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Composites Materials and Manufacturing Technologies for Space Applications

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Proceedings of a NASA-sponsored Technical
Interchange Conference held in New Orleans,
Louisiana, May 6–7, 2015.

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CONFERENCE PUBLICATION

COMPOSITES MATERIALS AND MANUFACTURING TECHNOLOGIES FOR SPACE APPLICATIONS

INTRODUCTION

Composites materials offer significant advantages in space applications with projections of weight reduction of 25% to 35% and cost savings of near 50%. Weight reduction is imperative since deep space systems demand significant weight reductions from conventional systems. However, the pathway to deployment of composites alternatives is problematic. Baseline materials and processes are entrenched in existing and emerging designs and new technologies, i.e., composite systems, face the requirement of buying their way into the designs and onto the systems. In many circles, composite materials are considered 'exotic.' This is interesting in light of the fact that the commercial aerospace industry accepts composites as an important strategic advantage for higher performance, improved strength, and lighter structures and propulsion systems.

In light of these opportunities and the challenges, improvements in the materials and processes are needed, and extensive testing is required to validate the performance and qualify the materials and processes and certify the components. Addressing these challenges could lead to the confident adoption of composites in space applications and provide spin-off technical capabilities for both the aerospace and other industries.

To address the issues associated with composites applications in space systems, NASA has sponsored a Technical Interchange entitled "Composites Materials and Manufacturing Technologies for Space Applications." This Conference Publication (CP) summarizes the results of that meeting that was held in New Orleans, Louisiana, May 6–7, 2015. The NASA Space Technology Mission Directorate and the Game Changing Program chartered the meeting. The meeting was hosted by the National Center for Advanced Manufacturing (NCAM)—a public/private partnership between NASA, the State of Louisiana, Louisiana State University, industry and academia—in association with the American Composites Manufacturers Association. The Louisiana Center for Manufacturing Sciences served as the coordinator for the interchange. Approximately 100 people participated in the interchange; participants are listed in appendix A.

The format of this CP recognizes the need to overview materials and to focus on the topics that are most relevant to that reader. A collection of brief synopses of each presentation is tabulated as the executive overview. The individual synopsis for each presentation or session is presented in italics before the more detailed overview of that content.

Day 1

WELCOME AND OPENING REMARKS

The welcoming and opening remarks for this meeting had special significance with the introduction of the National Center for Advanced Manufacturing (NCAM) 3.0. The opportunity was taken to engage the multiple stakeholders who champion both this interchange and NCAM 3.0. Key stakeholders and their messages are summarized below.

John Vickers was the convener and chief organizer for the interchange. John is the Associate Director of the Materials and Processes Laboratory at NASA Marshall Space Flight Center. In addition, he serves as the NASA project manager for NCAM, with operations in Huntsville, Alabama and New Orleans, Louisiana. John's message for the attendees included gratitude for the exceptional response to the meeting, excitement for the future of composites technologies and applications, and anticipation for the great successes that will result from everyone working together under the NCAM 3.0 banner.

Malcolm Wood is the Deputy Chief Operating Officer of NASA's Michoud Assembly Facility (MAF). MAF is NASA's only manufacturing facility, and has a rich legacy in producing systems for NASA's success including the Saturn V first stage booster and the external fuel tanks for the Space Shuttle Orbiter. Mr. Wood described his vision for MAF and NCAM, which includes becoming the national hub for advanced manufacturing research and development (R&D). He emphasized that education and outreach are key imperatives in achieving the vision for MAF.

Dr. Richard Koubek is the Dean of the College of Engineering at Louisiana State University (LSU). (He has since taken leave from that post to serve as Interim Provost for LSU). LSU is assigned by NASA and the State of Louisiana as the executive manager of NCAM 3.0, and, in this role, represents all of the engineering degree granting universities in the state of Louisiana. Dr. Koubek emphasized the following three areas of emphasis for NCAM:

- Exploiting the existing infrastructure, which includes more than $60M in state-of-the-art manufacturing equipment, mostly focused on large-scale structures.
- Research and development in addressing important challenges in materials and manufacturing processes—and including technology maturation to deployment.
- Education and outreach to create and retain good jobs for America.

Dr. Koubek emphasized that NCAM is excited about the gathering of the composites community and strongly desires to collaborate with that community.

Jeff Sheehy is the Senior Technical Officer of the Space Technology Mission Directorate. In this role, he manages an R&D portfolio focused on crosscutting space technologies that support emerging missions. Mr. Sheehy emphasized that his programs depend heavily on partnerships that mature technologies through the Technology Readiness Levels from discovery through mid-stage development efforts and including end-game demonstrations. Specific to the interchange, he highlighted existing research and development investments in composites technology and stated that he looks forward to defining new opportunities for collaboration.

Chris Crumbly is the Manager of the SLS Spacecraft/Payload Integration and Evolution Office. His message was very pointed and clear: composites need to be less about the exotic and more about the familiar. The challenges that are faced in utilizing composites in space applications are, perhaps, more cultural than technical, and the goal is to mature composites technology implementation as 'the norm.' There is a cultural shift in moving from metallics to composites, but the benefits dictate that the transition must be made. The tradeoff is clear: one pound reduction in the total space vehicle weight means one more pound of payload. The transition will not be immediate, and there will not be a large composites presence in the first stage and the early Space Launch System vehicles. However, upper stage and future activities will engage more and more composites. To make the transition to composites, the community must pay specific attention to the acquisition process. The specific language in the Request for Proposals must enable or mandate composite alternatives.

Charlie McBride is the President of the Louisiana Center for Manufacturing Sciences (LCMS). LCMS has been contracted by LSU to serve as the operating manager of NCAM 3.0. LCMS was founded in 1997 and focuses on manufacturing improvements in a range of activities and sectors, among them, space and aerospace, shipbuilding, land vehicles, munitions, and parts replacement. The LCMS team has aided in manufacturing-process improvements for many partners in Louisiana, the Gulf Coast region, and throughout the United States. In the role of operating manager of NCAM 3.0, LCMS will provide strategic direction, lead business development activities, and manage consortia and company-specific project activities. The activities of NCAM 3.0 are already under way. LCMS has won an award from the National Institute of Standards and Technologies Advanced Manufacturing Technology program to create an alliance to be known as the Center for Accelerated Development of Large-Scale Structures (CADLSS). Also, initial NCAM 3.0 R&D projects are being readied for launch before the end of the current fiscal year.

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GOVERNMENT AGENCY COMPOSITES ACTIVITIES

The first session of the interchange was focused on providing a foundational understanding of the national advanced manufacturing activities. It was noted that there are presently five manufacturing innovation institutes operational with others in the contractual phases and more new topics on the horizon. The operating institutes include:

- America Makes, focused on additive manufacturing and funded by the Department of Defense (DoD).
- Digital Manufacturing and Design Innovation, focused on integrated digital design and manufacturing and funded by DoD.
- Lightweight Innovations for Tomorrow, focused on lightweight metals and funded by DoD.
- Power America, focused on wide bandgap semiconductors and funded by the Department of Energy (DOE).
- The Institute of Advanced Composite Manufacturing Innovation (IACMI), focused on advanced fiber-reinforced polymer composites and funded by DOE.

Three other institutes are in the proposal solicitation or review process and seven new topics are anticipated soon. Present planning points to seven new topics that will include two from Agriculture, two from DOE, two from NIST, and one from DoD.

Four speakers addressed specific activities that are sponsored by DoD, DOE, and NASA. They are:

- Jacob Goodwin, Digital Manufacturing and Design Innovation Institute.
- Katie Shirey, Defense Advanced Research Projects Agency (DARPA).
- Steve Gaddis, Game-Changing Development Program (NASA).
- Mark Shuart, Advanced Manufacturing Office, Energy Efficiency and Renewable Energy (DOE).

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Digital Manufacturing and Design Innovation Institute

The mission of Digital Manufacturing and Design Innovation Institute (DMDII) is to significantly reduce development and deployment costs while creating billions of dollars in value for the industrial marketplace—spurring long-term U.S. economic growth and job creation. The work of the institute is underway with the initial roadmaps developed and early project investments being made in Advanced Manufacturing Enterprise, Intelligent Machining, and Advanced Analysis.

Jacob Goodwin is the Director of Membership Engagement and Communications for DMDII. Mr. Goodwin started his presentation by highlighting the decline in manufacturing employment and of the position of the U.S. in the global economy and the production of durable goods. He stated that the realization of the importance of preserving and strengthening our manufacturing base is the driver for the creation of the manufacturing innovation institutes. He highlighted the fact that significant investments are made in research and development (R&D), but that these developments struggle in maturation to deployment. This disconnect has been labeled 'the missing middle,' and the institutes are formed to and charged with mitigating and eliminating the disconnect.

The presentation quickly moved from a statement of the overall status of U.S. manufacturing to the specific activities of DMDII. The mission of DMDII is to significantly reduce development and deployment costs while creating billions of dollars in value for the industrial marketplace—spurring long-term U.S. economic growth and job creation. The major institute focus is digital manufacturing. Digital manufacturing is the application of computing and data analytics to improve manufacturing across the entire product life cycle, and the result is in bringing products to market at lower costs and with improved quality and performance. To achieve this improvement, the institute is focused on four goals:

- Foster and enable **collaborative investment** in precompetitive R&D for digital manufacturing technology.
- Facilitate the transition and insertion of **digital manufacturing technology** into the U.S. industrial manufacturing base (large and small).
- Assemble and integrate **workforce development initiatives** to prepare the future manufacturing work force for digital manufacturing technology.
- Establish an **online commons** for manufacturers to use as a marketplace, learn about digital manufacturing, exchange detailed product design information, access the latest innovative digital capabilities, and collaborate on design development—all on a secure, neutral, and IP-safe environment.

DMDII is off and running, and is making early investments in a project portfolio which includes:

- Advanced Manufacturing Enterprise.
- Intelligent Machining.
- Advanced Analysis.

DARPA Composites Activities

DARPA has two active programs that address composites activities and another is planned. Open Manufacturing seeks to validate and mature emerging technologies. Specifically for composites, the Transition Reliable Unitized Structure (TRUST) project seeks to develop the manufacturing process control necessary for certification of unitized bonded composite primary structures. The Materials Development for Platforms (MDP) is addressing the lengthy applied materials and process (M&P) development process, which often takes more than 10 years, with a goal of reducing the development cycle time for fielding a new material by 4X. DARPA plans to launch a composites program in 2015 focused on lowering the cost of composite parts while still retaining the aerospace rigor and standards compliance.

Katie Shirey represented the DARPA Defense Sciences Office. Her presentation focused first on a broad view of DARPA activities with a rapid transition to composites related projects.

DARPA's mission is to **create** and **prevent** surprise. DARPA invests in a huge range of technologies. Some notable successes include the internet, stealth technologies, and GPS capability.

