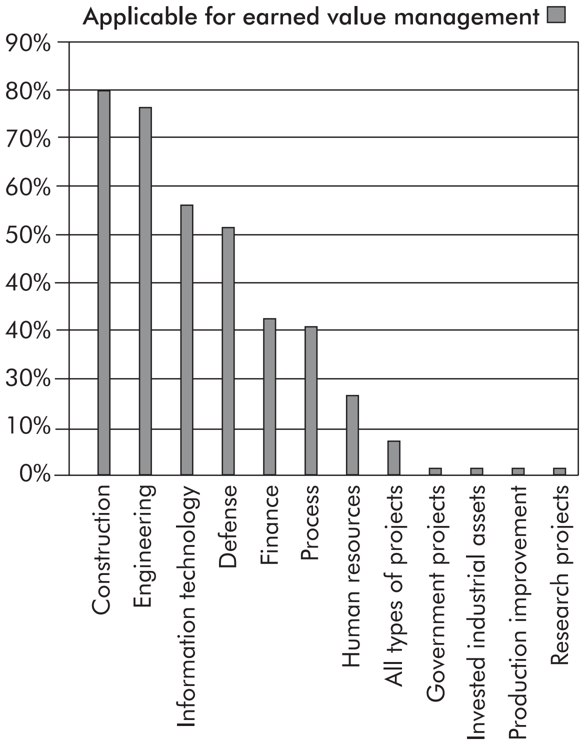

Figure 9-5. Project types suitable for earned value. (Source: ICPMA Response to Standards Australia on draft standard for Project Performance Measurement Using Earned Value V5.6, International Council for Project Management Advancement.)

PPM was ideal for MLAS because of the diverse manufacturing processes, locations, and personnel performing concurrent tasks. Each component and manufacturing process was managed as a separate project having three main objectives:

1. Portfolio value maximization derived from cost efficiencies, new process expertise, and common objectives;
2. balance within the portfolio; and
3. strategic alignment.

Strategic alignment outside the project was challenging. Northrop Grumman struggled with its investment of valuable research resources, such as key personnel and money, in a project that lay just outside the boundary of its objectives, product portfolio, and expertise. Northrop Grumman (through acquisitions) had a strong space legacy in satellites. However, the linkage to launch vehicles and investment motivation to add the expertise and link it to increased profitability was challenging.

MLAS used PPM value maximization to deal with resource allocation and meet both NASA and MLAS program/project objectives such as profitability, budget, and performance. At the same time, the parameters of the projects were balanced to assess the risk of each critical element by manufacturing process type. It was equally important that the final portfolio of projects such as fins, boost skirt, coast skirt, forward fairings, mock crew module, and other key components aligned within the critical timing of the launch window at Wallops Island, Va.

The stipulation that the portfolio of projects across suppliers and the company organization meet the launch window objectives was also critical. Each of these objectives considered location, supplier base, key personnel, and critical equipment in the selection process. Once project suppliers and manufacturing processes were selected, the issue became how to manage the portfolio of projects effectively. Fundamental to efficient project management of MLAS at all organizational levels was timeliness and effectiveness of project reporting. Timely, accurate, and actionable results became difficult to achieve due to the variation in business reporting methods and sophistication at suppliers and within the operating units of the corporation. Typical portfolio reporting methods include extensive narrative, bar charts of project metrics, project risk versus reward graphs, project progress charts, and tables showing the established project metrics. To refine the product for optimization of future performance, the ad hoc method of MLAS PPM project management left gaps and uncertainty. It was difficult to reconstruct the manufacturing build processes to convey information from the recovered parts back through the digital thread.

Many commercial tools are available for managing portfolios; however, at the time, there was increasing concern about managing project portfolios in a more efficient way to bring the expected and desired benefits to the stakeholders. Most organizations, including those involved with MLAS, were not completely satisfied with their project portfolio management methods (Cooper et al. 1998). The Center for Business Practices conducted a benchmark study of current practices using PPM. It showed that a considerable percentage of the organizations practicing PPM were at level 1 of maturity, which is defined as ad hoc processes only (Pennypacker and Sepate 2003). MLAS product reconstruction, design refinement, post-optimality analysis, and improvement of manufacturing processes suffered as a result.

Risk

Risk must be weighed in determining the degree of detail required for project artifacts such as requirements specification/documents, design documents, or test plans. The project team must decide how much detail is enough. In authentic spiral process cycles, these decisions are made by minimizing overall risk. The project requirements should precisely specify those features that reduce risk, such as interfaces between hardware and software, or interfaces between prime and subcontractors. Conversely, the project should not precisely specify those features that increase risk, such as graphical screen layouts, behavior of off-the-shelf components, or restrictive machine specifications where the supplier is limited to providing only what is asked for or specified. Restrictive specifications can limit supplier involvement as a partner in the spiral development of the product.

Anchor Milestones

Boehm's original description of the spiral model did not include any process milestones. In later refinements, he introduced three anchor-point milestones that serve as progress indicators and points of commitment. These anchor-point milestones can be characterized by key questions:

- Do the life-cycle objectives (LCO) provide sufficient definition of a technical and management approach to satisfying everyone's win conditions? If the stakeholders agree that the answer is "Yes," then the project has cleared this milestone. Otherwise, the project can be abandoned or the stakeholders can commit to another cycle to try to get to "Yes."

- Does the life-cycle architecture (LCA) provide sufficient definition of the preferred approach to satisfying everyone's win conditions, and are all significant risks eliminated or mitigated? If the stakeholders agree that the answer is "Yes," then the project has cleared this milestone. Otherwise, the project can be abandoned or the stakeholders can commit to another cycle to try to get to "Yes."
- Does the initial operational capability (IOC) provide for sufficient preparation of the product, site, users, operators, manufacturing capability, and maintainers to satisfy everyone's win conditions in launching the system? If the stakeholders agree that the answer is "Yes," then the project has cleared this milestone and is launched. Otherwise, the project can be abandoned or the stakeholders can commit to another cycle to try to get to "Yes."

Hazardous spiral look-alikes that violate this approach include evolutionary and incremental processes that commit significant resources to implementing a solution with a poorly defined architecture. The three anchor-point milestones fit easily into the rational unified process (RUP), with LCO marking the boundary between RUP's inception and elaboration phases, LCA marking the boundary between the elaboration and construction phases, and IOC marking the boundary between the construction and transition phases.

The system and its life-cycle invariant highlight the importance of the overall system and the long-term concerns spanning its life cycle. Hazardous spiral look-alikes that focus too much on initial development of software code, detailed design criteria, or work instructions are excluded. These processes can result from following published approaches to object-oriented or structured software analysis and design while neglecting other aspects of the project's process needs.

FORENSICS

The application of post-optimality analysis, the spiral development model, risk assessment, and anchor milestones are critical components to enhancing the future design of highly specialized, complex, and expensive products anticipated to be produced in low quantities. MLAS was a vehicle that met the criteria. Therefore, for forensic analysis, it was essential to collect all the pieces including waste material of any kind. Everything had value to the assessment process.

The boost skirt hit the water hard without parachutes or any other inhibitor except its shape to slow the descent and splash into the Atlantic Ocean. All the other components of the vehicle, including the coast skirt assembly, forward fairing assembly, and mock crew module had parachutes to slow their descent. Even with parachutes softening the impact, the geometry of the coast skirt and forward fairing assemblies, and the mock crew module were not sleek enough to soften the blow when they hit the water. The result was a splash reminiscent of a belly flop rather than an Olympic diver entering the water. There were anxious moments as the ship approached the floating pieces. Then there was surprise at their condition. Some looked almost as pristine as they did on top of the launch stand just a short time before launch.

Results and Extensibility

After post-optimality analysis and assessment of the parts, pieces, and components recovered, it was found that the strains, stress, vibration, and impact of the MLAS launch had little effect on the vehicle's structure. The design and manufacturing processes plus margins had been more than sufficient to produce the vehicle and allow it to withstand the flight regime and recovery. With some repair, they even could be reused if needed.

The evaluation also revealed that improvements could be made to the manufacturing processes. Further weight reduction could be instituted without performance knock-down, and design allowances for strength factors that had been overstated to ensure a successful MLAS performance could be reduced.

Although the data derived from analysis and assessment would be useful to improving the vehicle's design and manufacturing processes, the analysis was inhibited by the enabling project management processes. For example, the rapid prototyping approach that used spiral development methodology and project portfolio level 1 criteria with high-level anchor milestones, essential to the freedom needed to push the limits of materials, processes, and business management models, inhibited post-performance analysis. Absent the detailed records that normally accompany a manufactured product such as quality records, work instructions, and detailed planning, it was difficult to go back and determine how work was done and to what level of conformance to process specifications, design intent, and manufacturing tolerances. This contrary situation is a dilemma confronting any project that relies on aggressive schedules and pushes the boundaries of design, material, management, and manufacturing processes.

The dilemma is further compounded by a short development and delivery schedule where the focus is on the end product timing and performance as a measure of success. This overshadows the key elements that need documentation for improvement of the design and manufacturing processes (post-performance optimization). Validation of the new product's performance comes at the cost of the detailed records needed to improve the design for future iterations. The development and finalization of the design is frustrated and extended by lack of data. The conundrum is how to encourage the freedom and creativity of project and manufacturing engineers while collecting sufficient data during the build phase to reduce the iterations to final product design and manufacturing.

The key may lay in additive manufacturing and advanced analytics where data is collected and rapidly dispersed to the point of manufacture and back up the design and build chain. The use of direct digital manufacturing and advanced analytics enables the cornerstone of rapid prototyping (unencumbered creativity). It does this by seamlessly collecting the essential data needed to shorten the painful design and manufacturing improvement iterations required of complex, low-rate initial production products.

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10

UNIFIED AND LARGE STRUCTURE MANUFACTURE

"Genius ain't anything more than elegant common sense."

—Josh Billings

THE MOVE TO UNIFIED STRUCTURES

The Role of Composites Materials

The benefits derived by using composite materials in aerospace products are widely recognized. Over the last two decades, the percentage of composite material used in aerospace vehicles, and the number of parts produced using composite material, have increased significantly. The use of composite parts is beginning to expand beyond its original application as a replacement for metal.

The use of composite materials, such as graphite carbon epoxy (GFE), can provide distinct manufacturing advantages that parts fabricated and assembled from metal cannot. Northrop's B2, Boeing's 787, and Lockheed's F35 use composite materials extensively in their airframes and components. In addition, NASA's newest launch vehicle, ARES I, uses composite materials in one of its main structural components.

Until recently, composite materials have been used to replace metal parts on a one-to-one basis; thus these materials have gained the nickname, "Black Metal." Replacing the metal used to make components, such as skins, with a composite increased the challenges involved in fastening components together. Much of the substructure—bulkheads, for example—remained metallic. Therefore, a drill bit penetrated the soft composite skin before drilling through the metal subcomponent. As a result, challenges arose when harder material in the form of a chip was drawn through the softer composite material. The variability of stacked material types with varying thicknesses drove up manufacturing costs because of the increased complexity imposed on the assembly process by composites.

In-space Composite Material Concerns and Considerations

Composites materials have been tested and evaluated for their ability to retain strength over time (durability) while exposed to the atmospheric and performance demands of commercial and military air vehicles. If the confidence currently experienced by composites in air vehicles is to be extended to space vehicles, then the effects of long-term exposure to the spacecraft's operating environment must be better understood. The science of composite materials use in space is relatively new. Extensive testing is needed to determine the long-term effects of space environments on composites materials. New materials may have to be developed or current material types enhanced to meet the more stringent demands of space vehicles.

Testing has been done in facilities capable of simulating the major low-Earth-orbit (LEO) constituents such as high vacuum, ultraviolet (UV) radiation, thermal cycling, and atomic oxygen (AO) atmosphere. Under the simulated LEO space environment, graphite/epoxy composites, which are widely applied to space structures, were tested. Tensile properties, as well as mass loss of the graphite/epoxy composites after being exposed to the AO atmosphere and the synergistic LEO space environment, were investigated. The surface morphology of the composites was also observed by scanning electron microscope (SEM). Experimental results showed that the LEO environment and its synergistic effects cause considerable damage to the surface of composites (Chun-Gon 2006).

Before humans can be sent into deep space to explore for weeks or months encapsulated in composite vehicles, material development and testing are necessary. The drive for space-grade composites is motivated by the same cost, weight, and manufacturing considerations that spurred their use on air vehicles. It is only a matter of time before inhabited and uninhabited space vehicles see increased use of composite materials.

Composite solutions offer lower part counts resulting in a lower drawing count (~47), which helps reduce overall life cycle costs.

One of the primary design considerations for a lunar or Mars landing is the center of gravity (CG) of the vehicle as it descends onto a planet or lunar body with little gravity. Figure 10-1 shows a Project Constellation Lunar Lander concept. The fuel is stored in a donut-shaped tank, which distributes the weight around the center of the vehicle to balance the mass during descent and landing.

The vehicle's fuel donut was incorporated into a unified structure manufactured in-situ. A design concept for an in-situ fiber placement machine to layup in one piece the donut-shaped fuel module for the ALTAIR Lunar Lander was shown in Figure 3-8. In-situ manufacture of a unified structure reduces critical mass-property concerns. Further, a one-piece structure reduces the center of gravity calculations formerly needed when numerous parts were being assembled through a complex array of assembly stations.

ALTAIR Lunar Lander Design

The NASA Authorization Act of 2005 authorized, "The [NASA] Administrator [to] establish a program [(Constellation Program)]

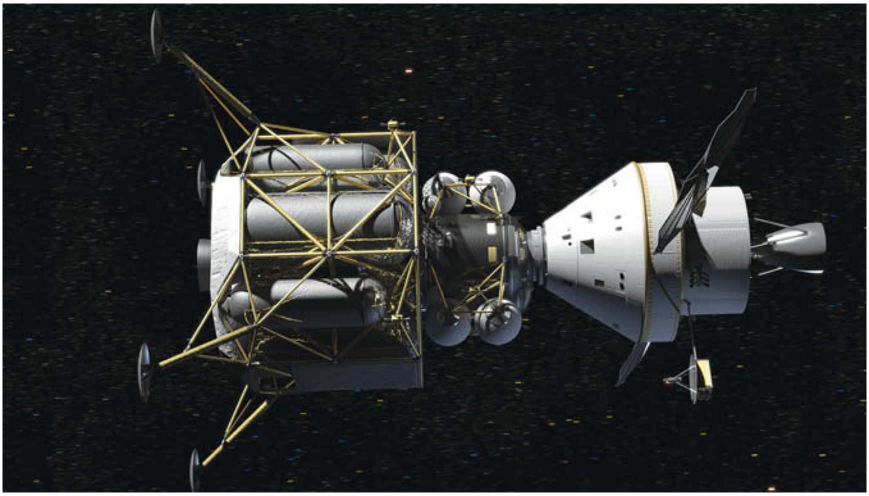

Figure 10-1. A Project Constellation Lunar Lander concept. (Courtesy NASA)

to develop a sustained human presence on the Moon, including a robust precursor program to promote exploration, science, commerce, and U.S. preeminence in space, and as a stepping stone to future exploration of Mars and other destinations." Innovative and developmental technologies were required to realize this vision for space exploration (VSE).