There are two existing DARPA programs with significant composites manufacturing content, and other programs are under development. Open Manufacturing started in 2012. Materials Development for Platforms (MDP) was launched in 2014. DARPA plans to launch a composites program focused on lowering the cost of composite parts while still retaining the aerospace rigor and standards compliance.

The Open Manufacturing program is focused on addressing the belief that new manufacturing technologies are often the perception and not the reality. Hence, open manufacturing addresses the evaluation, qualification, and improvement of emerging manufacturing technologies with the intent of preparing them for broad application. Phase 1 of the Open Manufacturing program pursued multiple activities aimed at building confidence in the emerging technologies. Phase 2 will narrow the scope to address composites manufacturing and metallic additive processes. For composites, the TRUST project seeks to develop the manufacturing process control necessary for certification of unitized bonded composite primary structures without redundant fasteners and to validate and quantify bonded assembly reliability. A system and model has been developed by Lockheed Martin to evaluate and confirm the quality of bonds and structures.

MDP is addressing the lengthy applied materials and process development process, which often takes more than 10 years. The goal of MDP is to reduce the development cycle time for fielding a new material by 4X, enabling the selection and application of better material alternatives—based on systems requirements. Hypersonics applications are the first thrust of MDP.

DARPA plans to launch a composites program focused on lowering the cost of composite parts while still retaining the aerospace rigor and standards compliance. A Request for Information was published in November 2014 entitled *Aerospace Performance at Automotive Efficiency*. The program objective will be the development of materials and techniques to significantly reduce the cost and time to make small composite parts that perform to aerospace standards. Industry day for the launch of this program is planned for the summer of 2015.

New Approaches to Manufacturing Innovation

This presentation highlighted the work of the Department of Energy Advanced Manufacturing Office, overviewed the National Network of Manufacturing Innovation Institutes, and highlighted the new Institute for Advanced Composite Materials Innovation (IACMI). The goals of the IACMI are to achieve a 50% reduction in carbon fiber-reinforced polymer composites, a 75% embodied energy savings, and a 75% avoidance of green house gas while creating new jobs and enhancing the composites production capacity.

Dr. Mark Shuart is the R&D Facilities Program Manager for the Advanced Manufacturing Office (AMO) of DOE. In his presentation, he overviewed the work of the DOE AMO and then zeroed in on the work in Advanced Composite Materials and Structures for Clean Energy Applications with an emphasis on the IACMI.

AMO's focus is to increase U.S. manufacturing competiveness through:

- Industrial efficiency for specific energy intensive industries.
- Manufacturing innovations for advanced energy technologies.
- Broadly applicable industrial efficiency technologies and practices.

To accomplish this mission, AMO addresses three broad topic areas including platform materials and technologies for energy applications, efficiency in manufacturing processes, and emergent topics in manufacturing.

On January 9, 2015, a consortium led by the University of Tennessee was selected to stand up and operate the IACMI. The structure of IACMI includes a partnership between emerging technology centers and applications centers. The emerging technology centers will develop solutions in composite materials and process technologies with an emphasis on innovative design and predictive modeling and simulation. Applications centers will utilize and showcase the emerging technologies. The applications centers include vehicles, wind turbines, and compressed gas storage. The 122-member IACMI consortium includes the leaders in all aspects of composite development and application. The five-year goals are:

- 50% reduction in carbon fiber-reinforced polymer composites.
- 75% embodied energy savings.
- 75% avoidance of green house gas.
- The creation of new jobs and enhanced composites production capacity.

The guiding objective of IACMI is to promote a national effort to move composites technology forward by engaging partnerships through IACMI.

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NASA COMPOSITES ACTIVITIES

NASA has been involved in composites research since the late 1960s. In the mid-to-late 1990s, significant effort was focused on the development of composite cryotanks for fuel storage and launch systems. These efforts have continued at various levels and in support of various programs. The Space Launch System (SLS) provides new impetus for the development of lighter weight tank systems and other components. The initial SLS configuration will provide a thrust of 70 metric tons and the system will be extended in later versions to 130 metric tons. The initial configuration will not include significant composites components, but there is a strong opportunity to 'buying' proven solutions that provide vital weight and cost reductions—extending the payload of the vehicle. Figure 1 illustrates the initial configuration and the migration to the envisioned functionality.

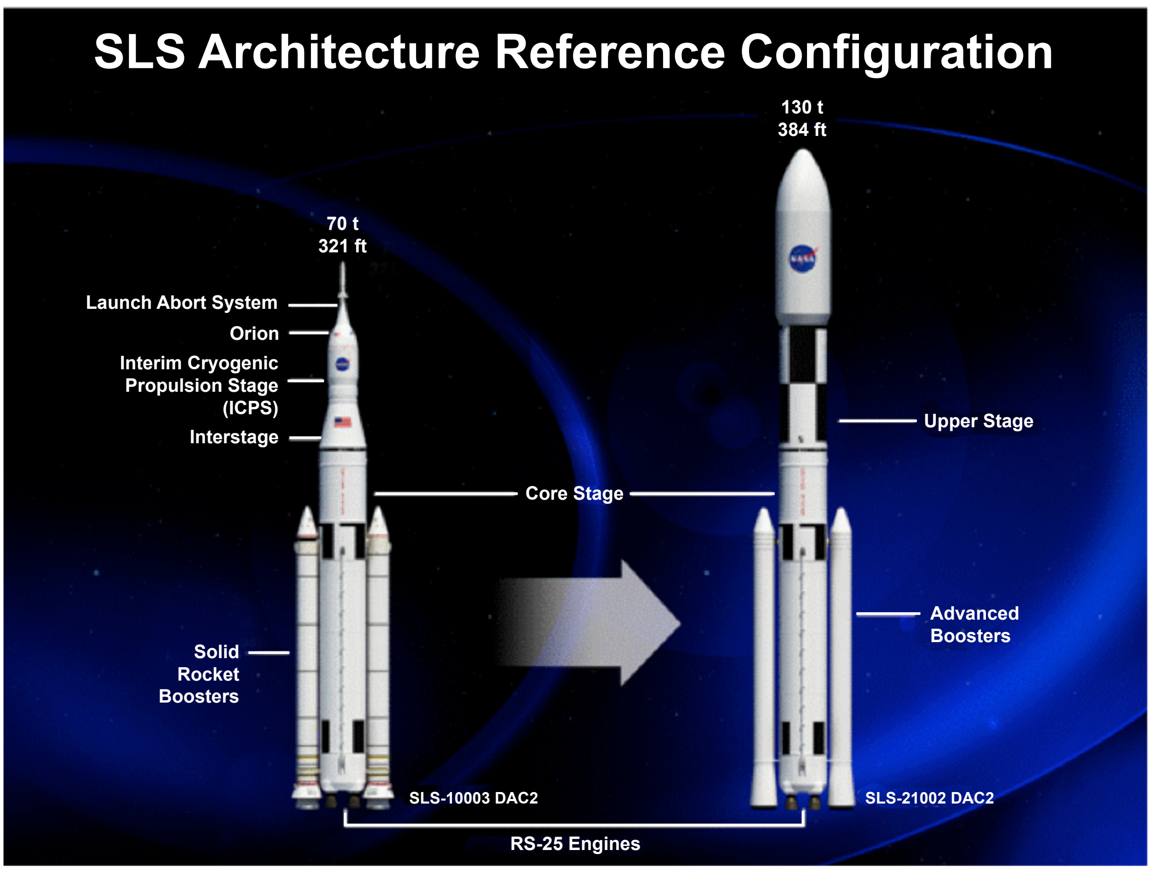

Figure 1. The NASA SLS will provide the boost needed for deep space exploration and will migrate from an initial 70 metric ton version to 130 metric tons of thrust.

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NASA Automated Fiber Placement Capabilities: Similar System Complementary Purposes

In support of the Space Launch System (SLS), the Composite Cryotank Technology Development (CCTD) project objective was to design, build, and test large prototype cryotanks for use in future launch vehicles. Two composite tanks, one 2.4 meters and one 5.5 meters in diameter, were built using automated fiber placement (AFP) and were tested at NASA Marshall Space Flight Center (MSFC) in 2014. Both NASA Langley Research Center (LaRC) and MSFC have installed or are now installing new robotic ATP systems. Both systems have working envelopes of approximately 12 ft by 12 ft by 33 ft.

Dr. Chauncey Wu is an engineer in the Structural Mechanics and Concepts Branch at LaRC. Dr. Wu's presentation addressed the drivers for using composites, automated fiber placement, the Composite Cryotank Technology Development (CCTD) project, LaRC and MSFC composites manufacturing capabilities, and Composites for the Exploration Upper Stage (C-EUS) project.

Composites development supports NASA missions and improves the Nation's manufacturing capabilities. Composites are identified in the NASA Space Technology roadmap under Technology Area 12 as an important enabler for NASA's future success. The development of the needed composites capabilities, and the validation/qualification of those capabilities, provides a strong opportunity for collaborative research between industry, NASA, and the broader research communities.

AFP systems have been in use since the 1980s. They enable fast, precise, and accurate lamination of tooling, following preprogrammed paths. The emerging robotic mobility platforms are game changers, reducing the cost of entry by at least a factor of 2.

The CCTD project objective was to design, build, and test large prototype cryotanks for use in future launch vehicles. Two composite tanks, one 2.4-meter diameter and one 5.5-meter diameter, were built using AFP and were tested at MSFC in 2014.

Both LaRC and MSFC have installed or are now installing new robotic ATP systems. The systems are similar with working envelopes of approximately 12 ft by 12 ft by 33 ft. The distinctive difference is that the LaRC system has a vertical rotator and the MSFC rotator is horizontal. Both systems support the use of tool changers with multiple end effectors, enabling the use of the systems for multiple manufacturing processes, including machining.

The C-EUS project objective is to design, build, and test prototype composite skirts for a future SLS upgrade. LaRC will build flat and curved panels for evaluation of structural joints. MSFC will build large curved panels for evaluation of full-scale structural test articles.

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Composites Community of Practice

To support communication and collaboration across the space community, a Composites Community of Practice (COP) has been established. The community is much more than a communications forum in that it is prioritizing common challenges and addressing those challenges. The first thrust of the COP is the management of, and shared access to, composites metadata. The COP has grown to over 200 participants and is now preparing a document that highlights key challenges for the composites community. The COP will use this priority listing to establish future priorities and define targets of opportunity.

David Lowry is employed at the Johnson Space Center in the Structures Branch and leads the Composites Community of Practice.