Central to the VSE was the development of new crew and cargo transportation vehicles for missions beyond LEO. This included the mass-critical vehicle, ALTAIR Lunar Lander.

Novel and lightweight structural concepts for the vehicle systems involved the judicious use of composite materials with their high strength-to-weight and stiffness-to-weight ratios. Internationally, industry has begun to use composites in Earth-bound and space transportation vehicle construction. NASA has leveraged the existing composites knowledge base, including expertise and technologies from industry. It has coordinated this with rapidly expanding flexible assembly systems and "game theory" simulation to maximize manufacturing and assembly efficiency. The task was to investigate fabrication and assembly concepts that could overcome engineering, manufacturing, and logistics obstacles and limitations involved with full-scale construction of large aerospace structures. The identified obstacles included:

- Exceeding material out-times,
- The necessity for extremely large autoclaves (>25 ft [7.6 m] diameter), and
- Shipping and handling limitations and complexities.

The effort was to include development of a segmented, multi-variant design, structural assembly concept for a human-rated space vehicle. Manufacturing and assembly plans were formulated under the assumption that all component parts were to be assembled at a single facility with merit given to minimize the assembly footprint. In addition, any supporting empirical data derived from advanced simulation methods included game theory. The result was a single-piece composite crew module (CCM) designed, developed, and manufactured using in-situ manufacturing processes and technology to minimize the manufacturing footprint.

One unique feature of the CCM's design was integration of the packaging backbone structurally with the floor and walls of the pressure shell. This provided a load path that accommodated load sharing with the heat shield for water landing load cases. Another unique feature was the use of lobes between the webs of the backbone, putting the floor into a membrane-type loading resulting in a lower-mass solution. Connecting the floor to the backbone and placing lobes into the floor resulted in mass savings of approximately 150 lb (68 kg) to the overall primary structure design. The complex shapes were enabled by composites.

The CCM design is constructed of two primary parts—an upper and lower pressure shell (refer to Figure 3-1). IM7/977-2 fiber and resin, a mature material system with extensive government and industry experience, was used. The two halves were joined together in an out-of-autoclave process to enable packaging of large or complex subsystems. Fabrication of the upper and lower pressure shells began in February 2008, and post-cure assembly operations started in May 2008.

A non-autoclave composite splice allowed concurrent fabrication, assembly, and integration of the major structural components and subsystems and provided a lower-cost tooling option. Inner-mold-line tooling offers the opportunity to optimize or change the design as loads and environments change with program maturation.

Advantages of Simplified Assembly

Manufacturing unified structures to reduce assembly cost and increase quality is not new. In the 1980s, the automotive industry, led by Toyota, began combining many pieces into larger and fewer components through a process called "implosion." The automotive industry found that larger, single-piece components reduced assembly steps, cost, and complexity, and improved product quality. Figure 10-2 shows the "implosion" of a segmented composite barrel into a single unified piece.

Fastener preparation (drilling and countersinking) and fastener installation represent the largest process operations involved in airframe assembly. Each component is critical to successful

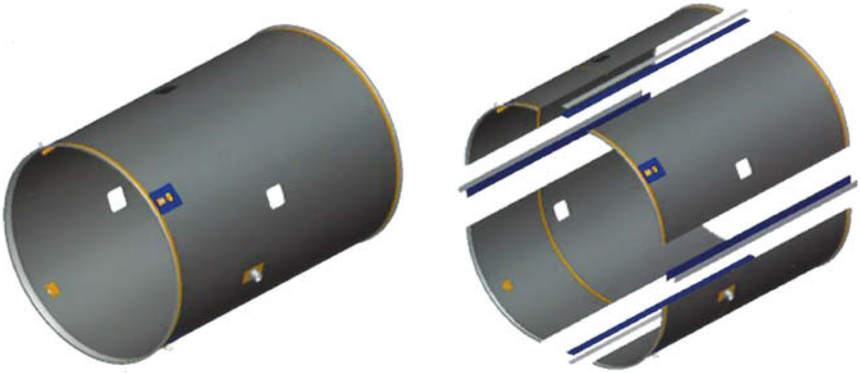

Figure 10-2. "Implosion" of a segmented composite barrel into a single unified piece.

assembly, and therefore must be tightly controlled. In addition, a complex system and supply chain of standard tools, training, tool and equipment maintenance, inspection, and other ancillary components and operations are necessary to properly ensure the successful installation of each fastener.

Drilling, countersinking, and fastener installation drive 80% of the cost of quality, and 80% of lost-time injuries. The initial approach to mitigating this was to introduce methods and technology like automated drilling and countersinking into the production assembly lines. The technique was to leverage numerical control (NC) and a precision machine approach to increase repeatability and drill rates, reduce mechanic fatigue, and eliminate a large number of the small tools used by mechanics that needed to be maintained. Recently, the approach has focused on increasing the sizes of components to create a unified structure. Larger assemblies without fasteners, or with greatly reduced use of fasteners, have been made possible with the use of composite materials.

In aerospace, the use of composite materials can enable many pieces once assembled with fasteners to be combined into a single large piece that incorporates all the design and strength benefits of the original assembly. The larger bonded or single-piece fabricated component reduces labor at the fabrication and assembly levels, while eliminating or significantly reducing the number of fasteners required and their associated hole preparation. Other advantages include reduced mass, elimination of longitudinal joints, integration of assembly and separation joints, and reduced minimum gage penalty. Part counts are reduced, as well as supply-chain complexities and assembly operations.

Upstream in the manufacturing process, investments in capital equipment and contract tooling are also significantly reduced or eliminated. When a segmented structure is fabricated, all the components must be made, trimmed, and held in position to the tolerances necessary to meet the final assembly's requirements. NC machines for trimming, tools for holding and positioning, and inspection machines, such as coordinate measuring machines (CMMs), must be purchased, installed, operated, and maintained. The increased precision necessary to build modern aircraft has driven up the cost and complexity of these investments. In addition, the cost and complexity of machines and tools for producing precision aerospace components prohibits facility flexibility. Factory reconfiguration is limited due to the foundations, isolation pads, and structures needed to sustain operations. Variability analysis and control of complex assemblies drives cost into the manufactured product and increases the intricacy of the process. The foregoing and many other issues have driven major aerospace companies to evaluate the use of composites as a means of combining segmented parts into larger and larger unified structures.

The Role of Out-of-autoclave Cure

The cost of fabricating and assembling aircraft and spacecraft parts and assemblies has led to initiatives to leverage the attributes of composites to transition to larger unified structures. The advantage of a unified structure for cost and weight reduction, as well as increased quality, incentivizes unified structural initiatives such as out-of-autoclave cure. Autoclaves, because they are costly to install and operate, have been among the prime targets for elimination to enable employment of large unified structures.

With all of the apparent advantages, the drive to mitigate the inhibitors to large integrated structures has been the focus of considerable research investment by universities, government, and industry. One of the main focus areas is elimination of the need for curing in the large and expensive autoclave. It has been identified for years as a necessary evil for curing the composite materials used to construct aerospace parts. As engineers identify parts that can transition from a segmented structure to a unified structure, autoclaves to accommodate the larger-size structures have become prohibitively expensive, with long lead times required to procure, build, and install the equipment. Autoclave operating cost also incentivizes the effort to develop out-of-autoclave materials and processes to eliminate the need for these capital investments, which are expensive to acquire and operate. Figure 10-3 shows the massive size of the autoclave required to cure large composite parts.

There are two main thrusts to eliminating the need for autoclave curing of aerospace-quality parts. One is the development of an out-of-autoclave cure process for autoclave-cure materials. The other is the continued development of materials, which cure at room temperature, for the liquid-resin infusion process. Both of these solutions were combined in the fabrication and assembly of NASA's Max Launch Abort System (MLAS). The multistage vehicle was composed of a boost skirt, coast skirt, and forward fairings that enclosed a crew module. The MLAS

Figure 10-3. Large autoclave for curing aerospace parts.

vehicle's three stages were fabricated in a Gulfport, Miss., shipbuilding facility using liquid-resin infusion and simple, low-cost tooling. The vehicle's fins were produced in Huntsville, Ala., using an out-of-autoclave process. Final vehicle assembly was carried out at NASA's Wallops Island, Va. facility.

Challenges of Unified Structures

Much material and process development has been undertaken to eliminate—or significantly reduce—the requirement for curing via autoclave, but other challenges need to be addressed. When the automotive industry transitioned to unified structures, customer satisfaction went up when rattles went down. But the side effect of unified body parts was increased repair cost. Before unification, a fender or bumper could be replaced if it was damaged. After unification, an entire quarter panel had to be replaced. Due to the cost and critical nature of aerospace parts, this problem is compounded in addition to maintainability concerns.

Under current segmented manufacturing processes, if a part is damaged, the assembly line can continue producing while a "surge" occurs to replace the part and install it downstream in the production flow. But if a large piece of unified structure is damaged, everything stops until the part is replaced. The same is true for tooling. In segmented processes, tooling can be cycled in and out of the production line for maintenance or calibration in a controlled manner to sustain production flow. A unified structural tool taken off the line could stop production. The same is true in the field. Currently, a segmented part can be replaced or repaired at its point of use with small out-of-service time and cost. Large segmented parts are more costly, and could potentially shut down vehicle production for weeks or months. With small parts, access to systems and subsystems by field support and maintenance crews is comparatively uncomplicated. For example, repair, test, and evaluation of wiring, tubing, systems, and other hidden elements may only require removal of a small part.

Another inhibitor is system, subsystem, and vehicle installation and integration. When small pieces are combined into a large structure, the ability to install components and provide access to the workforce becomes a consideration. Today fighter aircraft are built from the inside out with the covers (the skins) applied after all systems are installed and connected. And with segmented assembly, the production line is spread out to provide room for many operations to occur, and to allow mechanics to perform their work. When a segmented structure becomes unified, the confined workspace may slow the installation of systems and components.

Other challenges remain, among them material application rates. For example, as structures grow, tests need to be performed to confirm that the processes used for layup translate well to larger structures.

The benefits derived from combining many parts into a few offer so many advantages that the drive for unified structures will continue. Just as the automotive industry recognized two decades ago, reducing assembly steps through employment of unified structures reduces cost and increases quality. The move to translate this positive lesson from the automotive industry to aerospace and space structures should yield similar benefits.

The Role of Decision Models

The issues of unified structure damage and repair cost, and the challenges associated with access to unified structures are being addressed by decision models, which enable engineering and manufacturing personnel to make better decisions that leverage the advantages of a unified structure.

One of the models used to make decisions regarding the manufacturing breaks and unification of the MLAS vehicle was derived from the shipbuilding industry. Shipbuilders have made their products in large, unified-structure, modular segments for years. They realized early on that, based on a number of criteria, some components had to be broken into smaller segments. A main consideration was how much had to be installed into the segment once it was produced. The more that went into the segment, the more consideration was given to segmentation to facilitate access. The emptier the subassembly, the larger it could be made, because it did not inhibit installation of subsequent components and parts. There are also other considerations involved, such as the degrees of unification, production breaks, and segmentation.

In the model, decisions are made on a scale of one through ten as to the degree-of-difficulty for each criterion. Ten represents the highest degree of difficulty. The first step in the model is to quantify the number of subsystems, and their complexity and installation difficulty on the scale. Then, the decision model is overlaid onto a segmentation matrix to determine the size of the components to be produced, and where the production breaks should occur. Applying the process maximizes the unified structure's benefits, while recognizing the installation size limitations.

IN-SITU MANUFACTURING

In-situ means in its original place; in position. Therefore, *in-situ manufacturing* means the manufacture of a product or primary component of the product in position at or near its place of use or consumption. In-situ is not a new idea. According to the National Aeronautics and Space Administration (NASA), the use of in-situ resource utilization in space exploration furthers the goals of the space mission. In-situ will facilitate the manufacture of space vehicles on other astronomical objects, such as the Moon and Mars. Here on Earth, in-situ technology reduces the cost of manufacturing large, unified composite sections of launch vehicles.

Martin McLaughlin, former director of space structures for Northrop Grumman Corporation, introduced the in-situ unified space structure fabrication system for large composite structures. He and his team (which included the author) initiated, designed, developed, and proved the concept for large, composite, space launch vehicle components.

Large Structure Uses

Using carbon-fiber material, such as GFE prepreg, in fabrication and assembly of large structural components provides the opportunity for producing unified structures. The challenges inherent in manufacturing a large 98 or 131 ft (30 or 40 m) component with traditional staged operations would defeat the advantages of a one-piece structure. Further, the transport of a large composite structure to each assembly point in the production process endangers the part by exposing it to impact opportunities. The impact damage that could occur during transport is difficult to detect. The size of the part inhibits the observation of impacts that could cause hidden substrate damage sufficient to induce failure during functional operation.

Combining the various assembly operations traditionally done at process-specific locations in-situ reduces the danger of impacts during transport. Eliminating the movement of a large structure during the assembly process also minimizes part variability. Each time a part is moved by crane or dolly, it is put under strain. Vibration from movement over flooring or along crane rails resonates into the unfinished part, which can cause warpage and distortion. The large quarter-section parts for MLAS were constructed in Gulfport, Miss. and then transported to Wallops Island, Va. Preparation for transport required the parts' removal from fabrication fixtures, moving to holding fixtures via crane, and strapping down to the bed of trucks. On arrival, they were removed and craned into assembly fixtures. All of this movement caused part variation that would not have occurred had the parts been assembled in-situ.

Another challenge is material out-time to meet aging requirements. Large amounts of material are rapidly laid-down on a cure tool. The high-strength prepreg materials currently used to produce aerospace components start curing when they exit the freezer. The amount of material that has to be laid-down to fabricate a 98 ft (30 m) segment of a large launch vehicle exceeds the capability of modern fiber-placement machines. The lay-down rate is measured in pounds per hour (kg per hour) with the best machines attaining 100 lb (45 kg) in one hour. Even at the rate of 100 lb (45 kg) per hour, it is beyond the capability of the machine to provide a continuous flow of raw material. The machine can surge to a rate of 100 lb (45 kg) per hour, but only until it has to be restocked with more raw material. Compounding the out-time challenge is the incorporation of a core into the production process. Honeycomb core is placed between the inner and outer layers of a composite material to create a sandwich structure, which reduces weight while meeting the part's strength requirements. Incorporation of a core after the first prepreg is laid down increases the time in-station, further aging the first layer of material.

For the MLAS program, an in-situ manufacturing system was designed to address and mitigate the issues associated with the manufacture of a large, unified composite structure. It was designed to meet the transport and material out-time challenges while eliminating the need for an autoclave, reducing manufacturing floor space, and providing a rigid process platform to perform all necessary manufacturing operations.

Figure 10-4 shows the concept of an in-situ manufacturing system for large, unified composite structures. It depicts three stages of the operation: automated layup, non-autoclave cure, and drill. Nondestructive inspection (NDI) and extraction are also illustrated. The layup mandrel is mounted on a cantilever arm containing rollers to facilitate its rotation. A retractable cleanroom slides out over the mandrel during the layup process and then retracts while a portable oven then sides in over the mandrel to provide heat for curing. The oven is removed, and then the drill and NDI operations are performed with automated systems. An automated guided vehicle operating on air bearings features a fixture to provide support for the finished part as it is extracted from the in-situ fixture.

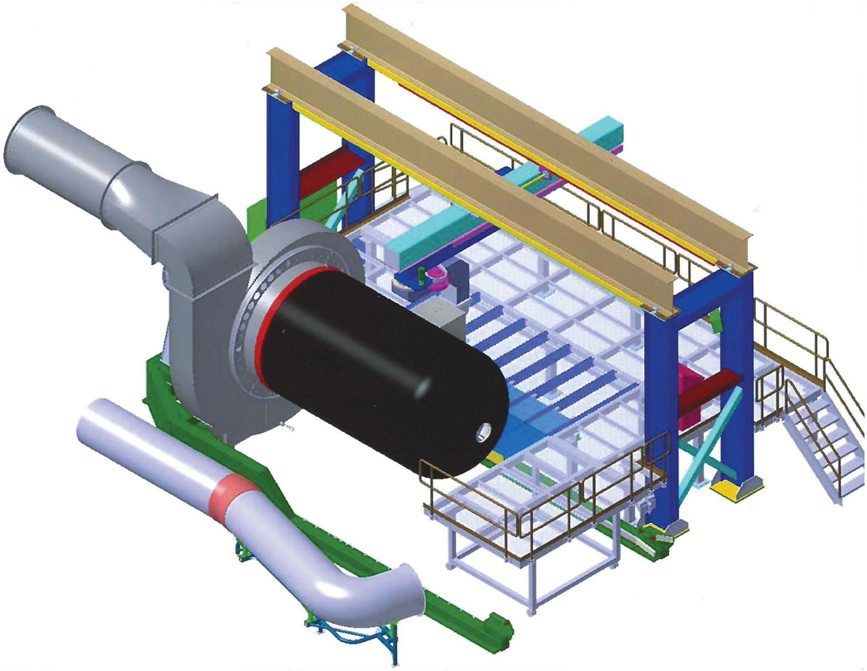

Figure 10-4. In-situ manufacturing system for large, unified composite structures.

The in-situ design took a building block approach for scale-up to 98-ft (30-m) diameter parts. The first phase was construction of a 10-ft (3-m) diameter working wooden mockup to validate all the elements needed to manufacture large composite parts in-situ. Testing included lay-down rate confirmation, safety systems, automated drilling and NDI, and mass, torque, and strain analysis for rotating a large structure. During the second building block phase, a 6-ft (1.8-m) diameter, fully functioning "hard" system was constructed to validate the components and system integration during operation.

Wind Turbine Blades

The proposition of deriving energy from wind is valid. However, it is in some critical ways a disappointing contributor to the quest for green energy. The inhibitors to generating energy from wind turbines as a viable alternative to nuclear and fossil fuels are inefficiency, cost, and centralized manufacturing. In-situ manufacturing can invigorate the use of wind for power by reducing cost, localizing production, and retrofitting old farms with new, highly efficient blades while minimizing disruption to the environment.

The logic and incentive to use in-situ manufacturing to produce wind turbine blades is the same as NASA's in regard to space vehicles. Factories manufacture wind turbine blades distant from wind turbine farms. Transportation accounts for a third of the cost of a wind turbine blade. Therefore, in-situ manufacture of wind turbine blades would save transportation cost. Figure 10-5 shows the public road footprint needed to transport a large, unwieldy, and cumbersome wind turbine blade.

Transportation cost is not the only incentive to manufacture wind turbine blades in-situ. Each blade requires oversize or wide load restrictions for shipment. Roads are carved through forests to make delivery to wind farms in remote areas. A 50-turbine farm with three blades per turbine requires 150 trips from the factory, which negatively affect the environment and surrounding communities. To deliver to ocean or lake wind farms, trucks and trains transport blades to a shipping dock where they are loaded on a barge or boat.

Wind turbine blades are perfect candidates for in-situ manufacturing. The process used to manufacture wind turbine blades is liquid resin infusion (LRI), which is labor intensive. Facility

Figure 10-5. The public road footprint needed to transport a wind turbine blade.

investment is minimal. The bulk of the LRI startup cost resides in tooling (molds, trim, and assembly). A major portion of the production cost resides in labor with material cost falling secondly. Therefore, blade designs and investment dollars are the barriers to entry into the wind turbine blade manufacturing business.

An in-situ manufacturing model for wind turbine blades would service two markets: blades manufactured for use at new or expanding wind farms and retrofit blades for existing wind turbines. In the latter case, new, high-efficiency wind turbine blades would replace the worn, damaged, or inefficient blades at the wind farm in-situ.

A Manufacturing Model

Wind turbine farms are collectives of wind turbines scattered across the geographic landscapes of many countries. New farms are fed by a supply base of factories, which manufacture and distribute the blades from as far away as 2,500 miles. The in-situ manufacturing model for wind turbine blades incorporates modular transportability. A modular factory is transported and installed in-situ at a wind farm and used until demand is depleted. After use, it is packed up and transported to the next wind farm. The factory model includes "rate" factories that will increase the proliferation of wind blades for turbines to meet green energy needs. *Rate factories* are clones or exact replicates of the first factory. Each one has a maximum capacity called a "rate" that determines how fast units can be produced. Adding in-situ factories increases the rate (speed) at which a product can be produced. These in-situ factories are replicated as demand increases. Modular and transportable in-situ manufacture (MTIM) of wind turbine blades minimizes damage to the environment wrought from leveraging the wind for energy.

The greatest positive impact to the generation of wind energy from the MTIM system would be retrofit of existing farms with high-output blades. Current wind turbines are only 20% efficient. Blade inefficiency and maintenance contribute to decreasing performance. High winds, harsh climates, and moisture absorption also contribute to the inefficiency. Research is ongoing and new blades are emerging that incorporate attributes capable of doubling or tripling turbine output. They can operate in higher winds, shed water to prevent icing, and prevent moisture absorption.

The cost of doubling output by retrofitting blades is 40% of the cost of installing a new turbine. In addition to reducing the impact to the environment, the MTIM system provides a low-cost rapid installation alternative for blade replacement. Because labor accounts for a significant portion of the blade manufacture process, an MTIM system neutralizes the desire to purchase low-cost-labor blades manufactured elsewhere. Blades built locally incentivize state economic development teams to invest in and expand wind energy initiatives.

The MTIM blade retrofit system includes a recycling center for grinding and packaging the old blades. The packaged material is sent back for remanufacture into products for sale. This reduces the scrap blades' transport cost and further reduces the cost of the new, higher-efficiency blades. It also contributes to the green environmental cycle of wind turbine blades.

MTIM System Uses, Configuration, and Logistics

The MTIM system design has roots deep into military rapid deployment technology. The U.S. Army Center of Excellence for Inflatable Composite Structure has developed air-beam technology, which is in use domestically and internationally. Beams use a high-strength fabric sleeve over an airtight bladder. Commercial air compressors inflate the bladders and are used in many applications including rapidly deployable aircraft hangers. When covered, they can be sealed and pressurized to meet nuclear, biological, and chemical (NBC) threats. NBC seals also make them suitable as clean-room environments. Each beam is an independent structure. They can be chained together to make a long factory, exactly what wind turbine blades require for their manufacture. Structurally sound, the largest ones support loads in excess of 1,000 lb (454 kg). Figure 10-6 shows a large, inflatable, air-transportable manufacturing facility.

Rapidly deployable factories are useful where factories are needed in remote locations or where large products create difficulties and expense when transported from large centralized

Figure 10-6. A large, inflatable, air-transportable manufacturing facility.

factories. Other use examples include situations where composite material freshness is an issue and large additive manufacturing applications.

Composite material freshness is a concern when fabricating a unified structure, which results in a large composite part. Large composite parts use greater amounts of composites material during the fabrication process. The long layup time for a large composite part increases the composite material's exposure to an environment outside its frozen-storage state. And composite material aging is accelerated when it is taken out of its frozen-storage state. Thus the potential for material expiration before the part is cured has driven research to increase composite material lay-down rates. Ideal lay-down rates to mitigate the expiration of composite materials before completion of large parts have not been attained. Size limitations driven by material expiration have prohibited unified structure scale-up and expansion. Consequently, the full potential for weight reduction and increased strength has not been realized.

Compounding the out-time concerns for large unified structural parts is the recent revelation that composite materials change their characteristics as they age. The previous assumption that the material expiration date was a go/no-go limit is no longer valid. Recent studies reveal a complex aging process that changes a composite material's performance characteristics from its time of manufacture until its cure. The material aging process can be affected by every environmental aspect of its life cycle. One example of environmental variability occurs in raw material transport. Transport trucks are refrigerated using a single cold-air generator/distribution system and a single-point temperature measurement gage. It is assumed that if the gage has recorded a temperature variation within a specified boundary, then all the material has been maintained within the specified temperature range. However, temperature analysis within frozen material trucks has shown that temperatures can vary outside the specified limits based on product placement and location within the trailer.

By rapidly deploying point-of-use, in-situ factories for site manufacture of composite materials, the aging process is slowed significantly. By providing fresh “farm-to-table” or direct-to-tool material, uniform material properties are possible and larger part sizes enabled. Point-of-use, in-situ factories have the added advantage of reducing material waste by eliminating the need for disposal of unused expired material. The shortened composite material supply chain when using point-of-use, in-situ factories is shown in Figure 10-7.

Rapidly deployable, point-of-use, in-situ factories can add value to the expansion of additive manufacturing. Since the advent of 3D printing, garage-shop businesses have popped up everywhere offering to design and make 3D printed parts. As 3D printing technology advances into larger parts and products, garages and small factories will have to grow, adding cost and complexity to the manufacturing transportation process. Large products such as houses, boats, and automobiles will again be driven from point-of-use factories into centralized production centers defeating an important attribute of 3D printing: point-of-use or near point-of-use distribution. A rapidly deployable 3D manufacturing center can be set up at its point of use with a minimum of capital investment. It can be redeployed after the local requirement for the product or part is satisfied.

Modeled after the U.S. military's rapidly deployable mobile camp environment, the MTIM system can be quickly set up to provide manufacturing, support, and living spaces. These modular manufacturing camps are a transferable technology to the

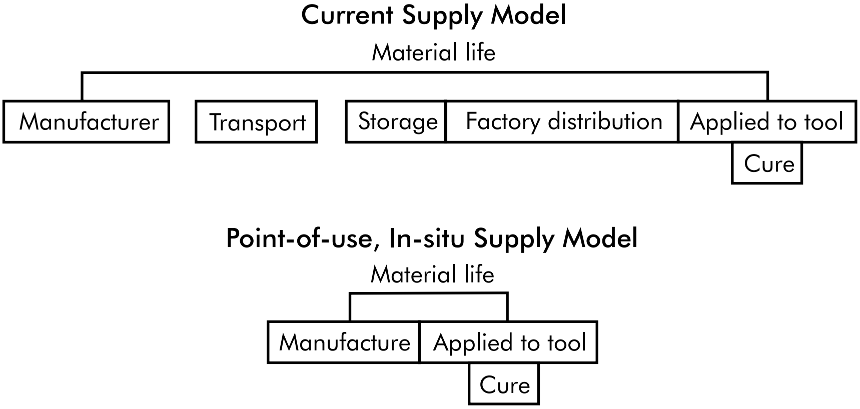

Figure 10-7. The shortened composite material supply chain when using point-of-use, in-situ factories.

civilian market, coming complete with water purification, waste management, environmental, and human habitation systems. Rapid deployment of the MTIM system is also modeled after the military, paving the way for transient green energy villages to produce wind turbine blades.

The MTIM model includes an air-transportable system to deliver the system to new wind turbine farms at remote locations. It uses a self-sustaining water collection and purification package, waste management, and recycling systems, a green power supply with backup power, power storage system, an initial 30-day food supply, and communication systems. Food would be resupplied every 28 days. Many of the remote sustainability processes for MTIM are derived from those used at NASA and for offshore drilling platforms. MTIM systems are designed to follow the same deployment strategy on land as on water. The difference is that water deployment requires a large barge.

A facilitation, equipment, and personnel package is also part of the MTIM system. Designed and built at a central location called an MTIM corporate hub, new MTIM systems are made, packaged, and shipped to accommodate customer specifications. Different wind turbines use different blades and blade attachments.

The corporate hub for the MTIM system houses the following functions: recruitment, training, research and development, customer specifications, a design center, material acquisition, distribution, testing before deployment, and a recycling center.

At existing wind turbine farms, the MTIM system is designed to tap into the farm energy grid to run the life support and environmental systems. The same energy grid is used to power factory, machinery, a medical support center, maintenance building, and other necessary operations and equipment.

For new wind farms, the MTIM design uses green technology, which promotes a healthy and minimally disrupted environment. The deployment strategy includes an MTIM refurbishment center for each state in which it operates. The refurbishment centers built at the MTIM corporate hub deploy to states using the MTIM system. The refurbishment center cycles each MTIM system after use at a wind turbine farm. The refurbishment cycle includes inspection, repair, upgrades, personnel recertification, redeployment coordination, and management. The refurbishment center also supports the storage and distribution of recyclable materials collected during retrofit blade operations.

The Business Model

The business model for ownership and operation of the MTIM system requires leveraging state government incentives and private investment to proliferate the systems rapidly across the United States.

Use of the MTIM system hinges on each state's commitment to wind energy initiatives, improving the unemployment rate, and increasing the existing number of wind generators. In the model, a state's Economic Development Team and the MTIM corporate coordinator would develop and initiate a Memo of Understanding detailing the incentives and responsibilities for deployment of the systems and refurbishment hub.