In evaluating the future direction for composites development, NASA determined that a systematic assessment of gaps and overlaps, and a collaborative effort to assure that the best solutions are provided, was essential for efficient investment. A recommendation was made that a COP be established. The composites COP is chartered to define and address some of the most compelling issues in composites design and manufacturing. One of the compelling needs that immediately rose to the top was access to the right data. Hence, the first activities are focused on the management of, including shared access to, needed composites metadata. This activity is being undertaken in concert with the Wichita State University National Center for Aviation Research (NCAMP) database. The first database being established manages Nondestructive Evaluation (NDE) data. 80% of the schema and structure of that database is complete. Databases are being developed to enable multivariable scans that can identify uncertainties and support the process of defining allowables for adapting processes and extending to new processes. A composite structures damage database is in early development. The goal is that contractors will never send data (that can be publicly shared) to NASA again, but will put it into the database.

A major challenge in a collaborative environment is the proper classification and protection of data. The goal is to assure that needed data are available to all who both need it and have a right to access it. The COP is setting up databases that can be used to properly share ITAR data within NASA and protect that data from other release. As data is declassified, it will be systematically released to NCAMP for contractor access, and, eventually and as is appropriate, shared with the contractors.

The COP has grown to over 200 participants. Beyond the first thrust of shared data access, shared access to software and models is being addressed. A roadmap council has been established to define the R&D priorities for potential investments in composites. The R&D priorities document will be forthcoming within a few months.

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Advanced Composites Project

The goal of the Advanced Composites Project (ACP) is to reduce the timeline for development and certification of innovative composite materials and structures, thereby helping American industry retain its global competitive advantage in aircraft/aerospace manufacturing. An Advanced Composites Consortium (ACC) began operation in January 2015. The purpose of the consortium is to foster collaborative R&D related to composites technologies with multiple partner teams. The government agencies have joined together with industry to produce a national plan to guide interagency aerospace activities related to assured airworthiness. The goal of the coordinated effort is to conduct a technology gap assessment to guide national R&D efforts aimed at structural certification and continued airworthiness.

Dr. Rick Young is the Project Manager for the ACP and works at the NASA Langley Research Center. The ACP is focused on reducing the timeline for development and certification of innovative composite materials and structures, which will help American industry retain their global competitive advantage in aircraft/aerospace manufacturing. In pursuit of this goal, the ACP is addressing three technical challenges:

- Predictive Capabilities intends to accelerate development by developing analysis methods that can replace or significantly reduce physical testing. In addition, improved preliminary design tools will provide for fewer redesigns.
- Rapid Inspection will focus on improving inspection capability for quantitative and automated characterization of defects.
- Enhanced Fabrication will develop fabrication and process models to cut manufacturing development time and improve quality control.

If these three technical challenges were addressed individually, there would be some benefit. However, if all three challenges are addresses as an integrated system, then it becomes possible to couple design, manufacturing, and inspection for optimum combinations of structural design parameters, fabrication parameters, and inspection techniques. The result will be minimized/optimized time to market, while achieving the required system performance.

ACP is a two-phase, $120 M project with a timeline from FY 2013 through FY 2018, with the activities in 2019 and beyond to be determined. Phase 1 is underway and is addressing the capture of baseline capability, definition of technical requirements, characterization of the state of practice, and small-scale testing. The results of the Phase 1 activities are feeding the development of the Phase 2 plan. Phase 2 will begin in FY 2017 and will include integration testing, subcomponent/component fabrication, evaluation, and standards and guidance development.

An ACC began operation in January 2015. The purpose of the consortium is to foster collaborative R&D related to composites technologies with multiple partner teams. The projects will be cost shared with a 50/50 match requirement. The founding members include NASA and the FAA from the government and industry partners including Boeing, GE Aviation, Lockheed Martin, United Technologies Corp., and the National Institute of Aerospace (NIA). The NIA has been selected as the consortium integrator.

The government agencies have joined together with industry to produce a national plan to guide interagency aerospace activities related to assured airworthiness. The goal of the coordinated effort is to conduct a technology gap assessment to guide national R&D efforts aimed at structural certification and continued airworthiness. The steering committee membership includes the Air Force, Army, Navy, NASA, FAA, and DARPA. OEM certification representatives include Bell Textron, Boeing, Lockheed Martin, Northrop Grumman, and Sikorsky.

Shell Buckling Knockdown Factor Project Overview and Status

Structural designs must provide an envelope of protection against the possibility of cylindrical shapes buckling under load. Historically, analytical systems have not reliably predicted buckling. Hence, very conservative designs have resulted, adding weight and cost that could be removed if the uncertainties were mitigated. The Shell Buckling Knockdown Factor (SBKF) project has the goal of improving the predictive capabilities and qualifying the modeling systems through extensive testing. By producing and testing seven 8-ft-diameter tanks and two 27-ft-diameter tanks and integrating the analytical and empirical capabilities, improved systems have been qualified, enabling tighter design allowables and significant cost reductions. The work to date has been with metallic tanks, but the project is moving forward to replicate the work for composite structures.

Dr. Mark Hilburger is the SBKF project lead and is employed at the NASA Langley Research Center. The SBKF project has as its objective the development and validation of new analysis-based shell buckling knockdown factors (KDFs) and design guidelines for launch vehicle structures.

Buckling under compressive load, and the design for operation within an envelope of safety, is a critical factor in the design of all cylindrical structures. Significant analysis has been done in an attempt to better understand buckling, and most of the evaluation has revealed considerable scatter in the data. Typically, the empirical data indicates buckling at lesser loads than theoretical predictions. Recent testing has demonstrated that these differences can be explained by geometric imperfections, i.e., out-of-roundness. Because of the uncertainty in the data, standard design practice includes the application of a design KDF to the theoretical predictions. The KDF represents the lower bounds of the design recommendation and the larger the deviation and uncertainty, the higher the system weight and cost. Shell buckling is the primary driver in many recent launch vehicle designs, and conservative design factors have the potential to result in overweight structural designs. The expected outcome of the SBKF project is reduced structural mass and mass-growth potential, enablement of new structural configurations, and increased KDF fidelity to improve design trades and reduce design cycle time/redesigns.

The SBKF project has been active since 2007 with the major focus to date being on metallic structures. In 2015, composite structures were added to the project scope. To date, seven of nine targeted subscale (8-ft-diameter) launch vehicle cylinders and two of two full-scale (27-ft-diameter) launch vehicle cylinders have been evaluated and analyzed. The tests and analysis results correlate well with the predictive models, validating the fact that high-fidelity analysis methods can be used to reliably derive design factors. These results have enabled the use of the KDFs in the design of the Block 1 SLS core stage. The resulting designs showed a mass savings of 2000 to 3000 pounds in the SLS core stage tanks, reduced materials costs by $300 K to $400 K per launch, and reductions in design cycle time. Cumulative savings of $5.45 M per launch were documented.

The work to date has been with metallic tanks. The composites activity is underway and lessons will be learned from the experience to date. The evaluation and analysis is expected to mirror the metallic effort. Trade studies have been conducted to identify the design space. Preliminary test planning is in process with the likely focus on 2.5 M to 4 M cylinders. Initial studies show that a 7% to 15 % weight savings is reasonable. These early studies also point to potential new designs with even more dramatic weight savings potential. Partnerships are being established to support a collaborative project.

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Space Launch System Technology Insertion Approach

NASA's SLS is an advanced launch vehicle designed to support a new era of space exploration—into deep space. An evolvable architecture allows NASA to provide the Nation with what will be the world's most powerful rocket. In support of this critical national mission, NASA is launching a portfolio of technology development tasks that include NASA internal activities, academic tasks for universities, and tasks for industry. The initial projects are underway and additional projects are forthcoming.

Dr. Fred Bickley is the SLS Chief Technologist and the Advanced Development Group Lead for the Spacecraft/Payload Integration and Evolution Office. NASA's SLS is an advanced launch vehicle designed to support a new era of space exploration—into deep space. An evolvable architecture allows NASA to provide the Nation with, what will be the world's most powerful rocket. Figure 2 shows the SLS evolution and highlights the benefits that will be delivered throughout the development process. The first version of SLS will lift a payload of 70 metric ton (77 tons) into low Earth orbit. A future version will lift a payload of 130 metric tons (143 tons), enabling deep space exploration. The achievement of the extreme goals of the SLS will require the development more powerful configurations with new cutting-edge technologies. The NASA Advanced Development Group is developing a portfolio of technology development tasks that include NASA internal activities, academic tasks for universities, and tasks for industry. In addition, cooperative activities for Advanced Booster Engineering Demonstration and Risk Reduction Tasks (ABEDRR) are included. Details of the individual tasks can be found at www.ntrs.nasa.gov.

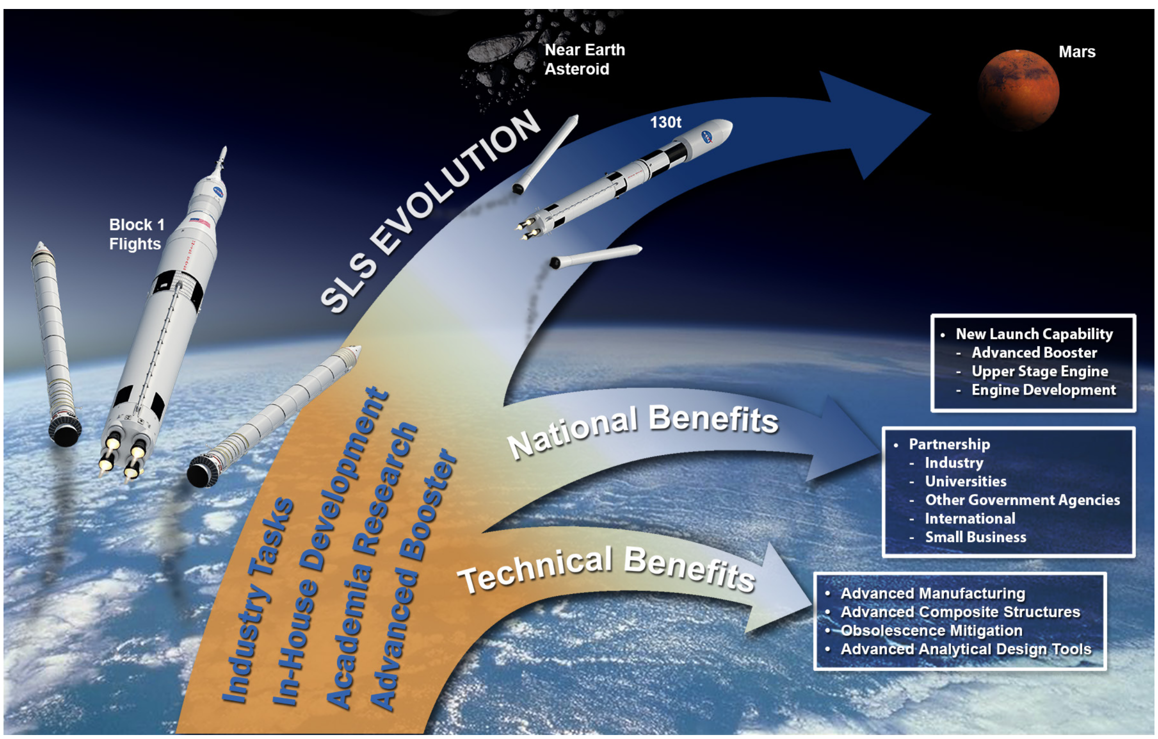

Figure 2. The SLS development will follow an evolutionary plan from the ability to lift a 70 metric ton payload into low Earth orbit to deep space capability with 130 metric tons of lift. As with earlier NASA programs, the Nation will receive significant benefits from the technologies that are developed in support of SLS.