The infusion of venture capital would also provide incentive for proliferation of the systems. Although the MTIM systems originate at the corporate hub, the individual systems operate under an independent owner or franchised management and control. The MTIM business model is similar to the MacDonald's model where quality control, uniformity of standards and processes, technology, and other attributes for operation, which make it unique, are under central control.

Management and local control of the MTIM enterprise would decide on either a lease or buy option based on what is most advantageous for the state and the MTIM unit. The MTIM corporate hub controls governance of the system, supply chain, training, quality standards, and operating procedures.

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11

EXTENSIBILITY: PRODUCT PROTOTYPES, NEW PRODUCTS, AND INNOVATIONS

"Do not go where the path may lead;
go instead where there is no path and leave a trail."
—Ralph Waldo Emerson

BUS PROTOTYPES AND NEW BUSES

Daimler Benz and other manufacturers have been developing zero emission transit bus concepts for over a decade.

Figure 11-1 shows the Daimler Benz new electric bus (NEBUS) prototype from the late 1990s. Northrop Grumman also built its advanced technology transit bus (ATTB) prototype in the mid-90s. The ATTB program began in 1992 with the objective of developing a lightweight, low-floor, low-emission transit bus by using proven, advanced technologies developed in the aerospace industries. The vehicle is designed to meet federal, state, and local (southern California) axle weight and clean-air requirements.

The ATTB has a compressed natural gas (CNG) diesel motor that charges a battery pack, which drives motor generators on each of four drive wheels. The bus uses glass composite materials similar to the Maximum Launch Abort System (MLAS) program skirts and fairings. The light material can be molded into sleek, seamless shapes that increase interior comfort while reducing the quantity of assembled components. The reduction of assembled components reduces maintenance and noise from parts loosening over time. There are no bolts or fasteners required, therefore lowering the chance of corrosion and failure points. The lightweight materials yields a bus approximately 10,000 lb (4,536 kg) lighter than a conventional bus. The ATTB uses a CNG-electric drivetrain in place of the traditional full-diesel or full-CNG

Figure 11-1. The Daimler Benz NEBUS prototype.

drivetrains commonly used. Using aerospace-type materials, MLAS-type construction techniques, and defense conversion technologies has yielded impressive results from the ATTB prototypes and test beds.

The ATTB's user-friendly design features wide doors and a low, flat floor (15-in. [381 mm] maximum floor height) for shorter dwell times and easy boarding/de-boarding of passengers. The lack of internal steps or risers eliminates significant tripping hazards.

The composite structure test bed was used to validate the design of the ATTB. The testing program included a side-impact crash test with a 4,000-lb (1,814 kg) car traveling at 25 mph (40 km/hr), which resulted in only cosmetic damage to the test bed. The mobile test bed was developed to evaluate the performance and handling characteristics of the vehicle such as its propulsion, control, braking, dynamometer, and suspension systems. Both test bed models successfully completed their testing programs. While the bus in its entirety was never produced, many of the components, design elements, hybrid features, and use of composites have been widely disseminated into bus transit systems worldwide.

Fuel Systems, Power, and Drive

The ATTB is low emission but not zero. NEBUS uses a hydrogen and ambient air oxygen fuel cell stack to charge the battery pack and has zero emissions. Both prototypes have limited ranges due to the low energy density by volume of compressed natural gas and especially compressed gaseous hydrogen. Composite cryo-tank technology developed for space applications can be adapted to transit buses to greatly extend their ranges using natural gas, propane, and hydrogen fuels.

The advanced technology bus (ATB-1X), also by Northrop Grumman, combines the lightweight, impact-resistant body of the ATTB with NASA's cryo-tank technology, further reducing weight while eliminating carbon emissions. Figure 11-2 shows the 6-ft (1.8-m)-diameter LH_2 composite cryo-tank developed and tested for space applications at the Marshall Space Flight Center. The fuel-cell electric hybrid ATB-1X uses a conformal composite LH_2 tank.

The tank has graphite composite outside mold line and inside mold line skins with a laser-perforated, non-metallic honeycomb core. The non-metallic core sidewalls have low thermal conductivity and the core is vacuum purged using the laser-perforated holes. This construction makes a very lightweight, structurally robust tank with integral "Thermos® bottle" insulation. Unlike metallic tanks, composite construction enables shapes other than simple cylinders. This is critical for cryo-tank applications like the ATB-1X road vehicle because of the low energy density of hydrogen.

The bus has a conventional chassis, suspension, passenger compartment, front wheels, and four rear drive wheels. Each drive wheel has a dedicated direct-current (DC) drive motor generator (DMG) for power and primary braking. Power flows to and from the DMGs through a power-conditioning unit (PCU) to a battery pack. The PCU sends drive power from the battery pack to the DMGs and braking power from the DMGs to the battery pack under control of the vehicle's management computer. A fuel cell stack converts onboard hydrogen and ambient oxygen into DC electric power that steady-state charges the battery pack. The fuel cell stack is sized to approximately the 50th percentile power-usage

Figure 11-2. NASA's award-winning composite LH_2 cryo-tank. (Courtesy NASA)

spectrum; the battery pack is sized to cover the maximum power requirement.

The system also contains a closed-loop liquid thermal management system (TMS), also controlled by the computer, which uses the cold-sink from the LH_2 tank to cool the fuel cell stack, battery pack, and DMGs. The TMS fluid can be aircraft-grade polyalphaolefin dielectric coolant or other fluids suited to the temperature extremes in the system. A fluid-to-air heat exchanger is used to control the passenger compartment's temperature. The closed-loop TMS utilizes available cold and hot sinks in the system and does not require an air-conditioning compressor. It maintains the battery pack, DMGs, fuel cell stack, and all other subsystems so they operate at optimal temperature conditions, leading to efficient performance, long component life, and passenger comfort.

Hydrogen is an efficient fuel on a weight basis, but due to its low density it requires much more volume and consequently large tanks. It delivers 39,000 W/kg making it an attractive fuel choice on a weight basis compared to diesel at only 13,762 W/kg. However, its energy density by volume of 2,600 W/L is only 24% of diesel's 10,942 W/L. This means that liquid hydrogen tanks need to hold approximately four times more volume than diesel tanks for equivalent energy. Actual road vehicle range and tank sizing depend on the stored fuel energy and efficiency of the system. System efficiency is contingent on energy conversion through an internal combustion engine for diesel and a fuel cell stack for hydrogen, the system's weight, regenerative braking, etc. The ATB-1X system is more efficient than conventional diesel systems but large tanks are required.

Cryo-tank technology minimizes the dry mass for large tanks and enables conformal shaping for various applications. The light weight of the tanks and fuel allow them to be mounted on the top of the ATB-1X without significant structural modification. A horizontal elliptical cross-section was chosen to effectively utilize the roof area of the bus and allow adequate space for subsystem routing. Many other shapes are possible to accommodate extended range or multi-segment (bender) variants.

System Options

The basic system described here can be enhanced by adding advanced systems. These enhancements are not required but will improve the efficiency and operability of the system. All of the infrastructure necessary to control, condition, and store power from solar arrays is already included in the basic system. Solar arrays can be added to the roof of the bus by embedding them into the composite structure. Solar power can then augment the fuel cell and external power in charging the battery pack.

City variants, especially smaller-size buses, do not require the same amount of stored LH_2 as full-size or interstate transit buses. City driving creates more battery power due to frequent DMG braking. Streamlined tanks allow more duct room for the TMS. This is needed in city driving with frequent stops, door openings, and passengers constantly cycling on and off the vehicle. The TMS is forced to work harder to maintain a constant environment. Long-duration steady-state operations do not require this variant configuration.

A double-length variant is able to house the same set of subsystems as the ATB-1X. The wheel configuration is unique to the double-length variant as the rear axle, wheels, and associated DMGs are either relocated to the extended rear end of the vehicle or a fourth axle. Each segment supports its own LH_2 tank, enabling smaller tanks or longer range, although only one vehicle management computer and one fuel cell stack are required.

TRUCKS

Truck Prototype

MLAS manufacturing processes, materials, and technology are extensible to fabricate an advanced tractor-trailer (ATT-1X). These types of advanced technology vehicles are currently in the proposal and development stages awaiting maturation of advanced composite cryogenic tank designs and development of an infrastructure for the hydrogen highway of the future. This zero-emission, semi-tractor-trailer, long-range road vehicle uses hydrogen and ambient air oxygen fuel cells to charge a battery pack that drives motor generators on each of four drive-wheel clusters (see Figure 11-3). The enabler is cryogenic hydrogen composite tank technology, which NASA has proven in space applications. Adaptation of composite cryo-tank technology is essential so that trucks are able to carry a sufficient volume of hydrogen on-board to meet the range requirements for commercial transport.

Figure 11-3 shows the cryo-tank configuration of the ATT-1X. A vertical elliptical cross-section was chosen to effectively use the space between the cab and the fifth wheel, avoiding the stay-out zone should the trailer jackknife. Many other shapes are possible to accommodate extended range or sleeper compartment variants.

Trailers and Containers

Tied to trucks are the trailers they tow. Traveling the truck-laden highways of the United States and Europe, you see a host of contraptions attached to trailers and containers to streamline airflow and reduce drag to increase fuel efficiency. The composite sandwich structures manufactured for MLAS fairings and boost and coast skirts are also ideal for trucks. Composites provide strength while reducing the weight of trailers and containers. Unitized composite sandwich structures enable aerodynamic design while maximizing the internal capacity of trailers and containers. GFE material composition eliminates corrosion and, when coated with nanoparticles, the skin sheds moisture and resists graffiti. Trailer and container designers are freed from the limitations

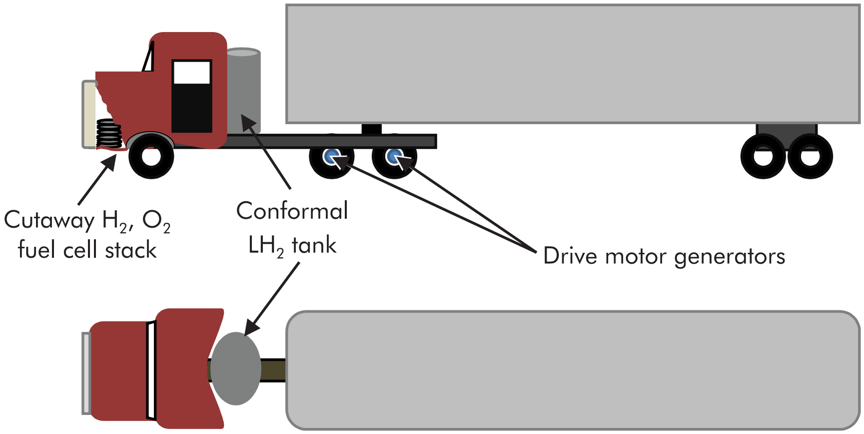

Figure 11-3. Tank configuration of the ATT-1X truck. (Courtesy M. McLaughlin)

of rigid metal construction and can design modular trailers and containers to right-size the transport medium to the load size and weight. Right-sizing maximizes fuel efficiency by limiting the exposure of the trailer or containers to drag.

Driver Health and Safety

One of the primary causes of truck-related accidents is driver fatigue. Large 18-wheel transport trucks cause 5,000 deaths per year and 1/10th all accidents, of which 101,000 are injury related. In tractor-trailer accidents, 98% of fatalities are individuals in the passenger vehicles involved (U.S. Department of Transportation 2014).

As an extension of textile-based embedded sensors motivated by the need for monitoring composite materials on the MLAS program, human-based monitoring systems have evolved to enable safer truck and bus operations. Products have been developed to monitor a driver's vital signs. Electrocardiogram (ECG), blood pressure, pulse rate, and heart rate variability can be checked in continuous real-time. For example, a cuffless blood-pressure monitor can be woven into clothing or a truck seat with networking to a point-of-care health facility (similar to a home security system). This technology is available for trucking companies at large. These devices are most beneficial to ensure that drivers of large vehicles are performing at their optimum mental and physical capabilities to warrant safe operations.

Based on wireless communication technology, a nanowire and nanostructure-based sensor system can be coupled with a smart phone (and/or Wi-Fi®) and app to monitor a driver's health. The system employs unique, dry-nanotechnology-based electrodes, which are washable and textile based. These act as neuro-sensors and transmit the ECG to an associated wireless and cloud-based system for data collection, data analysis, and data dissemination. This is useful for monitoring heart rate and various neurological disorders including sleep rhythms, sleep disorders, and sleep apnea. Designed primarily for out-patient monitoring, these devices can collect and transmit a surprising array of ECG, electroencephalogram (EEG), and electrooculogram (EOG) data with a unique radio-frequency identification (RFID) allocated for the truck or bus driver (thus confidentiality is maintained). The prototypes developed for real-time cardiac monitoring include t-shirts (with washable textile nano-electrodes) and e-health gear (a vest with washable textile electrodes).

The nanosensor component uses either gold-nanowire-based electrodes, textile electrodes, or a combination of both to capture ECG and heart rate variability, EEG, EOG and other neurological signals. Unlike commercial electrodes that require an electrolytic gel to improve electrode-skin contact, dry nanosensors have good contact with the skin without the need for gels that can lead to skin irritation and skin disease for patients. Coupled with a low-power microcontroller and Bluetooth® module (ZigBee®, Wi-Fi, and other communication protocols as appropriate), the sensor data can be streamed to commercial off-the-shelf cell phones and handheld devices.

There is a software system for cellular smart phones that can collect sensor data over Bluetooth and relay it over 3G, Wi-Fi, WiMAX®, or any outgoing connection with RFID. Apart from the cost benefits of using an off-the-shelf cell phone for data relaying, the software system provides other distinguishing features. First, it implements filtering algorithms on the cell phone to mitigate issues due to motion and other artifacts, rendering clean data. And it provides a visualization interface at the cell phone through which users can see salient features of their heart activity such as heart rate. The technology will monitor and provide the optimization and alert measures needed for a given individual and it tags the data with the location of the user. The location (latitude, longitude) collected is key for both backend services and the user in case of a medical emergency. The software on the phone runs simple machine learning algorithms to perform preliminary anomaly detection. In case of an emergency, the system can either alert the user and recommend hospital locations near the present location or make an automated call to the driver's physician and employer indicating the user's present location. Employers can access vital information anywhere and anytime within the networks (as long as they are set for global-level, active monitoring). The ZigBee-based Wi-Fi system is capable of handling 65,000 drivers at a given time (Varandan 2012).

The technology provides additional benefits for employees and employer where individuals could use the devices to report beneficial activities (exercising, taking medications, sleeping) and receive incentives from partners (doctors, insurance companies).

CITY RAPID-TRANSIT VEHICLES

The same sandwich GFE unitized structure approach used for MLAS can be used to maximize passenger comfort and minimize noise from metal rapid-transit systems. Composite unitized GFE cars require less maintenance than metallic cars that weather and experience loosened fastener joints and attach points. Graffiti, dirt, and unsightly scrapes are mitigated through the use of coatings on GFE, rendering them easier to clean. Less energy is used for environmental system distribution. Composite design and material attributes enable integrated ducting further reducing manufacture and maintenance costs. The insulating effect of a unitized structure is further enhanced by the lack of joints and seams, prevalent in metal or assembled ducting, which leach heat or cold air.

INFRASTRUCTURE HEALTH MONITORING

The aging infrastructure of the United States is beginning to literally “crumble.” Current inspection methods discover defects that have potentially catastrophic implications. Worse yet are the times between inspections when the bridges fail and people die. The application of composite “wraps” embedded with health-monitoring sensors would greatly reduce inspections and notify officials of potentially catastrophic damage before collapses that could cause death. A widely based test could be performed. Modeled on the MLAS rapid development process, it could encapsulate the various critical bridge structures with composites woven with embedded sensors. This methodology could be commercialized and spread across the infrastructure grid of the United States, reducing the incidence of failure by predictive maintenance.

Bridges and overpasses show damage from fatigue and, in more extreme examples, collapse. One of the most recent and dramatic was the Oakland Bay Bridge where a critical support beam was found to have a huge structural tear. The tear was not discovered until routine periodic maintenance was performed. The crack was so large that the entire bridge was shut down so engineers could assess the damage, recommend the fix, and repair it. Structural damage due to impact from vehicles and ships can also cause unseen structural damage. These are especially dangerous if the impact goes undetected or unreported.

The problem is the dramatic discovery of cracks, tears, or in extreme cases, the collapse of bridges without prior knowledge that any catastrophic event was about to occur. Earthquake-resistant composite wraps have been used to reinforce the columns supporting freeways in California. These passive column wraps require periodic inspections and after 6.0 earthquakes occur.

The MLAS program developments in the field of embedded passive RFID sensors woven into the composite materials could be applied. This could provide constant monitoring by readers mounted to city, county, and state vehicles. Or active readers could be positioned under the bridges and stimulated to send signals to a central location through an email alert describing the size of the event and the precise location.

To address failure issues due to fatigue damage, crack initiation, moisture absorption, wind gusts, and lightning strikes, "smart" bridges with embedded, wireless, lightweight sensors can provide continuous monitoring over the life of the bridge and its support beams. In addition, these sensors are capable of addressing issues such bridge vortex flex from wind and degradation from rain, sand, and particle erosion. An embedded sensor array comprised of integrated, organic thin-film sensors is a key feature of bridge structural health monitoring systems (SHMS). These systems also have a network of devices including control modules and RFID circuitry for wireless communications.

A large benefit to SHMS is reduction in the cost of maintenance and late discovery of potentially catastrophic wear or damage. The bridge SHMS continuously monitors the onset and progress of structural damage. This enables rapid and accurate diagnosis of significant events. Active monitoring is a means of prevention and encourages the proactive repair of bridges before critical failure.

SHIPS

Technology Transfer

In 2002 and 2005, Eric Greene developed technology roadmaps for naval composites research to support the U.S. Navy's ManTech program. The work was contracted by the South Carolina Research Authority. The purpose of the strategic plan was to identify technology gaps, plan ManTech projects to coordinate with platform insertion opportunities, and define future composites applications (Greene 2012).

The first technology development/demonstration project was a forward director room on the DDG 51 destroyer. Northrop Grumman built a technology demonstrator at its El Segundo, Calif. facility using the vacuum-assisted resin transfer molding (VARTM) process. The completed technology demonstrator successfully underwent shock testing.

As a result, the Zumwalt (DDG 1000) and Michael Monsoor (DDG 1001) are being built with composite superstructures and hangars using the VARTM process. Although these ships are built at Bath, Maine, the composite structures are made at the Huntington Ingalls Industries Composites Center of Excellence in Gulfport, Miss. The small shipyard, nearly destroyed in 2005 by Hurricane Katrina, builds the Zumwalt structures as well as tower masts for LPD 17 San Antonio-class amphibious ships.

Early in the MLAS program it became apparent that VARTM had divergent processes and applications when applied to aerospace and shipbuilding. The topside structure demonstrator was constructed by aerospace manufacturing research engineers using aerospace facilities, processes, and inspection technology. It was also constructed using precise measuring instruments and tooling transferred from the aerospace expert knowledge base. The assumption was that the early development articles and their processes for production were being used at the Gulf Port shipbuilding facility. But nothing could be further from the truth. The shipbuilding process is rough by aerospace standards using wood fixtures, rule-of-thumb measurement, basic measurement devices such as wooden scales, and fabrication accuracies in the .25–.50 in. (6.35–12.70 mm) range. Work instructions are basic, often verbal, and rarely inspected to precise completion. While the shipbuilding manufacturing processes and environment are more than adequate for shipbuilding, they are lacking for controlling the precision components of air and space vehicles.

First exposure to the facility and the first MLAS parts led to a reevaluation of the assumption that VARTM was the same wherever it was used. The different product/different application lesson led to teams of engineers and aerospace manufacturing experts flying to Gulf Port from California to take up residency. They were tasked with transferring aerospace VARTM expert knowledge to the shipbuilding workforce who looked upon this as an invasion of their domain and space. The initial clash of cultures eventually settled into a compromise for expediency to produce acceptable parts on-schedule and get the aerospace people out of the Gulf Port shipbuilder's hair.

The Gulf Port, Miss. Composites Center of Excellence produces some of the finest composite ship components in the world to shipbuilding standards. And the use of composites is new to shipbuilding where production of large parts for U.S. Navy vessels is a recent endeavor compared to the decades of evolutionary pain aerospace manufacturing workers and facilities have gone through.

Lessons Learned

The MLAS shipbuilding case experience led to several lessons for technology extensibility across diverse product types.

- Considerations and allowances should be made for the desired outcome. In most cases, aerospace manufacturing precision is not needed for ships or other products such as bicycles or trucks. The lower-cost manufacturing alternatives outside the pure infusion of resin, such as tooling and structure placement, may be more than sufficient to support rate, quality, and cost goals.
- Conversely, many products manufactured to acceptable levels by a similar process may not provide adequate levels of control to transfer the same process to precision products such as air and space vehicles. If low-cost prototypes are desired and dissimilar product manufacturing facilities and labor used, detailed technical specifications, work instructions, and vigilant oversight should accompany the contract award.

- The interface and interaction between divergent manufacturing product standards is not a bad experience. Subsequent to the MLAS-Gulf Port "cultural exchange program," the Gulf Port workers became acquainted with and acquired technologies they might not have considered prior to the MLAS experience. One example is the use of laser trackers for part positioning, best-fit assembly, and inspection. MLAS project managers flew in laser tracker teams. The exposure and observation of their use led to Gulf Port buying several laser tracker systems. The MLAS team learned from exposure to the composite shipbuilding process as well. Many aerospace processes slow down development by rigid controls unnecessary for a rapid prototype project. While many shipbuilding process controls and manufacturing methods were unacceptable, many others were more than acceptable for a prototype test vehicle.

WIND TURBINES

Large investments are being made in current wind turbines. Turbine blades could be improved by integration of MLAS technology such as resin transfer molding and rapid production methods incorporating embedded sensors. "Smart blades" could be manufactured with the latest technology from space and aerospace, which would reduce blade cost while increasing the blade efficiency by 300%.

Composite wind-turbine blades produced today are "dumb" blades. They are subject to wind and elements that prohibit their widespread use in the most productive geographic areas of the Earth. They crack and break even in marginal areas where wind gusts are unpredictable and they are incapable to respond. The blades require periodic shutdown to inspect and evaluate the impact of intermittent gusts that exceed the design's allowance for strain. Rogue gusts have toppled entire wind-turbine structures. Current wind turbine blades absorb moisture, adding to weight. The moisture promotes mold growth that necessitates shutdown and cleaning of the blades. These shutdowns account for 50% of the downtime and maintenance cost of composite wind-turbine blades. These effects also erode the efficiency of the blades by as much as 25%. Extreme cold shuts down wind turbine generators due to blade icing during winter months. And today's composite wind turbine blades are prohibited from installation in continuously extreme cold areas with high winds. This is precisely where they would generate continuous power at the highest levels of output.

There is a backlash in the U.S. and Europe from environmental groups for wind farm installations because of their disruption of bird migratory routes and land creature habitats. In addition, there is a backlash against their installation for aesthetic reasons in Europe where precious, pristine, remote areas have become almost saturated with them. A smart-composite wind-turbine blade manufactured with a low-cost health monitoring system, water-shedding nano-coating, and deicing capability could mitigate some of the negative issues associated with wind energy.

The benefit of smart-composite wind-turbine blades would be proliferation of wind farms into previously prohibitive harsh environments. The number of wind turbines would expand by a factor of four. An additional 55% of the Earth's surface would be opened for wind-turbine installation.

The latest technologies recently developed for other industries could be adapted to wind-turbine blades. Current passive hybrid tags have been embedded in composites. They can determine temperature, vibration, strain, and other health diagnostics. These tags could be woven into the blades at the time of manufacture. Readers would be attached to the generator's mounting post. Each time the blade passes the post (once a second) the read data would be sent to the blade gears through a simple PLC to maintain optimal efficiency and reduce excessive strain. University developed nano-coatings could be sprayed onto the blades during the manufacturing process. These coatings are moving to commercialization and shed moisture when applied. They increase blade energy efficiency and reduce icing as well as eliminate mold growth. Deicing systems incorporated into the blade would eliminate icing.

On a smart blade, the sensor array is based on an active matrix configuration in which each sensor can be addressed by thin-film-transistor (TFT) sensors. A row of pixels is selected by first applying appropriate voltages to the TFT gates connected to the row. Desired voltages are then applied to each pixel through the data lines to read the data from each sensor cell. Non-selected pixels are completely isolated from the voltage operation of the selected pixels. Therefore, the TFT active matrix here can be considered as a switch for selecting and isolating the pixels (sensors). It is proposed to employ these flexible, polymer-based, health-monitoring sensors so that a significant reduction in blade maintenance, downtime, and cost can be achieved. These lightweight, wireless, and cost-effective, polymer-based sensors can be embedded in the composite structure or surface-mounted onto the blades with a protective polymer coating (Varadan and Saxena 2011).

Incorporation of smart attributes during the manufacturing process would add 1/10th of 1% to the manufacturing cost of a 33 ft (10 m) composite wind-turbine blade while increasing utilization rates and efficiencies by 25%. Currently, the cost of a kW of wind-generated energy is twice the cost of a kW produced from fossil fuel. The ability to function in previously inhibitive environments where winds are continuous and vigorous, reduction in maintenance costs, and other efficiencies as the result of “educating” a blade would move the generating costs of wind to align with the current cost of fossil-fuel-generated power.

LIFTING AND SUPPORT DEVICES

Emergency strut systems are designed to assist fire/rescue personnel in stabilizing automobiles, light aircrafts, trees, and structures. They are used by a variety of first and later responders including forestry personnel. In many accidents, vehicles need to be stabilized before human extrication can take place. In other cases, houses that have been damaged from earthquake or tornado have to be stabilized to extricate victims or retrieve personal items.

Emergency strut systems range in length from ≈20–40 in. (≈508–1,016 mm) collapsed and telescope mechanically in increments to as long as 8 ft (2.4 m). The struts are meant to stabilize, not lift, as their purpose is to be wedged or positioned under areas needing support. They hold the unstable vehicle, tree, or structure in a stable position so people can work without fear of being pinned. Struts carry loads up to 5,000–10,000 lb (2,268–4,536 kg). The issue is their weight. The steel emergency struts are ≈25–100 lb (≈11–45 kg). In use, they are often grouped to provide better rigidity and support (see Figure 11-4).

Transporting the heavy steel stabilizing struts strains human capability to respond quickly especially where emergency personnel must carrying the struts by hand for distances when roads are closed and access limited. There are composite struts available but their materials and manufacturing methods fall short of the performance needed in the field. Pultruded fiberglass-reinforced-polymer (FRP) composite struts do not offer the needed abrasion and impact resistance, operating heat requirements, and confidence that filament-wound, graphite composite, autoclave-cured struts could provide.

The MLAS struts with their metal clevis offer a high-strength alternative at half the weight of steel struts. The hand-wound manufacturing process provides an economic alternative to existing heavy steel emergency struts and provides superior

Figure 11-4. Emergency struts are often grouped to provide better rigidity and support.

performance over the current FRP alternative. The thread clevis also provides an attachment medium for end fittings, jack units, a load spreading pad, hooks, straps, chains, pickets, cribbing, wedges, and step blocks.

INNOVATIONS

New Lighter-than-air Ship (NLAS)

Trucks account for 10% of fatal accidents, 1/3 of emission pollution, 1/2 the wear, damage, and aging to roads and bridges, are significant contributors to road congestion, are noisy at 84 dB, and consume 10% of the nation's fuel. A new lighter-than-air ship (NLAS) design is based on slightly heavier-than-air technology. It incorporates a broad spectrum of advanced technology that has recently been demonstrated and proven in prototypes that exceeded lift and transport performance targets. In short, the results exceeded design expectations.

While the NLAS vehicle uses helium as the primary lift component, advances in technology have increased the lift capability, reduced size, and expanded the operational utility of the Zeppelin lighter-than-air ships of the past. The NLAS vehicle incorporates hydrogen-fuel-cell-powered, air-cushion-lift-fan technology for ground movement and low-vibration, electric fan technology energized by embedded solar cells to provide thrust. Lift is supplied in hybrid form through a combination of helium, lift fans, and the vehicle's aerodynamic shape, which is enabled through the use of lightweight advanced composite materials.

The NLAS vehicle would operate in the relatively unused airspace between 2,000–15,000 ft (610–4,572 m) altitude over low-density population areas to deliver product and people. The system does not require runways. Similar to air-cushion technology, it incorporates the recently developed vertical lift fans for the F35 and the low vibration and quiet composite blades of the C130. These technologies enable the NLAS vehicle to land and move over ground or water to pick up or deliver product and people safely, quietly, and efficiently.