Questions and Answers for the NASA Composites Activities Panel

Key points from the panel discussion:

- *NASA is working closely with the manufacturing innovation institutes and specifically with IACMI.*
- *The community of practice is committed to sharing data through the National Center for Advanced Materials Performance (NCAMP) at Wichita State University when it is appropriate to share that data. ITAR or other protected data will be managed appropriately.*
- *The present strategy of the national composites activities is to develop a roadmap to define what is being done by whom, and to define the critical voids. The end result will be improved communication and collaboration.*

Question: What is the business case for fiber placement machines versus hand placement?
Answer: They certainly are faster and more efficient. A main driver includes advancing state-of-the-art capability. To evaluate the performance, it is necessary to have the best high-level capability. The equipment also enables development, testing, and evaluation with the same equipment that is used in high-end applications in industry which supports the comparison and relevance of experience.

Question: What is the relationship between NASA's needs in composites and the emerging national activities, including the DOE/Oak Ridge manufacturing innovation center?
Answer: There is a desire and a commitment by all parties to collaborate in all appropriate shared activities that address both the general capabilities that can be applied for NASA solutions and in supporting specific activities that address NASA needs. Specific to the institute, *there are discussions underway with the institute about specific projects that will address NASA needs.* The early emphasis on automotive at the institute is driven by the fact that aerospace composites tend toward very high performance and very high costs. The national focus with the broadest impact is expected to come from lower cost composites in automotive and other sectors. Meetings like this one highlight the specific needs and the opportunities for collaboration within the institute and elsewhere.

Question: What data are available from the NASA composites community of practice?
Answer: There are two kinds of data to be considered: data that can be pubicly available and ITAR and other controlled data. Data that are developed through the COP that can be made pubicly available will be submitted to the National Center for Advanced Materials Performance (NCAMP) at Wichita State University for use in qualification activities and for sharing with the membership. Data that are initially ITAR protected but are declassified will be made available if and when it is appropriate to do so. Other data will receive the level of management and control that is appropriate. The data will be made available to the extent that is in the best interest of the Nation.

Question: What are the goal and the scope of the national composites activity that was discussed in the context of the Advanced Composites Project?
Answer: The present strategy is to develop a roadmap to define who is doing what, and to define the critical voids. A gap analysis is now being conducted. It is anticipated that the definition and prioritization of needs and solution paths will be forthcoming. It is noted that the national plan is mostly about airworthiness and certification (not specifically focused on composites manufacturing challenges).

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BOEING COMPOSITES TANK PROJECT

This session highlighted the Composite Cryotank Technologies and Demonstration (CCTD) project with a series of presentations from project overview to more detailed discussions of the design allowables, fabrication strategies and results, and testing and evaluation.

Composite Cryotank Technologies and Demonstration Project Overview

The goal of the Composite Cryotank Technologies and Demonstration (CCTD) project is to provide new and innovative cryotank technologies that enable human space exploration to destinations beyond low Earth orbit such as the Moon, near-Earth asteroids, and Mars. The more specific goal is to mature technologies in preparation for potential system level flight demonstrations through significant ground-based testing and/or laboratory experimentation. Using a 5.5-meter-diameter composite hydrogen fuel tank as the product platform, the project seeks to demonstrate a 20% to 25% weight savings and a 20% to 25% cost savings. Significant achievements to date include the demonstration of prepreg materials in out-of-autoclave (OOA) processing, application of a large-scale, spherical segmented tool that enables a lightweight, one-piece shell, the successful production and nondestructive inspection (NDI) of a large-scale graphite/epoxy fluted core sandwich structure, all composite bolted cover joints, the application of a hybrid laminate with thin plies prevented microcracking, and reduced permeation levels.

John Fikes is the cryogenic tank deputy project manager at NASA Marshall Space Flight Center. The fundamental goal of this project is to provide new and innovative cryotank technologies that enable human space exploration to destinations beyond low Earth orbit such as the Moon, near-Earth asteroids, and Mars. The more specific goal is to mature technologies in preparation for potential system level flight demonstrations through significant ground-based testing and/or laboratory experimentation. The project approach includes materials, structures, and manufacturing issues related to composite cryotank fabrication and application, including OOA. Using a 5.5-meter-diameter composite hydrogen fuel tank as the product platform, the project seeks to demonstrate 20% to 25% weight and cost savings. Figure 3 highlights the various features of the 5.5-meter tank and the technologies that are being developed/matured to address the demanding requirements for cryotanks performance.

CCTD adopted a building block approach that included the use of a 2.4-meter precursor tank. Technologies and capabilities were demonstrated and evaluated using the smaller tank and were systematically matured for application in the 5.5-meter activity. Some of the major accomplishments included:

- The use of 5320-1/1M7 prepreg composite materials for OOA curing.
- The application, and successful extraction, of a large-scale, spherical segmented tool that enables a lightweight, one-piece shell.
- The successful production and NDI of a large-scale graphite/epoxy fluted core sandwich structure.
- All-composite bolted cover joints.
- Hybrid laminate with thin plies prevented microcracking and reduced permeation levels.

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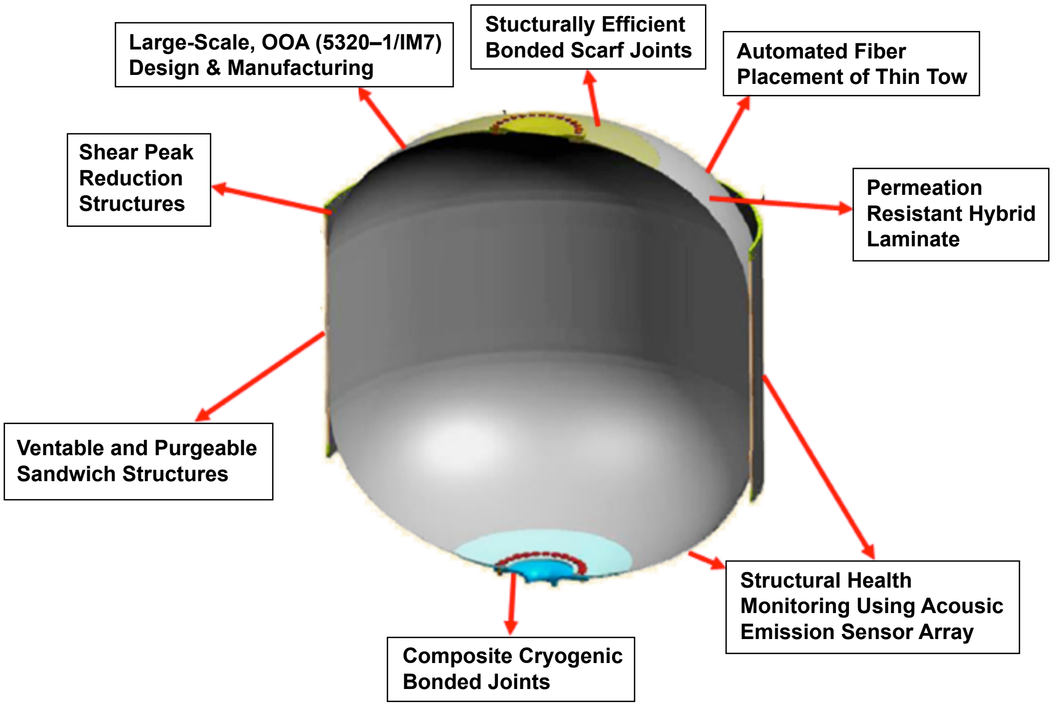

Figure 3. The 5.5-meter tank addressed the critical components and joints for a successful cryotank for space applications. Technologies were matured through a building block approach.

The evaluation data validated that the tank design used in this study meets both upper state and booster stage permeability requirements, but does not meet the CCTD goals that support future applications. Testing with autoclave coupons and the same materials did not show measurable permeability, and several recommendations were made for improvement in future designs. The project demonstrated a weight savings of 33% and successfully addressed the barriers that had been previously identified for liquid hydrogen tanks.

Design and Allowables—Design of Lightweight Impermeable Composite Cryotanks for Space Applications

This presentation highlighted the projected benefits and the state of the art in thin-ply composite structures. Over several applications, the weight savings that are realized in replacing metallic tanks with composite alternatives are consistent in the range of 33% to 45 %. Emerging design alternatives point to potentially even greater advantages. The weight savings trade directly to increases in payload, which translates to cost savings in hundreds of millions of dollars. Thin-ply structures offer many advantages in composite tank manufacture including resistance to microcracking. On the other hand, they are more difficult to manufacture. The manufacturing problems are being addressed in the exploration of the use of automated placement equipment. Hybrid structures are also being evaluated—showing similar performance to the thin plies. This presentation presents a very positive evaluation of the state of composite tank development stating that the permeation problem has been solved, critical design features are well understood, and liquid oxygen compatibility has been established.

Mike Robinson is an Associate Technical Fellow in the Boeing Research and Technology organization at Huntington Beach, California. His presentation contained detailed data regarding the performance of composite cryotanks—some of which are not available for public release. Therefore, only generic assertions from the presentation are included in this summary.

Success in cryotanks is opening the door to many potential applications. In multiple applications, the weight savings are consistent from 33% to 43 % with projections that indicate even better potential. The dollar savings per launch range from a few million to tens of millions of dollars. Due to the tradeoff between vehicle weight and payload, composite tanks mean heavier payloads or fewer vehicles or both. Saving one vehicle launch, while delivering the same payload, saves hundreds of millions of dollars.

Thin-ply composite structures offer many advantages in composite tank manufacture. They are far more resistant to formation of microcracks. Also, tougher resins have been developed that offer protection against microcracking (may be used in conjunction with the thin plies). The downside of the thin plies is that they make manufacturing more difficult. Present development efforts are exploring the use of fiber placement equipment to place the thin plies. Hybrid laminates are demonstrating the same performance as the thin plies. Excellent permeability results are achieved by both methods.

One of the major choices in cryotank production is whether to use one-piece or two-piece tooling. One-piece tooling requires a larger polar opening and is more expensive. Two-piece tooling is heavier, riskier, and requires complex joining solutions. There is strong evidence that the investment in one-piece tooling is money well spent. In conclusion, Mr. Robinson stated that:

- The permeation problem has been solved.
- Critical design features are well understood.
- Liquid oxygen compatibility has been established.