Modular "lock and load" composite container systems embedded in the NLAS understructure provide highly versatile rapid load and unload capabilities. This increases the utility of the NLAS vehicle for a wide variety of uses beyond cargo and people. An example would be delivery of emergency goods to distressed areas where natural disasters have occurred. Where roads and runways are closed and helicopter rotors wash, the operational expense and limited load capability would be eclipsed by the performance of these "gentle giants."

NLAS incorporates technologies such as dry-fiber composites with embedded solar cells and hydrogen motors that provide lift and propulsion. The composite materials are also sprayed with carbon-based nanotubes and embedded with RFID health-monitoring systems. This increases the effectiveness of the materials, safety, and vehicle control.

The MLAS program breakthroughs in low-cost, large-carbon composite component manufacture will lead to aerodynamic shapes, reduced vehicle weight, and improved weight and mass properties for the NLAS vehicle's design. Autonomous flight controls, such as those incorporated into Global Hawk and NUCAS, are also transferable to the NLAS vehicle to reduce crew fatigue, vehicle size, and costs.

Advantages of NLAS

The U.S. is incentivized by the triple crisis of rising energy costs, global warming, and economic stagnation to develop and implement highly innovative technology. The nation's roads and bridges are beginning to crumble under the weight of age, overuse, and lack of maintenance.

Uniquely positioned geographically and technically, the U.S. is capable of leveraging its resources to become the center for a revolution in transportation that would migrate across the globe. The design, development, and operational implementation of a hybrid, environment friendly, and highly efficient air-ship transport system would again position the United States as the world's leader for "game-changing" solutions.

Advantages of an NLAS vehicle extend beyond zero emissions and reduced transport times. For example, trucks are size limited due to bridge heights (13.5 ft [4.1m]), span or length, and width. Low-cost aerial transportation would increase the size of loads that could be carried and reduce oversize loads on the roadways of the U.S.

There are over 2.5 million 18-wheel vehicles operating in the United States today. Another 250,000 18-wheelers operate in Canada. If 10% of these vehicles were replaced by NLAS vehicles, the market potential would be 275,000 vehicles. With a target flyaway cost of \$2.5 million U.S. each, the market value of these vehicles would be \$675.5 billion. Each NLAS vehicle would carry the load of up to four 18-wheel trucks. An 18-wheel truck with trailer is priced at \$250,000 U.S. Operating fuel is 15,000 gal (≈56,781 L) annually at \$3.00 gal (≈\$0.79 L) = \$45,000 U.S. for each truck. The service life of an 18-wheeler is 10 years. Therefore, the purchase and operating cost (fuel only) of four 18-wheel trucks is \$2.8 million U.S. If no other consideration was included, the life cost of a NLAS vehicle would be \$300,000 less than the 18-wheeler it replaces. And the projected life span of the NLAS would be double (20 years), further adding to its total life-cycle cost value. In addition, using the sample transport times between Fayetteville, Ark. and Denver, Colo. for an 18-wheeler, a 50% reduction in transport time would be achieved using the NLAS vehicle instead. A similar sample between Fayetteville, Ark. and New Orleans, La. also resulted in a 50% reduction in transport time.

Advanced Systems

Advanced systems that can be integrated into the composite material's structure to maximize safety and efficiency are now emerging into the market. The "skin" of air and land vehicles is an interface between the internal and the hostile external environment. Environmental stressors include:

1. Water-based electrolytic agents that can cause gradual corrosion;
2. Surface scratches caused by handling and maintenance in depots as well as during take-off and landing of aircraft under sandy conditions; and
3. Fatigue stresses associated with vibration and thermal shocks that are characteristic of service conditions.

This combination of aggressive environments and stresses leads to numerous field maintenance problems with the potential of being catastrophic. Maintenance programs are designed to mitigate such failures but these measures add considerably to the operating cost of the fleet. For trucks and other ground transportation vehicles, recent developments in nano- and micro-technologies offer effective materials and device solutions that will allow the application of multifunctional coatings. Developed as offshoots of the MLAS program, smart, multifunctional, corrosion-resistant coatings with embedded sensors are capable of providing on-line condition assessment of damage due to fatigue. The enabler of multifunctional coatings is the integration of three key technologies:

1. Bio-inspired "lotus leaf" micro-texturing for surfaces, which promotes super-hydrophobicity;
2. Anti-corrosion nanoparticles buried in the skin that can bleed into fresh metal exposed due to scratches, and
3. Structural-health-monitoring-sensor arrays using integrated micro-technologies.

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12

THE DIGITAL TAPESTRY

"Nature uses only the longest threads to weave her patterns,
so that each small piece of her fabric reveals
the organization of the entire tapestry."

—Richard P. Feynman

INTRODUCTION

Of all the extensible technology, the one that would have the greatest value if extended out into other industries is the example that MLAS set for use of the digital thread woven into a digital tapestry.

MODELING AND SIMULATION

Solid models are used for machine programming and simulation, model-based definition of process parameters, and model-based definition of key part characteristics. Facilities and equipment are linked through a digital thread that maximizes resource activities and minimizes downstream inefficiency and design iterations. The digital thread is used to validate many designs for manufacturing before they ever reach the production floor.

Design and simulation models verify the fit of assembled parts, tools, equipment, and the ergonomic needs of personnel performing the work. Assembly interface tolerances are verified with laser, photogrammetric, and other inspection methods back to digital masters with accuracies that often exceed those obtained with a hard master.

Use of manufacturing assembly and flow simulation models helps resolve issues early, provides lean assembly sequences, visual graphics, and data integrated into electronic work instructions. These and other tools have maximized the utilization and efficiencies of facilities and equipment.

MLAS program participants successfully demonstrated the capabilities of determinant assembly. Determinant assembly defines the key characteristics and part features required to physically index parts to each other during assembly. This facilitates using a distributed supply chain with assured fit at integration. Application of determinant assembly has eliminated the need for coordination tools and reduced assembly spans.

Modern 3D solid design and design for manufacture and assembly (DFMA) tools enable significant collaboration, particularly when it comes to producibility. The digital thread continues to flow into production operations through use of handheld terminals containing the build information. The same systems have been developed for portable maintenance terminals.

Certified technicians use on-line work instructions and a photo database, both indexed to subsystems for closeouts. A digital imagery plan documents as-built configurations that are reconciled back to the original engineering. This is a significant benefit to problem resolution and cycle time reduction for ground, lab, or operational conditions.

Automated engineering design instructions and recommended computer-aided design (CAD) modeling techniques optimize utilization of the primary design tool and support a common platform for model reviews with design engineers. Behavioral modeling packages allow the rapid performance of sensitivity and feasibility studies on multiple design configurations yielding an unbiased and optimized set of design concepts. This approach efficiently performs design and analysis to determine customer-usable designs for use in addition to the required trade-study final reports. The capability to rapidly fabricate, break, and test structures provides the design and build team the opportunity to participate in hands-on tests and demonstrations. This approach ensures that qualification issues are taken into account early in the development process. Even more importantly, everything presented is buildable and directly applicable to the manufacturing process.

INTEGRATED PRODUCT DESIGN TOOLS

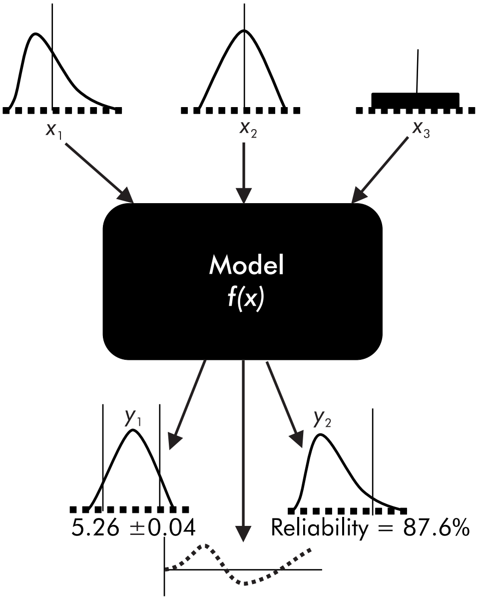
The digital thread enables integrated product design tools (IPDT). These tools are used to:

- Determine the implications of specific processes/approaches using advanced analysis tools such as manufacturing simulation analysis and variation simulation analysis (optimized for downstream and upstream users);
- Determine the visual, ergonomic impacts of planned work (safety and physical constraints) through simulation and modeling prior to application on the shop floor;
- Determine the need for equipment maintenance, repair, and replacement during manufacturing, integration, and test;
- Test manufacturing tools, processes, and machinery to be used during operations to ensure continuity of the system to meet manufacturing process performance standards;
- Develop lead times for material;
- Identify commonality with other product elements;
- Assess the uniqueness of a process and identify alternate/backup sources of a capability or process;
- Determine facility location and availability;
- Assess the relative costs of competing or alternate processes using manufacturing build sequencing simulations (verification of planned statement of work);
- Recommend design option selections based on manufacturing constraints with consideration of the trade matrix of cost, weight, availability, and risks associated with each option.

Figure 12-1 shows the sensitivity analysis derived from a Monte Carlo simulation. It illustrates the largest contributor to assembly difficulty in relation to the cost of a representative part. Design changes occurring after manufacturing has begun have the highest impact. Once identified, the high contributors can be targeted for cost reduction and design re-analysis for manufacture before parts enter the manufacturing stream.

ROBUST NETWORKING

Also woven into the MLAS program was a common network that extended from design, through production, and across the supply chain. The capability included automatic synchronization of configurations, digital high-fidelity simulations, graphic planning, and digital manufacturing processes. This approach optimized the manufacture and production of the MLAS vehicle. It resulted in



- *3D Monte Carlo simulation*
- *Sensitivity analysis identifies largest contributors*
- *Key to determinant assembly and minimum assembly footprint*

Figure 12-1. Sensitivity analysis derived from a Monte Carlo simulation, which identifies the high drivers.

reduced tooling, tolerance accumulation, and product variability. It identified manufacturing requirements and cooperatively recommended design enhancements for manufacturability.

Space launch vehicle manufacture and assembly requires a robust interaction between design and manufacturing to ensure first vehicle success and continuous improvement to reduce lifecycle costs.

Application of simulation, automated systems, and the digital tapestry on the F/A-18, F-35 and B-2 programs have resulted in dramatic increases in quality (90% defect reduction and 80% variability reduction), decreases in cost (50% reduction), and a 95% reduction in lost-time injuries. This systems approach optimizes the design process through the involvement and interaction of integrated product development teams. Figure 12-2 shows process/product coordinated design flow and how it works to lower production costs.

The teams are responsible for identifying relevant technologies and processes for design and manufacture with a focus on their

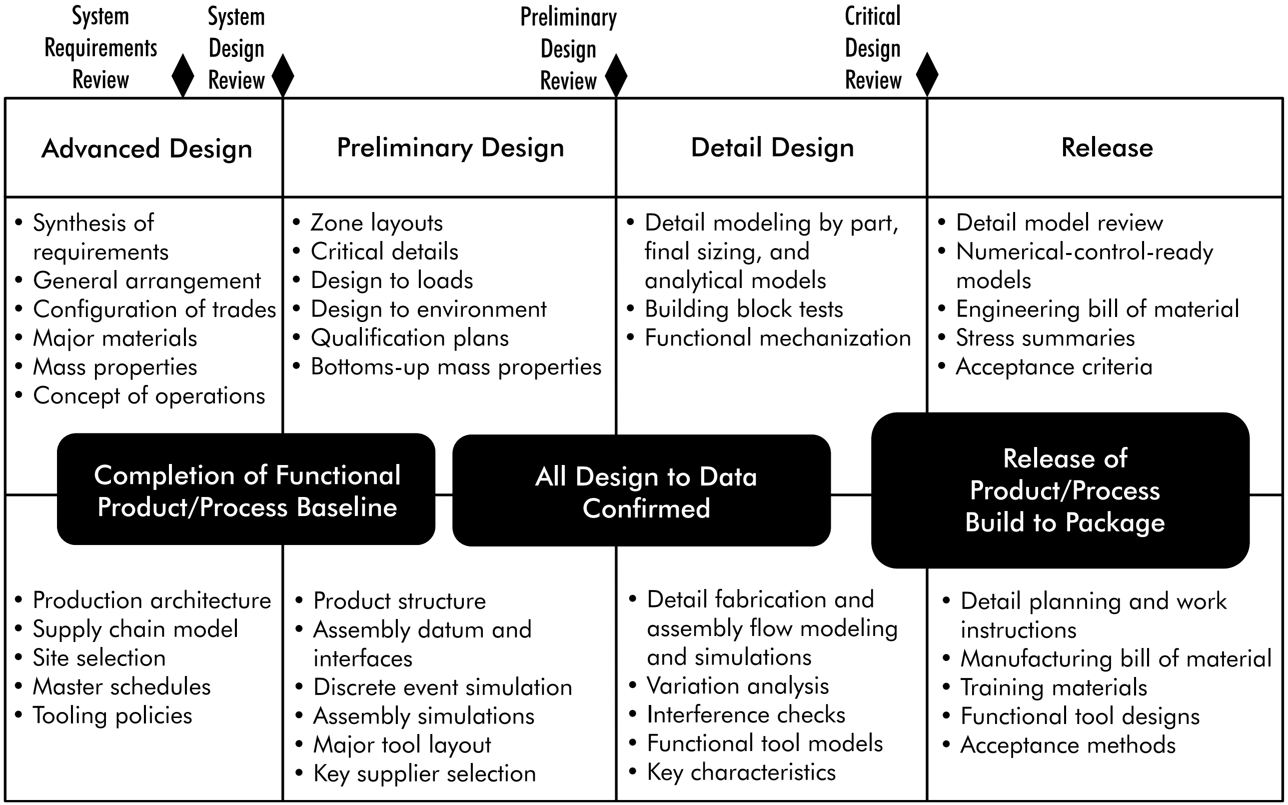


Figure 12-2. Process/product coordinated design flow and how it works to lower production costs.

cost benefit, quality, and function. The approach invigorates development of the identified technologies through a clearly defined process for maturity and transition to production (TTP), which facilitates fluid integration into the manufacturing and production value stream. It enables migration across the company for maximization of resources and outlines sustainment policies and procedures that provide incentives for involvement of the supplier base.

ADVANCED ANALYTICS

Advanced analytics are analytical techniques applied to as-manufactured data, which go beyond simply describing the data. They include a digital imagery plan to document as-built configurations for reconciliation back to the original engineering. The analytics explore the hidden relationships and patterns within the data. They provide insight into things that are happening, which cannot be seen with simpler cross-tab analysis.

For automated assembly, advanced analytics begins with enterprise-wide intelligence software. This enables event-driven analytics and process improvements. The software identifies, quantifies, and normalizes:

- *Rogues*: A part within a family that widely varies (dimensionally) from part to part.
- *Outliers* (sometimes called *outlanders*): Part(s) that lie near the edges of the upper control limit/lower control limit.