Manufacturing Overview of a 5.5-Meter Composite Cryotank

A major goal of the composite tank program was to move the critical emerging technologies and capabilities from a feasibility Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) of 2–4 to a demonstrated and piloted capability of 5–6. A 2.4-meter tank was used as a development platform for technology maturation to a 5.5-meter tank. The 5.5-meter tank went through a complete manufacturing flow and testing with delivery of a fully evaluated tank to MSFC. All targeted critical technologies were moved to the TRL 5–6 zone. Out-of-autoclave (OOA) production for space capable cryotanks was proven as viable.

Carlos Guzman is a Manufacturing Research and Development Engineer with Boeing's Research and Technology Division. A major goal of the composite tank program was to move the critical emerging technologies and capabilities from a feasibility TRL and MRL of 2–4 to a demonstrated and piloted capability of 5–6. Some of the foundational requirements for the project included:

- The use of robotic AFP.
- Multipiece breakdown tool for one-piece tank.
- Structurally efficient co-bonded and hot-bonded joints.
- Delivery of the tank in 13 months.

All of the work in the fabrication of the tank was done at the Boeing facilities in Seattle, and the development ranged from coupon production and evaluation to full-scale joint testing. The production of a 2.4-meter tank as a precursor to the 5.5-meter tank provided an opportunity to work through all of the manufacturing processes to prepare for the 5.5-meter tank. In the flow from the 2.4- to the 5.5-meter tank, the following capabilities were evaluated and matured for full application on the larger tank:

- Skirt tooling installation.
- Breakdown tank tooling.
- Thin-ply steering and OOA material.
- Softened strip installation (at joints).
- Composite sump to tank using furan steel.
- Large-scale OOA co-bond and hot bonds.
- Structural health monitoring during fabrication.

The 5.5-meter tanks went through a complete manufacturing flow and testing with delivery of a fully evaluated tank to MSFC. Sixteen major tooling systems were used in layup, cure, and transport. Acoustic emission sensors were used throughout the process to determine any impacts of potential damage to the tank. Battery-operated AE sensors were used in all transport. Approximately 80% of the composites, by weight, were laid up using a Boeing-developed, customized robotic FPM, enabling a smaller polar opening and full use of available fiber angles in design. The finger rings for end fitting weighed as much as the total tank. The installation of the rings had to be done with great care to avoid damage to the tank. The shipping fixture was perhaps the most complex challenge in the project.

In conclusion, all targeted critical technologies were moved to the TRL 5–6 zone. OOA production for space capable cryotanks was proven as viable.

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Composite Cryotank Technologies and Demonstration Testing Overview

This presentation focused on the testing procedures and the results for the 5.5-meter cryotank. 135 psi was achieved with the tank filled with liquid hydrogen. The test protocol included 83 pressure cycles, 2 thermal cycles, 2 maximum pressure cases, and 1 combined load cycle. Load/strain response, thermal response, laminate permeation rate, and bolted joint performance data were acquired. The measurements revealed that the tank meets upper stage and booster stage allowables, but the permeability exceeds the Composite Cryotank Technologies and Demonstration (CCTD) lunar lander-based requirement. Based on the results of this evaluation, it is evident that, to reduce porosity, and eliminate permeability for out of autoclave (OOA), it is necessary to increase the number of thin plies and to reduce porosity by improving the OOA materials architecture and fiber placement processes.

Justin Jackson is a Project Engineer for the NASA Composite Cryotank Technology Demonstration Project. His presentation focused on the testing procedures and the results for the 5.5-meter cryotank. In summary, 135 psi was achieved with the tank filled with liquid hydrogen. The tank was subjected to 20 pressurization/depressurization cycles from 20 psi to 100 psi, and permeation measurements were conducted with multiple test conditions. The test protocol included 83 pressure cycles, two thermal cycles, two maximum pressure cases, and one combined load cycle. From these test procedures, load/strain response, thermal response, laminate permeation rate, and bolted joint performance data were acquired. Figure 4 depicts the installation of the test article, and the results of the testing are presented in Table 1.

The evaluation of the permeability confirmed—what is known—that accurate measurement in large-scale industrial environments is difficult. The tests confirmed that there is still work to be done in producing out-of-autoclave tanks that meet the stringent permeability requirements that are projected for future space missions. The measurements revealed that the tank meets upper stage and booster stage allowables, but the permeability exceeds the CCTD lunar lander-based requirement. For further evaluation, hybrid laminates fiber-placed panels were produced at Boeing and evaluated at MSFC. The laminates were made up of 12 plies of 5.4 mil and 5 plies of 2.5 mil material. The OOA laminates exhibited approximately 4% porosity. No porosity was evident in the autoclave-cured laminates. Evaluation of the OOA laminates revealed that microcracks formed in the thin plies, primarily due to the porosity in the laminate. To reduce porosity, and eliminate permeability for OOA, it is necessary to increase the number of thin plies and to reduce porosity by improving the OOA materials architecture and fiber placement processes.

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Figure 4. A ground test program was conducted for the 5.5-meter tank that included measurement of ambient pressure; cryogenic pressure; ambient pressure plus mechanical loads; and cryogenic cyclic pressure. Eighty-three pressure cycles were executed.

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Table 1. Testing results for the 5.5-meter tank.

Testing Summary	Date	Type	Details
Ambient pressure test (nitrogen) was successfully conducted	5/22/2014	Ambient (nitrogen)	Achieved target pressure and reached 80% of target strain
Liquid hydrogen cryogenic pressure test was successfully conducted	7/20/2014	Cryogenic (liquid hydrogen)	Achieved pressure and 100% of strain in the forward dome acreage (permeation samples taken)
Combined ambient pressure (nitrogen) and load test was successfully conducted	7/30/2014	Ambient (nitrogen)	Achieved 100% desired pressure with 100% load on the tank
Liquid hydrogen combined cryogenic pressure and load test was performed	8/16/2014	Cryogenic (liquid hydrogen)	The test was prematurely stopped at 20% mechanical loads due to mechanical issues with applying the loads in the test facility (permeation samples taken)
Liquid hydrogen cryogenic pressure cycle test was successfully conducted	8/17/2014	Cryogenic (liquid hydrogen)	Achieved our goal of 80 pressure cycles (20% to 90% max pressure) on the tank (permeation samples taken)
Permeation with gaseous hydrogen test was conducted	8/22/2014	Ambient (gaseous hydrogen)	Achieved desired pressure. Issues with a leak in facility piping and a leak in the bag prevented any useful permeation data
Permeation with gaseous hydrogen test was conducted	8/28/2014	Ambient (gaseous hydrogen)	Achieved desired pressure; obtained permeation data

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COMPOSITES AND COMPOSITE TANK DEVELOPMENT IN THE AEROSPACE SECTOR

The next session in the interchange was an industry panel moderated by John Vickers. The motivation for the discussion was for NASA and other participants to hear from the industry experts who understand both the commercial aerospace environment and the space environment. Two important points were stressed in the discussion including the readiness of composite technologies/ capabilities for space application and the key needs for additional research and development.

Questions and Answers for the Industry Panel

Key points from the panel discussion:

- Composites are routinely used in many commercial and defense aerospace applications.
- There are relevant and mature standards and procedures that can be utilized for space applications.
- Because of the size of the space components, NASA has the compelling demand for, and the lead in developing OOA capability for low permeability.
- Dramatic improvements are being made in the processes for producing composite structures resulting in cost and weight reductions. Weight reductions in components of 75% to 81% are being demonstrated with 25% total system weight reduction.
- Thin-ply lamination have produced 16 time improvements in leak elimination.
- Commercial aerospace sees the goal of 'aerospace structures by automotive methods' as the mantra for composites development.
- Bonded structures (instead of rivets) are seen as the future joining method, but there is risk and uncertainty at the present level of maturity. Further development is required.
- 'Big data' and advanced analysis methods will help lower the level of proof testing required, and the better the processes become (the lower the variability and uncertainty), the more the reliance on proof testing will be reduced—but the panel sees no end to the prudent use of proof testing.
- To achieve rapid qualification, there are two requirements: (1) make composites better and reduce the risk, and (2) develop faster and more effective methods of measurement and evaluation.
- The technologies and systems to produce high quality (composites that meet very demanding requirements) are in place. The challenges are now less technical than cultural.

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Specific Comments From Panel Members

Nicholas Melillo is a Senior Manager in the Boeing Company Research and Technology business unit. He has supported the detailed design of many Boeing projects including the RAH-6 Comanche, V-22 Osprey, F/A 18-E-/F Super Hornet, MD-11, T-45 Goshawk, and the Model 360 Composite Helicopter Demonstration. Mr. Melillo stated that composites have been flying on tactical aircraft since the 1970s. The DoD and FAA have very mature specifications and standards. These documents are compatible with space challenges. While there is much compatibility, there are additional challenges in space applications resulting from the large size, low rate, and the extreme requirements in certain applications (like cryotanks). Because of the size factor, the requirement for autoclave curing is a huge cost driver for NASA. Hence, NASA has the motivation and the lead role in developing advanced OOA systems.

Bobby Biggs is the Manager of Advanced Materials and Structures Development Programs for the Civil Space line of business within Lockheed Martin Corporation. In this role, he is engaged in managing the development of composite systems for:

- High-performance applications (high temp, high loads, low mass).
- Unitized structure configurations (3D preform joints, low cost, multifunctional use).
- Large-scale fabrication and assembly (automation, OOA fabrication, and joining).

Lockheed Martin is engaged with the Air Force Research Laboratory (AFRL) and the Southwest Research Institute in the Future-responsive Access to Space Technologies (FAST) Airframe and Structural Health Monitoring (SHM) Ground Experiment Program (AFGE). FAST AFGE is an AFRL project focused on demonstrating the integration of composite structures technologies for application in future space launch vehicle airframes. In this project, a ground test article is being produced that consists of a linerless, load-bearing, composite cryogenic propellant tank with an integral common bulkhead and integral skirts. Features of the project include AFP of integral structures and 3D woven preform co-bonded joints. All integrated airframe objectives have been met. Additional development will focus on increased mission cycles, damage tolerance, and advanced load testing.

Lockheed Martin is also working on composite integrated structures for the Sierra Nevada Dream Chaser. The developments in this activity include:

- Reduced layup tools from 57 to 6.
- Integrates 208 co-bonded parts.
- Weight savings of 1307 pounds.

Through its engagement in multiple development and demonstration programs, Lockheed Martin has demonstrated weight and cost reductions over traditional mechanical joints through:

- Reducing the weight of components by 75% to 81%.
- Achieving up to 15% to 25% total weight savings for total systems.
- Reducing joint assembly costs by 45% –68%.
- Demonstrating up to 25% labor savings expected for total fabrication and assembly costs.
- Reducing capital investment by eliminating autoclave requirements. Note: Mr. Biggs offers the caution that OOA of still a low TRL activity for space applications.

Tod Palm is the Northrop Grumman Cryogenic Tank Project Leader. Mr. Palm strongly disagrees with the belief, held by many, that composites are 'exotic.' He stated that, "every day we routinely build parts for the F18 and the F35." Development is also underway for an all-composite wing structure for the Triton. Scaled Composites, a Northrop Grumman subsidiary, has been selected to build the largest aircraft ever constructed—a carrier aircraft with a wingspan of 385 feet that will deliver its 10,000 pound-class payloads to optimum launch points. The structures for the Triton will be produced with OOA curing.

The CCTD results are important and informative. After the X-33, Northrop did extensive development in thin-ply composites structures and great progress has been made. Thin-ply lamination has produced 16 times improvements in leak elimination.

William Hooper is the Senior Manager R&D Engineering/Launch & Contract Research and Development Business Development at Orbital ATK. Mr. Hooper has 22 years of experience in solid rocket motors. He was involved in defining the requirements for qualification of composite components for Ares I. The Orbital ATK focus in composites is strongly toward commercial aircraft including stringers and structures. Mr. Hooper emphasized that there are challenges to be addressed in moving forward with composites systems. He encouraged the systematic definition and prioritization of those opportunities with an open view of lessons to be learned from aircraft production. He emphasized that the path forward is all about managing the costs with the expected low rate of production. An open assessment of alternatives with dependence on modeling, testing, and validation for qualification is a new way of thinking for the space industry, and there are many lessons to be learned.

David Powell is the Senior Manager of Manufacturing Engineering at Space Exploration Technologies (SpaceX). In this role, he is responsible for a broad range of polymer- and ceramic-matrix composite materials and processes including larger OOA sandwich structures, bulk and sheet molding, infusion, assembly bonding, and supplier interaction. Mr. Powell sees the goal for aerospace composites development as captured in the statement, "aerospace structures by automotive methods." In the automotive world, BMW has the lead in the development and deployment of composites with lots of emphasis on OOA. The pressures for an increased rate of production and minimum cost are pervasive. SpaceX is moving to bolted structures in producing large polymer matrix composites structures—while pushing the development and maturation of bonded systems. They are ramping up to build larger volumes of large structures very soon.

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Questions for the Industry Panel

Question: Please help us understand the development and acceptance of bonded structures and joints in various applications.

Answers:

Lockheed Martin: It is a huge challenge to go to an all-bonded structure without rivets and bolts. The DoD is probably pushing this technology harder than NASA. With proper testing and evaluation, this is a good direction for space, but the challenge should be fully appreciated.

Northrop: In the DoD, there must be the demonstrated ability to carry a load as well as with an unbonded structure. That sets a high bar for performance and for verification of capability.

SpaceX: Part of the reason that Space X is moving toward bolted structures is the qualification issue—but SpaceX still believes in fully bonded joints.

Orbital ATK: Space launch structures with people onboard presents some additional challenges in learning everything that we need to know about the bonded structures.

Boeing: Proof loading is heavily used in evaluating bonded structures. On the F35, there are metal-to-composites bonded joints. The discipline of validated careful adherence to procedures, extensive testing, and assured quality assurance are essential elements for success in the application of bonded joints. In situ qualification of a bond is seen as the pathway to future qualification and adoption.

Question: What is the future of big data and proof testing in the future?

Answers:

SpaceX: At SpaceX, as improved data collection, analysis, and predictive tools are developed, we will make use of these tools. However, we will continue to do a lot of testing!

Orbital ATK: In the context of SLS, there are requirements for 100% nondestructive inspection, proof testing, and repeated proof testing. This seems excessive and does not seem logical in the context of present capabilities.

Northrop: We must define areas of variability and minimize that variability. We will never completely eliminate variability nor will we eliminate testing. The goal is to define experiments that help lower the intensity and cost of testing and qualification.

Boeing: The building block development approach means that we mix physical testing and virtual testing, maturing capabilities and moving toward qualified materials and processes. This approach is a proven strategy for reducing costs AND for speeding up the development and adoption of new materials.

Lockheed Martin: We will not get away from testing because it establishes well understood acceptable risks. In some past programs, rigorous development and testing were required, but proof testing acceptance was not required. In the future, we expect proof testing to be a continued necessity.

Follow-on question: For reuse, what about proof testing at Space X?

SpaceX: I don’t see us getting away from proof testing even when reusing hardware.

Question: What is the recipe for qualification?

Group Discussion: Faster and more effective nondestructive methods are essential for rapid development and qualification. Improved quality of composites will assist in reduced qualification costs. As strength and performance increases, and as performance moves away from the boundaries of the allowables, qualification challenges are reduced. Hence, the goal has two components: (1) make composites better and reduce the risk, and (2) develop faster and more effective methods of measurement and evaluation.

It is common practice to design everything to notched allowables. We are very confident in the quality of the products. We need to build that confidence in NASA. The challenge is not so much about technical issues as it is a challenge of perceived risk.

Damage tolerance must be built into the designs and the systems. The structures are robust, and that message needs to be shared.

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Day 2

COMPOSITES RESEARCH—OPENING REMARKS

Composites are presently being traded out of system designs. The technical challenges have been/are being met. Composites are mainstream in the commercial sector. The participants in the interchange were challenged to become missionaries for the cause of composites—because of the value that they deliver for NASA and for the Nation.

Christopher Singer is Director of the Engineering Directorate at NASA's Marshall Space Flight Center. His message is one of hope and excitement. Composites are presently being 'traded out' of systems designs. At this workshop, we have discussed the fact that many of the technical challenges have been met. We have broken through in the commercial sector. Now the space programs need to follow through to deployment. We must all become emissaries to demonstrate that composites are ready for deployment, and the rewards are great. This message must be carried to the decision makers. Mr. Singer stated that this role of emissary is not a trivial one. He encouraged the formation of partnerships to share the common message. Specifically, he asked interchange participants to find a colleague, form a team, and go two-by-two, working together to 'punch through' the challenges that inhibit composites deployment.

Simulation in Composites Manufacturing

As a keynote for the research session, this presentation presented the key theme that, 'while the central features of composites that provide enhanced light-weighting are the same for all applications, the microstructure must be specifically controlled to achieve specific stiffness and lifetime performance from a given structure.'

Uncertainty quantification is a key to controlling variability and delivering affordable products. Scale-up from capabilities demonstration to full-scale production and out-of-autoclave processing are key imperatives for space viability. The Composites Design and Manufacturing HUB (cdmHUB) has been established by Purdue University. The cdmHUB has four focus areas: Certification by Analysis, Education and Evaluation, and Simulation Best Practices. In addition, the HUB provides Web-based access to users to determine the availability and readiness of composites toolsets with emphasis on modeling and simulation.

Dr. R. Byron Pipes is the John L. Bray Distinguished Professor of Engineering at Purdue University. His presentation focused on the innovations needed to specifically satisfy the needs for space vehicle manufacture. He highlighted the Composites Virtual Factory HUB, and highlighted the work that Purdue is performing in concert with the IACMI. He stated a foundational premise: *"While the central features of composites that provide enhanced light-weighting are the same for all applications, the microstructure must be specifically controlled to achieve specific stiffness and lifetime performance from a given structure*." He highlighted the view that scale-up from capabilities demonstration to full-scale production and out-of-autoclave processing as key composites challenges for space viability, and defined five key technology challenges that must be addressed to accomplish the needed scale-up and maturation.

He highlighted scale-up from capabilities demonstration to full-scale production and OOA processing as key composites challenges for space viability. To meet these challenges, innovations are needed in:

- Design for manufacturability through end-to-end simulation tool suites.
- Optimization for thermoset polymer life in manufacturing—new materials systems.
- In situ characterization during manufacture.
- Characterization and detection of manufacturing defects.
- In-factory repair of integrated composite structures.

Uncertainty Quantification (UQ) is an established methodology to predict the range in expected outcomes through simulation. By combining simulation and experimental data, it is possible to define the actual range of expected performance with minimized testing and physical evaluation. Combining UQ with composites manufacturing simulation tools can provide the foundation for certification of composite products with reduced manufacturing variability and thereby, enhance the economic competitiveness of composites relative to their metallic counterparts.

Education and training for a new generation of aerospace engineers is imperative. The next generation has the opportunity and potential to transform the aerospace industry from metals based to composites based. Simulation tools that can support near optimum design and manufacturing processes are essential in this transformation.

Purdue University is assembling the global composites community through a HUB-based platform. The mission of the cdmHUB is to convene the composites community to advance certification by analysis, increasing the use of simulation tools by an order of magnitude. Enhancing the simulation toolset and educating the composites community to the capabilities that are available to them will accomplish this. The HUB has three focus areas: Certification by Analysis, Education and Evaluation, and Simulation Best Practices. The specific goals of the HUB are:

- To accelerate the rate of development of composites simulation tools by an order of magnitude.
- To develop a comprehensive set of simulation tools that connect composites from their birth in manufacturing to their lifetime prediction.
- To advance the certification of composite products by analysis validated by experiments.
- To teach the use of these tools to the current and future generations of engineers.
- To work with industry, academia, and government to put these tools in the hands of engineers who will design future products that require the performance characteristics of composites.

The HUB will assist users in understanding what tools are available, what tool is best for a specific problem, the functionalities and limitations of a particular simulation tool, how tools integrate with other tools, and the voids in the current simulation toolset. To support a common lexicon, a Simulation Tool Taxonomy has been developed. One of the most important features of the HUB is the development of a Tool Maturity Level system. Tailored after the Technology Readiness Levels, the Tool Maturity Level supports the evaluation of simulation tools from 1 (exploratory) to 7 (proven ability to predict performance and variability distribution).

The HUB (cdm.HUB.org) was launched in 2013 and has deployed 13 simulation tools and 61 other composites resources and has conducted an initial simulation tool needs assessment. Over 100 users are currently using the HUB with a goal of 10,000 users. With the DOE announcement of the formation of the IACMI, the Composites Simulation Center of Excellence was established at Purdue.

Beyond the present cdmHUB, the leadership envisions the creation of the Composites Virtual Factory HUB (cvfHUB). The cvfHUB platform will provide access to an array of simulation tools and will support the development of the human talent to support the composites design and manufacturing simulation enterprise. It is envisioned that the cvfHUB will provide browser-based access to physics-based simulations that support specific composites manufacturing platforms.