The digital thread is critical to advanced analytics, providing the “highway” for manufacturing feedback to maintain functional continuity between the design and as-manufactured assembly. Advanced analytics support the needs of companies to enhance the requirements, management, and use of digital data within all aspects of a product’s life cycle.

Four enablers to maximizing the digital thread and leveraging the full benefits achievable through advanced analytics are multi-disciplinary design and analysis optimization (MDAO), actionable intelligence with I-Triple A (hereafter referred to as I-Triple A), factory command, communication, and control (Factory C^3), and expert systems.

MDAO

Multi-disciplinary design and analysis optimization (MDAO) of advanced analytics enables reduced design optimization cost and lead times for complex engineering systems. MDAO is a methodology for the design of complex engineering systems and subsystems that coherently exploit the synergism of mutually interacting phenomena. MDAO provides a process to:

1. Decide what can be changed and to what extent while providing options to minimize the disruptive impact to the supply chain and internal operations, schedule, and product manufacture efficiencies.
2. Computationally tie together design, modeling, simulation, and analysis of multi-disciplinary tools.
3. Enable rapid system-level design and analysis to get early visibility into the available design space and an understanding of component-level impacts.

MDAO is applicable to all phases of systems development by appropriately varying the number and fidelity of component models.

To date, MDAO focus has been on engineering disciplines such as configuration, propulsion, mass properties, and performance while providing an infrastructure that integrates common tools and best practices for affordability and first-time engineering quality. There are opportunities to expand the scope of MDAO with manufacturing modules that consider material types, manufacturability/producibility, operations, and support, which are critical factors in weighing system concepts and life-cycle costs.

MDAO with manufacturing modules can provide product-level and sub-process-level manufacturing costs the same way finite element analysis currently optimizes structural design, creating "finite element manufacturing" analysis software. This capability will help erase the current lag in manufacturing influence on the final design, which can often result in missed cost avoidance opportunities. Figure 12-3 illustrates the impact of the design and development phase where up to 85% of a system's total life-cycle cost is committed.

It is production's charter to influence the design process with producibility enhancements; however, the manufacturing subject

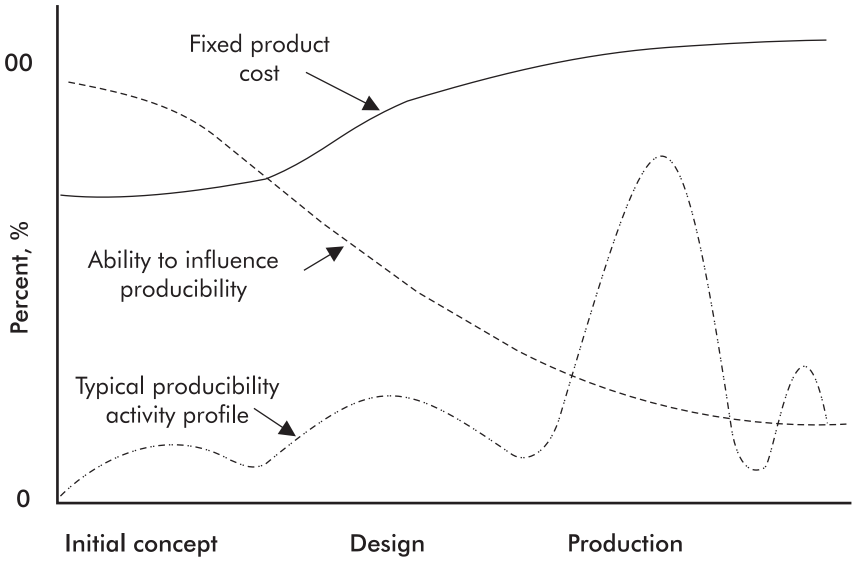


Figure 12-3. The impact of design changes after manufacturing has begun.

matter experts may not be available during all phases of concept design and development. This inhibits best-practice sharing and the opportunity for design optimization of manufacturing processes. Parametric design automation, based upon engineering and manufacturing requirements, includes specific manufacturing and assembly constraints. Unique build processes, material fabrication limitations, shop-specific practices, and a detailed database of production long-lead and procurement metrics are described. This knowledge base drives change decisions based on cost and schedule and, if changes are approved, gives detailed implementation points called *production effectivity* to minimize the impact on production.

Manufacturing MDAO modules have the opportunity to lead the digital manufacturing architecture, addressing the design and development portions of product life-cycle costs that represent the largest potential for reduced costs and lead times. The key benefits of MDAO include:

1. Significantly reduces system costs and accelerates time to market by accounting for manufacturability of advanced

programs within the initial design, thereby reducing the number of design changes.

2. Quantifies and associates manufacturing processes to material and design iterations by considering high-fidelity impacts to production, lead time, cost, and mission capabilities.
3. Aligns systems to the supply base with data to forecast the needs for next-generation products.
4. Creates an automated, collaborative environment with all engineering disciplines communicating during the initial stages of product design, and fosters enhanced communication during detail design.
5. Incorporates training and workforce-specific processes into the conceptual design and cost phases through production. *Cost phases* are production cost aggregation points. Each cost phase or cost center manages the assembly of a complex collection of parts and their cost within the center. By managing the cost phase/center, the overall cost of complex products can be controlled.

I-Triple A

Actionable intelligence with I-Triple A (or I-Triple A) refers to implementation of automation outside of high-volume production. Low-volume application is necessary to expand the capabilities of automation for multipurpose, multirole systems. Future systems will require a combination of classic automation equipment supplemented with interchangeable peripheral sensors, displays, and human cohabitation capabilities to create an intelligent machine capable of addressing limited quantities and variable inputs. Intelligent machines must be integrated within the factory network database to enable a direct connection from the 3D design model to the end as-built product. Implementing a database to both supply data for assembly and archive the as-built data condition is required for digital twin approaches and intelligent machines to perform four basic tasks: identify, analyze, adjust, and assist (I-Triple A). The digital twin data approach compares the active data being collected during the build cycle to the previously as-built data to refine the family-of-parts analysis for best fit at assembly.

Automation capabilities need to be enabled through interconnected hardware sensors and systems. The architecture must be flexible to connect with new and existing manufacturing enterprise systems and shop-floor control plans. A key enabler for I-Triple A will be to capture “as-built” conditions. Integrated sensors will be used to analyze, adjust, and inspect during the manufacturing process.

The key benefits of fully capable I-Triple A are:

- Multipurpose, multi-use machines;
- Reduced total product cost and increased business case opportunities across various products and platforms;
- Workforce development in advanced technologies and creation of job opportunities for a multi-disciplinary, technical workforce; and
- Continuous research opportunities to further enhance, refine, and compile system functionality for reduced costs and time to market.

Actionable Intelligence with I-Triple A will be complementary to efforts for the integration of factory command, communication, and control (Factory C^3).

Factory C^3

Factory command, communication, and control (Factory C^3) focuses on the interconnection of manufacturing disciplines and associated information systems. In many cases, data resides on separate systems, with engineers and technicians using various programs to accomplish tasks. Factory C^3 provides a network of information, from design engineering to work instructions, on one cohesive system.

Factory C^3 is a web-based, configurable, and unrestricted enterprise-level framework that seamlessly expedites the interplay of data, information, and knowledge among design, manufacturing, and sustainment disciplines. The architecture is both modular and extensible, making it easy to accept new sources of information. It is inspired by the pervasive open-architecture, plug-and-play philosophy. The development of universal interfaces based on the extensible markup language (XML) schema enables users to configure the system for specific needs or incorporate individual modules for transition into specific environments. Since the software system is web-based, users have the advantages and conveniences that come with a website while leveraging the functionality of the Internet. This web-based, modular system is designed to meet the diverse requirements of myriad users (e.g., designers, developers, engineers, production operations personnel, and managers). The C^3 architecture provides each with their unique requirements and privileges.

Factory C^3 architecture enables interconnectivity with all engineering disciplines and factory management groups to facilitate organization. It is complementary to the manufacturing MDAO and intelligent machine efforts. Further, it can be exploited to enable rapid design change coupled with equally rapid manufacturing response. Changes to visual work instructions and planning sequences disseminate without the inefficiencies of the current processes.

Automation acts upon information within the advanced manufacturing enterprise and collects data for analysis. This philosophy provides a thoroughfare of information, eliminating islands of data as currently experienced within manufacturing. Data flow eliminates physical and cultural barriers between disciplines. It enables sharing best practices within manufacturing and engineering while integrating intelligent machines with advanced analytics to realize the benefits of all systems. Factory C^3 standardizes the methodology to create consistent quality products overall. The system brings data down to the operators while providing feedback to optimize the design and processes for the program and manufacture of products.

Key enablers of Factory C^3 needed for aerospace applications, which have extensibility to other product manufacture are:

- Systems that provide the capability to create a digital thread to expedite kitting and project part, workpiece, and component location on the product;
- Integrated metrology systems to measure as-built geometry for the purposes of controlling critical part interfaces;
- Key characteristic interface measurement across multiple suppliers/subassemblies, enabling virtual assembly of the final product;

- Development of a factory network architecture and infrastructure allowing interconnectivity with every engineering discipline and production operations to facilitate organization; and
- Interconnected manufacturing planning and non-conformance traceability software to facilitate inter-organizational communications.

The key benefits of a C^3 system include:

- Integration of data flow accelerates time to market by reducing design alterations and accounts for manufacturability of advanced programs within the initial design;
- Commercialization of a short-time-series expression miner (STEM), Java®-based software program to optimize data flow; and
- Development of technologies to utilize, track, and control data on the production flow and provide feedback to the internal engineering teams and supply chain for product improvements.

EXPERT SYSTEMS

The dramatic increase in data and information flowing from design through product delivery, out to the end user and back, comes with the burden of massive amounts of cumulative data that can overwhelm the recipients. Much like the fighter pilot's response when overwhelmed with data in a crisis, the design and production department's response may be to simply turn off the advanced analytics systems and go back to the comfort of flying by the seat of their pants. As the human response to data overload has become recognized and understood, expert systems have emerged as filters to organize, categorize, prioritize, and present best options for optimal performance to users.

In artificial intelligence, an *expert system* is a computer system that emulates the decision-making ability of a human expert (Jackson 1998). Expert systems are designed to solve complex problems by reasoning about knowledge, like an expert, and not by following the procedure of a developer such as a conventional programmer (Leondes 2002). The first expert systems were created in the 1970s and then proliferated in the 1980s. Expert systems were among the first truly successful forms of artificial intelligence software (McCorduck 2004; Luger and Stubblefield 2004).

An expert system has a unique structure, different from traditional computer programming. It is divided into two parts: one fixed, independent of the expert system called the *inference engine*; and one variable, the *knowledge base*. To run an expert system, the engine reasons about the knowledge base like a human. In the 1980s a third part appeared: a *dialog interface* to communicate with users (Koch et al. 1988/2002). This ability to conduct a conversation with users was later called "conversational" (McTear 2002; Löwgren and Nordqvist 1992).

Expert systems are not new to aerospace or other industries that produce complex products. In the 1990s, I was principal investigator for a structured knowledge base, object-oriented expert system called Advanced Tooling Manufacture for Composite Structures (ATMCS). ATMCS was a U.S. Air Force and industry -sponsored effort to automate the tool design and tool manufacturing processes for composite parts. Experts were interviewed and a structured knowledge base developed to provide a system that would optimize tooling based on part complexity, composite system, production rate, and cost. When implemented in the mid-1990s, the expert system provided the capability to assimilate tool modeling materials and analyze information by means of a knowledge-base advisor system for the presentation of tooling options. Trade-off studies relative to part quality, tool durability, and lower cost/cycle time provided the user with best options.

The advancement and use of expert systems has grown. They have evolved into powerful aids to minimize data overload by filtering and providing the user with best-option scenarios when confronted with critical design and production choices. Adding the power of an expert system to the tool chest of advanced analytics optimizes the data flow and decision points for better quality parts and reduced impact on production efficiency.

GAME THEORY

Applying data mining algorithms together with game theory poses a significant potential as a way to analyze complex engineering systems, such as strategy selection in manufacturing analysis (Wang 2007). Game theory is becoming important and widely used as a tool to select strategies. The complex behavior of the agents and a huge amount of data and information generated from the manufacturing environment require data mining techniques for extracting the few but critical bits of knowledge that populate the expert system and optimize the decision process.

The assumption of human rationality implies that decision-makers are capable of having complete knowledge of relevant information, perfect anticipation of future consequences, and the cognitive capacity and time available to do so. In reality, none of these assumptions are sufficiently met (Sterman 2000).

Integrating game theory components (modules) into a product design and manufacturing expert system is essential. Behavior and choices are difficult to address because people might not always behave rationally. Irrational behavior may follow from a failure to update an action from new information that becomes available; acting on perception(s) that are in fact false; acting on personal agendas; and poor understanding of interdependencies between events (Meyer and Booker 2001).

In manufacturing engineering, game theory has been used in many areas. It was used to establish cooperative alliances and competitive strategies in small manufacturing firms (Golden and Dollinger 1993). Further, game theory was used to design hybrid controllers for complex systems, which are ideally suited for a multi-agent setting (Lygeros et al. 1996). These and other recent examples provide evidence that game theory, when combined with experts systems and advanced analytics, can revolutionize the product design through end-of-life-cycle model to enhance quality, efficiency, time to market, and customer satisfaction.

BEST ATHLETE

I was recently admonished when I suggested that optimization of the digital thread could be realized by advanced analytics, expert systems, and game theory. The assumption that raised the ire of my colleague was that they would eliminate the human contributors and participants from the thread. Nothing is further from the truth. MLAS was successful because it maximized human resources by giving users performance maximization tools.

The digital thread is assumed to be a tool composed of data related to engineering design attributes. With MLAS it was used as a tool to identify and recruit the best engineers and technicians from a database that contained individuals with their specific skill sets and levels of expertise (skill set maturity). Manufacturing and production personnel were unencumbered by rigid job descriptions. Incentives and training facilitated the growth of a highly capable, multi-skilled workforce enabled for the self-inspection process recognized and approved by the U.S. Department of Defense. The digital thread enabled identification, coordination, and acquisition of not only the "best athletes" from across the United States within the corporation, but also the required equipment from a central database. The best people came from diverse geographic locations to coalesce into a highly effective team, precisely coordinated with the arrival of the necessary tools needed for them to perform their tasks.