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Composite Materials Research at Louisiana State University and Southern University

The composites research program at LSU is addressing a broad range of emerging composites technologies and applications. One area of major emphasis is adhesively-bonded joints. Specific emphasis is being placed on smart composite joints using piezoelectric responses to counterbalance applied loads, modeling of fractures at composite joints, and self-healing composite joints. A number of methods are being investigated for self-healing embedding shape memory polymers and 'artificial muscle' made from non-shape memory polymers in which energy is stored. Modeling of damage in composite materials is also an area of great interest.

Dr. Guogiang Li is the John W. Rhea Jr. Professor of Mechanical Engineering with a joint appointment as the Contractors Educational Trust Fund Endowed Professorship at Southern University. The Composites Materials Research activities at LSU were initiated in 1987 and have grown to include four full-time faculty members. The research addresses a broad range of composites materials, design, and manufacturing issues, including:

- Adhesively-bonded composite joints.
- Biomimetic self-healing composites.
- Composite piping systems and pressure vessels.
- Grid-stiffened composites.
- Impact on composite structures.
- Mechanics of composite materials.
- Multifunctional composites.
- Nanocomposites.
- Shape memory polymer composites.
- Solid mechanics.
- Syntactic foam and foam cored sandwich.

LSU is conducting significant research in adhesively-bonded composite joints. Within the broader scope, specific activities are addressing:

- Smart composite joints which includes piezoelectric sensing to counterbalance the applied load, shape memory alloy wire to reduce stress concentration, and shape memory polymer adhesives for self-healing systems.
- Modeling of fractures in composite joints including modeling of factures with small-scale yielding ahead of crack tip and energy release rate under fracture.
- Cohesive law modeling addressing J-integral bridging global and local fracture tests and congestive laws with variable adhesive thicknesses.
- Self-healing composite joints applying biomimetic two-step, close-then-heal processes.

Constitutive modeling of shape memory polymers is being addressed in several research projects. Areas of focus include:

- Physics-based phase evolution law.
- Thermo-viscoelasticity and thermo-viscoplasticity.
- Cold-compression programming.
- Multiscale modeling.
- Statistical mechanics modeling.
- Modeling of damage-healing.

Good results are being demonstrated from the healing-on-demand research activities. Both shape memory polymers and conventional, nonshape memory polymers, such as sewing thread and fishing line, are delivering good results. The conventional materials are being used to create polymer-based 'artificial muscles' through twisting and coiling.

These and other activities highlight the present research thrust at LSU and Southern University. Significant investment is being made in understanding the needs of government and industry, and in growing the composites research program. This growth is anticipated to include additional faculty positions.

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Multiscale Modeling of Multifunctional Polymer Composites

The Research Center for Flight Vehicles and Composites (RESPET) was established as a flight research laboratory over 60 years ago. Multiscale modeling is integral to much of the composites research that is conducted at Mississippi State University (MSU). Multiscale progressive failure modeling has been utilized for both metal-matrix and polymer-matrix structures. The body of research and the successes being achieved point to the future achievement of Integrated Computational Materials Engineering (ICME) for composite design optimization—and the realization of the Airframe Digital Twin.

Dr. Thomas Lacy is a professor and interim head of the Department of Aerospace Engineering at MSU. His presentation highlighted the capabilities and research activities at MSU with a specific focus on composites modeling.

RESPET was established as a flight research laboratory over 60 years ago. It possesses a rich heritage in full-scale manned and unmanned flight vehicle design, fabrication, and testing and advanced composites development. The 100,000 sq. ft. facility includes a flight test laboratory, a hanger, and a capable complement of aerospace relevant fabrication equipment. These capabilities include full-scale testing of composite structures.

Multiscale modeling is integral to much of the composites research that is conducted at MSU. Multiscale progressive failure modeling has been utilized for both metal-matrix and polymer-matrix structures. Full domain analysis is not feasible for large degree-of-freedom problems. A micromechanics approach has been implemented to perform adaptive, multiscale analysis. The results of this research point to the achievement of an ICME–based Airframe Digital Twin.

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Overview and Highlights—Delaware Center for Composite Materials

The Center for Composite Material (CCM) was founded in 1974 with a three-part mission to conduct basic and applied research, educate scientists and engineers, and transition technology to industry. In support of this mission, the CCM possesses capabilities and facilities to support the needed design, experimentation, production, and analysis of composite components and systems. They also support the Composite Design and Simulation Software: CDS3.0, which is a real-time environment for predicting composite structures and supporting design optimization.

Dr. Shridhar Yarlagadda is the Assistant Director for Research for the Delaware Center for Composite Materials (CCM). The CCM was founded in 1974 with a three-part mission:

- Conduct basic and applied research.
- Educate scientists and engineers.
- Transition technology to industry.

Capabilities and areas of emphasis include:

- Materials characterization—mechanical testing, chemical characterization, and microstructure characterization.
- Automated material placement systems including a custom-designed, robotics-based system with swappable modules including modules for stitching, coating, and sprayable bagging processes.
- A high-energy drop tower for impact testing of composites.
- Code development and maintenance, including the development and support of the CDS3.0. CDS3.0 is a real-time environment for predicting composite structures and supporting design optimization.
- High strain rate characterization and modeling.
- Ceramic matrix composites modeling for analysis, structural design, and manufacturing processing.
- Design and optimization of the automated tape placement process, including knowledge-based models.

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Questions and Answers for the Research Panel

Several questions were directed to the panel, and the audience engaged conversation. The discussion focused on one basic question: "What is needed to develop and support the development of the next generation of composites professionals?" Ideas discussed included:

- The establishment of more degree programs with specialties in composites. There was strong support for this idea. However, the realities of accreditation, pressures to compress the pathway to graduation, and other barriers to added programs were acknowledged.
- The education of the design community concerning the reality of 'the possible' and the desirable state of maturity of composites technologies/capabilities.
- The opportunity to include composites studies in existing curricula and existing coursework, without the burden of major changes to the entrenched academic structure. This idea was met with acceptance as being a positive and realistic approach.
- The case was also made for additional funding for focused research in meeting the defined challenges.

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MODELING AND SIMULATION ADVANCEMENT FOR COMPOSITE DEVELOPMENT

The purpose of this session was to provide a concise overview of the current state of modeling and simulation tools for composites, some information about what is presently missing, and a look to the future. Modeling and simulation is well integrated across the composites design and manufacturing environment. Hence, discussion of modeling and simulation activities and tools was included in many of the presentations in the technical interchange.

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Digital Twin: Manufacturing Excellence Through Virtual Factory Replication

"The digital twin is a virtual representation of what has been produced. By comparing the digital twin to the design information, it is possible to better understand what was produced versus what was designed, tightening the loop between design and execution.[1]" The Digital Twin contains three main parts: (1) *physical products in real space,* (2) *virtual products in virtual space, and* (3) *the connections of data and information that ties the virtual and real products together. The ability to understand the physical product has greatly improved with the improvements in data collection and analysis. The 3D representation of products and the analytical predictive tools are much improved. However, the integration of the virtual and physical is lagging. The fully annotated 3D model that includes manufacturing information is seen as the integrating medium in achieving the digital twin.*

Dr. Michael Grieves is an author, professor, and business executive with a broad range of interests. He is a recognized expert in all things related to Product Lifecycle Management and is the author of several books on the subject. He was forced to miss his presentation at the Interchange, but granted permission for us to abstract his work.

In layman's terms, the digital twin defines the long-sought unity between the virtual product and the physical product. This unity supports transformational improvement in assuring that the product meets all requirements in the design, manufacture, and operation phases of the product lifecycle. The Digital Twin contains three main parts: (1) physical products in real space, (b) virtual products in virtual space, and (3) the connections of data and information that ties the virtual and real products together. On the virtual side, the amount and quality of the information has dramatically improved. Behavioral characteristics have been added, so the virtual product cannot only be visualized, but also can support the virtual testing of performance characteristics. On the physical side, the ability to manage and analyze large amounts of data and to extract information (and knowledge) from that data enables a never-before-achieved level of awareness about the product.

While the amount and quality of information about the virtual and physical product have progressed rapidly over the last decade, the realization of the two-way communication between real and virtual space has lagged behind. We have not developed the connection between the two products so we can work with them simultaneously. The typical way to make that connection is to develop a fully annotated 3D model that contains all of the information necessary to support the design, production, and, ultimately, the lifecycle support of the product. Bringing the 3D data to the factory floor in the virtual model and integrating that model with the factory operations data achieve real-time unity, enabling intelligent and adaptive control of product and process attributes. This capability assures the quality of the product and the compliance of the processes throughout the design and manufacturing lifecycle, and extending to lifecycle support.

[1]Michael Grieves, "Digital Twin: Manufacturing Excellence through Virtual Factory Replication," <http://innovate.fit.edu/plm/documents/doc_mgr/912/1411.0_Digital_Twin_White_Paper_Dr_Grieves.pdf>.

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The Siemens PLM Software Ecosystem for Composites Analysis

This presentation introduced the Siemens composite analysis toolset and discussed the capabilities and applications of that toolset. The capabilities include composite design and manufacturing, composite linear analysis, and composite advanced nonlinear analysis. Among the highlights of the toolset is the capability for damage prediction and assessment.

Scott McDougall is a Senior Applications Engineer with Siemens PLM Software. In his presentation, he introduced the Siemens composite analysis toolset and discussed the capabilities and applications of that toolset.

Fibersim/CAD supports composite design and manufacturing. It provides for fast and accurate laminate design, determines fiber orientation, and provides as-manufactured layup information. With accurate draping simulation, Fibersim supports producibility analysis, design modification, and flat pattern creation.

NX CAE/NASTRAN enables composite linear analysis. NX NASTRAN is a finite element solution package that is useful for analysis of stress, vibration, buckling, structural failure, heat transfer, acoustics, aero-elasticity, and other attributes in composites.

SAMCEF is a nonlinear finite element code. For composites, the system enables analysis of nonlinear buckling and post-buckling to collapse, interlaminar/intralaminar failure, and nonlinear flexible mechanism dynamics. The SAMCEF system includes a comprehensive library of finite elements for multilayer composites, a large range of structural analysis methods for composite structures, advanced models for progressive damage analysis in composites, and specific tools for composite structures optimization.

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Nondestructive Evaluation in the Aerospace Industry

This presentation overviewed the challenges and emerging capabilities in evaluating composite structures. The presenter defined Non-Destructive Testing/Inspection (NDT/I) as, 'the use of noninvasive techniques to determine the integrity of a material, component, or structure or to quantitatively measure some characteristic of an object.' It is noted that there is a circular relationship between modeling and simulation, NDT, and design and manufacturing. The evaluation of the product joins with the foundational science to inform the development of accurate product and process models. The actual information from the product and the processes enables a continuously improving environment, moving to minimization of the cost and requirements for actual evaluation, pointing to a virtual development environment.