Technical integration, road mapping, and resource allocation increases integration across programs. Thus more technology areas are needed as technology advancements and pursuits flourish. Aerospace thrives on being a technology-intensive industry. The tactical advantage will be obtained by the company that is best able to:

1. Forecast/define customer needs,
2. Combine the right mix of creative talent to define potential solutions,
3. Focus the available resources on the highest payoff solutions,
4. Successfully execute the development and experimental trials in a timely manner, and
5. Deliver the proven/mature technology product to the customer.

It is important in this world of electronic communication to remember number two above. Humans make the difference. I have been blessed to have been given advice and mentored by brilliant people, many with advanced degrees in the science, technology, engineering, and mathematics disciplines. But one of the best pieces of advice I ever received was from a yokel who never graduated high school. He told me, "When everything is thought through and done, stand back and see if it smells." This is sound advice. The best gage for measuring the wisdom of a decision after all the computer analysis, advanced analytics, expert systems, and game theory spit out their advice is for the human in the loop to stand back and see if it makes sense.

APPENDIX: ADVANCED ANALYTICS TERMINOLOGY

Artificial neural networks extend regression and clustering methods to non-linear multivariate models.

Canonical correlation analysis finds linear relationships among two sets of variables; it is the generalized (i.e., canonical) version of bivariate correlation.

Canonical (or "constrained") correspondence analysis (CCA) is for summarizing the joint variation in two sets of variables (like redundancy analysis); it is the combination of correspondence analysis and multivariate regression analysis. The underlying model assumes chi-squared dissimilarities among records (cases).

Clustering systems assign objects into groups (called clusters) so that objects (cases) from the same cluster are more similar to each other than objects from different clusters.

Correspondence analysis (CA), or reciprocal averaging, finds (like PCA) a set of synthetic variables that summarize the original set. The underlying model assumes chi-squared dissimilarities among records (cases).

Discriminant analysis (or canonical variate analysis) attempts to establish whether a set of variables can be used to distinguish between two or more groups of cases.

Discriminant function analysis is used to predict a categorical dependent variable (called a *grouping variable*) by one or more continuous or binary independent variables (called *predictor variables*).

Factor analysis is similar to PCA but allows the user to extract a specified number of synthetic variables, fewer than the original set, leaving the remaining unexplained variation as error. The extracted variables are known as *latent variables* or *factors*; each one may be supposed to account for co-variation in a group of observed variables.

Linear discriminant analysis (LDA) computes a linear predictor from two sets of normally distributed data to allow for classification of new observations.

Multidimensional scaling comprises various algorithms to determine a set of synthetic variables that best represent the pairwise distances between records. The original method is principal coordinate analysis (based on principal component analysis).

Multivariate analysis of variance (or multiple analysis of variance) (MANOVA) is a statistical test procedure for comparing the multivariate (population) means of several groups. Unlike univariate ANOVA, it uses the variance-covariance between variables in testing the statistical significance of the mean differences.

Multivariate regression analysis attempts to determine a formula that can describe how elements in a vector of variables respond simultaneously to changes in others. For linear relations, regression analyses are based on forms of the general linear model.

Principal component analysis (PCA) creates a new set of orthogonal variables that contain the same information as the original set. It rotates the axes of variation to give a new set of orthogonal axes ordered so that they summarize decreasing proportions of the variation.

Recursive partitioning creates a decision tree that attempts to correctly classify members of the population based on a dichotomous dependent variable.

Redundancy analysis (RDA) is similar to canonical correlation analysis but allows the user to derive a specified number of synthetic variables from one set of (independent) variables that explain as much variance as possible in another (independent) set. It is a multivariate analogue of regression.

Statistical graphics such as tours, parallel coordinate plots, and scatter-plot matrices can be used to explore multivariate data.

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13

EPILOGUE

"Great deeds are usually wrought at great risk."

—Herodotus

LESSONS

It is natural and right after a dramatic success like the MLAS launch to clap and celebrate, pat each other on the back, and share the deserving accolades and awards derived from hard work successfully executed. The launch of an uninhabited vehicle without gimbals to control thrust vector or the need for any human or computer guidance system's intervention is awe inspiring. It is also intensely nerve-wracking for those who spent months laboring to ensure its success when that moment comes to push the launch button. Any malfunction during the approximately 60 seconds separating launch from splashdown could have meant failure. A motor misfire could have sent the stubby-looking vehicle tumbling into oblivion. The mass property calculations and assembly execution had to be precise so the motor's thrust would lift the vehicle skyward on the predicted trajectory. The parts, pieces, and components had to be assembled precisely so the vehicle would fly unhindered by asymmetric airflow and induced vibration that could cause it to veer off its intended course.

Adding finality to the completion of the MLAS launch and flight was the drama inherent in the ground-shaking, deafening roar of motors exploding to life as the team watched the vehicle rise 7,000 ft (2,134 m) in seven seconds, and then silence. The team watched as it performed the other operations flawlessly and then splashed into the ocean. Cheers erupted. A week later, the highly motivated and geographically diverse teams of skilled engineers and technicians returned to their homerooms, gave out-briefings, and moved on to their next assignments. It is in the DNA of manufacturing that nothing stands still. The ego is brought back to Earth with, "What have you done lately?"

When the MLAS experience came to a close, the teams faced the challenge: Of what use has this experience been? Has it been an accomplishment that will result in recounting the tales, trials, and tribulations of the experience only when surrounded by others who add flavor to the conversation? Have we learned more from this experience about manufacturing than if we had stayed home? Have we derived some illumination of our present condition, guidance in our judgments, or insights into the vicissitudes of change? Did we find some regularity in the experience so that we can predict the future actions of events for similar projects? Or, was it an example of an experience destined to be repeated in that age-old definition of crazy, as a weary rehearsal for mistakes of the future?

It is easy to focus on the successful launch of the MLAS vehicle as the singular defining outcome of the program. After all, its purpose was to demonstrate and to some extent validate a proposed alternative to the Max Faget-invented "tractor" launch escape system (LES). NASA planned for its use on the Orion spacecraft in the event that an Ares I malfunction occurred during launch requiring an immediate abort. The "pad abort" flight test of the MLAS performed at NASA's Wallops Flight Facility on July 8, 2009 at just after 6:25 a.m. met the test goal for successful separation of the mock crew capsule from the abort system.

The MLAS success for NASA also meant that the companies supporting MLAS were successful. They had a highly satisfied customer and their reputation was enhanced. The MLAS experience was a valuable addition to their resumes for inclusion in future bids for contracts and they made money.

Much like other NASA programs and projects, the MLAS launch overshadowed the depth and breadth of technology that emerged from it as viable for expansion out and into a range of other applications. Even during the MLAS design and build phase, the program spawned other projects, such as the composite crew module. Such projects have led to significant advancements and understanding of composite design and manufacturing for products used in space, aerospace, land, and sea.

On the surface, the technologies used to manufacture composite structures for the MLAS vehicle might seem to contain a few core manufacturing values that should be highlighted for attentive evaluation and dissemination. The manufacturing technology for composites was innovative and changed many assumptions about the "absolutes" needed to make robust aerospace parts that conform to design specifications. Producing space-launch-vehicle parts using a shipbuilding facility that had never produced anything but composite ship components is one example. It led to a re-evaluation of what a facility should look like, the skill levels needed, and equipment needed to make space- and aerospace-grade parts. The vacuum-assisted resin transfer molding (VARTM) process to build large parts for an air and space vehicle was also progressive. Digging deeper in this example reveals a higher value than the demonstration of VARTM and its potential as a viable manufacturing-process candidate for space- and aerospace-grade parts. The shipbuilding facility and personnel gained an understanding of the tools, processes, and equipment needed to manufacture better ship parts. The aerospace personnel learned that the VARTM process did not require the fidelity and complexity often resident in the manufacturing processes for space and aerospace vehicle parts. The value of the experience extended to a deeper understanding of processes, which on the surface seem the same, but when applied for different product types, can vary. The realization that an acceptable VARTM process for one product might need to be adjusted for the acceptable transfer of the technology to a different product was a painful lesson.

The fins for MLAS were another example. The use of out-of-autoclave cure (OAC) of autoclave-grade composite materials demonstrated their potential for use in high-quality parts. By extension, the manufacturing innovations surrounding the OAC process added significant advantages. Retractable clean rooms and ovens are two examples that reduced equipment cost, provided for flexible assembly, and demonstrated how minimal footprint manufacturing facilities can expand the manufacturing base. Innovations such as these reduce the barriers to entry for low-cost producers of high-grade, aerospace-quality, GFE composite parts.

EXTENSIBILITY

Another of the MLAS lessons is that the accomplishment of the launch cannot overshadow the greater benefits of the journey. Many of the composite manufacturing technologies, the digital thread, forensic analysis tools, shared resources, rapid prototyping, in-situ manufacture, and innovative assembly techniques have value far beyond the stubby vehicle that had 60 seconds of fame. All of these, in whole or in part, are extensible to a vast network of products that share common material, engineering, and production goals. Many have been identified in this book including wind turbine blades and posts, buses, trucks, lighter-than-air vehicles, ballistic containers, bridge and overpass structures, ships, and even undersea vehicles.

If there are two take-aways from the MLAS experience relative to extensibility, one is that a process like VARTM may have completely divergent applications when used to produce different products. The other is that diversity enhances divergent applications. In example, when aerospace projects are built at ship-building facilities, each product manufacturer learns from the other. Without this type of manufacturing interaction, aerospace companies evolve in the context of their specific knowledge bubble and so do ship builders. When they interact to build products, each derives benefit through exchange of knowledge about how they apply specific processes to their respective products. It was an eye-opening shock when the MLAS aerospace engineers walked into the shipbuilding facility in Mississippi. They assumed that the VARTM process was a universal process, uniformly applied across product types. The experience provided an example of judicious application where the product requirements defined the process controls and limits.

Further, the clash between two different manufacturing cultures at the shipbuilding facility resulted in better manufacturing practices for both. Aerospace engineers and technicians learned that in a rapid prototype environment, many shipbuilding processes are sufficient to meet the design requirements. And shipbuilding engineers and technicians learned about process controls and advanced measurement tools that improved their products.

Appendix

ABBREVIATIONS

A

AE	acoustic emission
AGV	automated guided vehicle
AIS	autonomous information system
AIT	Advanced Integration Technology, Inc., automatic identification technology
AO	atomic oxygen
API	application programming interface
APL-UW	Applied Physics Laboratory, University of Washington
APS	advanced planning system
ATB-1X	advanced technology bus
ATMCS	Advanced Tooling for Manufacture of Composite Structure
ATT-1X	advanced tractor-trailer
ATTB	advanced technology transit bus
AU	astronomical unit, acoustic-ultrasonic

B

BR&T	Boeing Research & Technology

C

CAD	computer-aided design
CAGE	commercial and government entity
CCM	composite crew module
CEV	crew exploration vehicle
CFRP	carbon-fiber-reinforced polymer
CG	center of gravity
CMM	coordinate measuring machine
CNC	computer numerically controlled
CNG	compressed natural gas
CNT	carbon nanotube
CTE	coefficient of thermal expansion

D

DA	determinant assembly
DARPA	Defense Advanced Research Projects Agency
DC	direct current
DMG	drive motor generator
DFMA	design for manufacture and assembly
DoD	Department of Defense
DSM	design structure matrix

E

ECG	electrocardiogram
EEG	electroencephalogram
EMPDL	Engineering, Manufacturing, Production, and Development Lab
EOG	electrooculogram
ERP	enterprise resource management
EVM	earned value management

F

FAA	Federal Aviation Administration
Factory C^3	factory command, communication, and control
FE	forensic engineering
FMEA	failure modes and effects analysis
FRP	fiberglass-reinforced polymer
FSTG	Flammability Standardization Task Group

G

GD&T	geometric dimensioning and tolerancing
GF	glass fiber
GFE	graphite fiber epoxy
GPS	global positioning system
GRE	glass-reinforced epoxy

H

HFLT	handling fixture lifting tool

I

IACG	Inter-agency Consultative Group
IAL	integrated assembly line
IML	inner mold line
INCITS	International Committee for Information Technology Standards
IOC	initial operational capability
IPDT	integrated product design tool
ISHM	integrated structural health monitoring
ISO	International Organization for Standardization
IUID	item unique identifier

J

JIT	just-in-time
JPL	Jet Propulsion Labs

K

kph	kilometer per hour

L

LAS	launch abort system
LCA	life cycle architecture
LCO	life cycle objectives
LEO	low Earth orbit
LES	launch escape system
LH_2	liquid hydrogen
LRI	liquid resin infusion
LRIP	low-rate initial production
LRT	launch, retrieval, and transport

M

MDAO	multidisciplinary design and analysis optimization
MDT	mountain daylight time
MEMS	micro electro-mechanical systems
MES	manufacturing execution system
MIL-STD	military standard
MLAS	Max Launch Abort System
MRL	manufacturing readiness level
MTIM	modular and transportable in-situ manufacture
MURI	Multidisciplinary University Research Initiative
MW	mega watt
MWh	mega watt hour

N

NASA	National Aeronautics and Space Administration
NBC	nuclear, biological, chemical
NC	numeric control
NDI	nondestructive inspection
NEBUS	new electric bus (Daimler Benz)
NESC	NASA Engineering and Safety Center
NGC	Northrop Grumman Corporation
NLAS	new lighter-than-air ship

O

OAC	out-of-autoclave cure
OEM	original equipment manufacturer
OML	outer mold line

P

PAO	polyalphaolefin
PBL	performance-based logistics
PCU	power conditioning unit
PLM	product life cycle management
PMT	portable maintenance terminal
POA	post-optimality analysis
PPM	project portfolio management

R

RAA	responsible, accountable, authority
RF	radio frequency
RFID	radio frequency identification
RFP	request for proposal
RICA	resin-impregnated carbon ablator
ROV	remotely operated vehicle

RTLS	real-time locating system
RTM	resin transfer molding
RUP	rational unified process

S

SCWTB	smart composite wind turbine blade
SEM	scanning electron microscope
SHMS	structural health monitoring system
SMC	sheet molding compound
STS	space transportation system
STEM	short-time-series expression miner

T

TFT	thin film transistor
TMS	thermal management system
TPHS	transportation, packaging, handling, and shipping
TPS	thermal protection system
TRL	technology readiness level
TTP	transition to production

U

UID	unique identification
USV	uninhabited space vehicle
UTL	ultrasonic tape lamination
UV	ultraviolet

V

VARTM	vacuum-assisted resin transfer molding
VCA	volumetric compensation algorithm
VDP	vacuum degas processing
VECA	volumetric error compensation algorithm

VIM	Voyager interstellar mission
VMC	vehicle management computer
VSE	vision for space exploration

X

XML	extensible markup language

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