Facilitation Industry By Engineering, Roadmapping and Science (FIBERS) for the Composites Industry. FIBERS is a newly formed alliance of industry, government, and academia focused on developing a roadmap for composites development and implementing that roadmap in a collaborative environment.

Dr. Vinay Dayal is an Associate Professor of Aerospace Engineering at Iowa State University. His presentation focused on NDT/I which he defined as, "the use of noninvasive techniques to determine the integrity of a material, component, or structure or to quantitatively measure some characteristic of an object." In short, the objective is to quantitatively and accurately measure needed parameters without doing harm to the product. There is an important circular relationship between modeling and simulation, NDT, and design and manufacturing. The evaluation of the product joins with the foundational science to inform the development of accurate product and process models. The actual information from the product and the processes enables a continuously improving environment, moving to minimization of the cost and requirements for actual evaluation, pointing to a virtual development environment. Dr. Dayal sees the future for composites NDT/I and for composites manufacturing as including structural health monitoring, in situ damage detection, active damage prognosis, and additive manufacturing processes which assure the quality of the product as it is produced—all of this with unity of the modeling and simulation and the actual production environments.

Dr. Dayal introduced the Facilitation Industry By Engineering, Roadmapping and Science (FIBERS) for the Composites Industry. FIBERS is a newly formed alliance of industry, government, and academia focused on developing a roadmap for composites development and implementing that roadmap in a collaborative environment. Areas of specific focus for FIBERS include computational modeling, advanced processing and fabrication, automated manufacturing, and design tools and methodologies.

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Five Things That We Should Know About Composites

This presentation highlighted five important points of knowledge concerning composites and their applications including:

(1) Composites are everywhere—composites are proven valuable elements of the design and manufacturing environment.

(2) 3D design tools are mature and broadly used in industry—the full realization of the digital twin is moving to reality.

(3) Education is a Challenge—There are two challenges: educating the composites community that the tools are available and educating the decision makers regarding the maturity and value of composites.

(4) Simulation tools are available for the composites designer. Modeling and simulation tools are available to, and useful by, the composites designers—not just the finite analysis experts.

(5) Optimized manufacturing processes exist today. The tools to support process optimization from design data are available bringing the digital thread to reality.

Rani Richardson is a composites consultant with Dassault Systèmes—The 3D Experience Company. Her presentation sought to establish foundational facts about the current state of the technologies that support composites applications.

Dassault Systèmes employs 13,300 people and serves 190,000 customers. From a legacy as an early provider of 3D design tools, Dassault has matured through the expansion to product lifecycle management and is now branding the 3D Experience which addresses the broader business environment.

The key facts that we should all know, and which are foundational for composites applications, include the following:

- Composites are everywhere. They are no longer exotic, expensive, risky alternatives, but are proven valuable elements of the design and manufacturing environment from sporting equipment, to windmills, to cars, and including an explosion in the commercial aircraft sector.

- 3D design tools are mature and broadly used in industry. There is no more space for 2D drawings, hand calculations, trial and error solutions, and spreadsheets. The tools are available to support the development of the 3D design, to use that design in process development and process execution, and to address lifecycle issues in the development. The ability to 'mirror' the actual product and the processing environment through the 'digital twin' is an emerging capability that offers great advantage in accelerating process development and assuring the production of quality products—all of the time. The digital twin capability includes the integration of advanced analysis and simulation tools in the design and manufacturing process. A new generation of composites software is available on the cloud.

- Education is a Challenge. Perhaps the greatest challenge of all is in educating the design and manufacturing community that the tools and technologies are available to support a modeling and simulation-rich design and processing optimization environment. Further, there is an additional challenge in conveying the advantage and readiness of composites for adoption by the decision makers. Dassault is working with government agencies, research labs, academic institutions, strategic customers, and trade associations to get the word out and to provide education and training in the new toolset.

- Simulation tools are available for the composites designer. Modeling and simulation tools are available to, and useful by, the composites designers—not just the finite analysis experts. These tools enable rapid sizing, efficient optimization, and certification of producible parts.

- Optimized manufacturing processes exist today. Today's capabilities support manufacturing in a 3D virtual environment for hand layup, automated placement, dynamic draping simulation, and braiding. For each of these processes/capabilities, a complete digital representation—the digital thread—is created from design to process information.

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A Practitioner's View of Modeling and Simulation Needs

The capabilities exist, and are in routine use, to build excellent composites products with an accelerated development cycle. From the small manufacturer's perspective, better tools are needed to support accurate estimates and planning based on requirements—very early in the product development process. While design tools for composites are commonly utilized, the ability to support effective design optimization is deficient. The composites development toolset, including modeling and simulation tools, do not interoperate, which limits the ability to achieve best-in-class analysis and forces small manufacturers to purchase multiple toolsets to match the customer's choices. The validation of models is important. For example, there are models to simulate damage from drop testing, but they are not validated, so the value is limited. Taking a lesson from the additive manufacturing community, the composites community should move quickly to develop systems to enable the rapid development and production of excellent products.

Dr. Andreas Vlahinos is a Principal of Advanced Engineering Solutions, Inc. (AESI), which is a small firm offering R&D, and Computer-Aided Engineering Services. At AESI, Dr. Vlahinos concentrates on rapid new product development. He is also a professor at the University of Colorado, teaching courses in Structural Mechanics and Computer-Aided Structural Engineering. His presentation highlighted the needs that he sees as a user of the state-of-the-art toolsets in designing and producing composite systems and in improving the design and processing of existing systems.

The capability exists, and is routinely exercised, to build excellent composite systems, and to accelerate the composites development process. The capabilities need to be exercised in building cost-effective composite structures with the cost-effectiveness resulting from an accelerated development cycle.

We can be spoiled by overuse of computer-aided innovation tools. These tools are useful in the requirements and concepts phases, but the use of the toolsets must be accompanied by human innovation. The composites design toolsets are improving, but the capability to assist in design optimization is still lacking. For example, better tools are needed to optimize fiber orientation.

It is essential that we quickly estimate preliminary designs from requirements in the proposal phase. We need to evaluate all alternative materials—performance, time to manufacture, cost, etc. There is a void in the ability to rapidly process requirements, create concepts, and support preliminary designs with accurate cost estimates.

As is the case with all of the design and manufacturing space, the tools do not interoperate. As a small company providing engineering services, AESI (and all small companies) must use what the customer uses, which dictates that we support multiple systems.

Validated data are not available to support heavy drop tests. The simulations are done, but AESI is not comfortable with the validation of the codes, so the results are not as useful as is needed.

3D printing/additive manufacturing offers great opportunity for the composites community. We need to quickly develop and mature technologies that enable the rapid fabrication of many good products. As a community, we need to do good designs and make good products—fast.

SMALL INDUSTRY PERSPECTIVE ON COMPOSITES RESEARCH AND DEVELOPMENT

The objective of this session was to highlight the opportunities for small businesses—both technology suppliers and product developer/manufacturers in the composites industry.

Building America's Next Heavy-Lift Launch Vehicle—Composites for the Upper Stage and Space Launch System

This presentation extolled the virtues of NASA investment in technology development across the supply network as beneficial to NASA and to the Nation. The SLS 70 metric ton, initial configuration, is very buildable, but the evolution of the launch vehicle to the projected capabilities (130 metric ton) will require advanced development. Areas of needed development include improved affordability, increased reliability, and increased performance—specifically lift capacity. Documented processes, procedures, and industrial time standards are needed to support an effective industrial base for composites. The engagement of the supply base is critical for SLS success and for the additional value added to the Nation's industrial capability and capacity. The emerging national programs, especially the manufacturing innovation institutes, must engage the supply base and must invest R&D dollars in those companies.

Les Cohen is the Senior Vice President, New Business Development and Strategic Technology HITCO. His presentation thesis was 'the development of advanced materials and manufacturing technologies will enable the use of composites in space applications and provide an avenue to align with, accelerate, and realize research and development programs for national needs and will better prepare the industrial base for future participation.'

Mr. Cohen stated that the SLS 70 metric ton initial configuration is very buildable, but the evolution of the launch vehicle to the projected capabilities (130 metric ton) will require advanced development. Areas of needed development include improved affordability, increased reliability, and increased performance, specifically lift capacity. The model of using public funding, i.e., NASA to develop core competencies that NASA needs and publishing the results so the community knowledge and capability is increased is applauded.

The presentation highlighted state-of-the-art applications in the aerospace industry. One of the areas of emphasis was automated fiber placement. It was noted that honeycomb panels defeat the advantages of AFP. Dr. Cohen emphasized the following key points:

- The need for documented processes, procedures, and industrial time standards to build composites structures for the U.S. and the SLS is endemic to the enterprise that supports NASA.

- The ability to capture innovation and technological advancement that manifests itself in top line production ability, capital equipment, manufacturing, and cost reduction is directly related to NASA's ability to transfer the know-how and ability to the Tier 2 Industrial Base**.** The Tier 2 capabilities must be enhanced, nurtured, and embraced. NASA must insure that its composite upper stage/SLS development is driven down into the industrial base to capture affordability, producibility, and made in America.

- Small businesses must be able to participate in the activities of the manufacturing institutes and other government supported programs and receive significant R&D dollars. Government must assure that the money is spread across the supply base with a strong emphasis on technology deployment and insertion.

SPACE APPLICATIONS IN COMPOSITES

After one-and-one-half days of presentations and discussion, the final session of the Technical Interchange gave the participants an opportunity to process the information that was shared and to interact with decision makers and leaders in the space applications and composites arenas. Participants in the panel discussion included:

- Chris Crumbly, Manager of the SLS Spacecraft/Payload Integration and Evolution Office.
- Jeff Sheehy, Senior Technical Officer of the Space Technology Mission Directorate.
- Byron Pipes, John L. Bray Distinguished Professor of Engineering at Purdue University.
- Mark Shuart, R&D Facilities Program Manager for the Advanced Manufacturing Office of DOE.

Key points from this panel discussion are as follows:

- The RFPs often do not reflect a good understanding of the capabilities that exist. Visible and widely publicized showcases and announcements serve to inform those who write the RFPs.
- The norm is to specify what has always been done. Perhaps the right solution is to specify composite components.
- Program offices respond to immediate needs and requirements. When these opportunities arise, creating an opening for best solutions—possibly composites—is critical. Perhaps the pathway to success is not in requiring but in allowing alternatives.
- There are three communities that must embrace change: the program community, the engineering community, and the safety community. A program requirement that cannot be met with traditional solutions is necessary to enable alternatives, and these three communities must be aware/convinced of the value. A deep understanding of the composites capabilities is essential to enable that change. Definitive recipes for certification and qualification of composite components are required.
- Validated models can be important assets in gaining acceptance of composite alternatives.

Question: The composites Community of Practice is going strong with over 200 people engaged. The community is 6 months away from architecting recommendations regarding key standards and requirements. We need a deeper review of those recommendations. Would members of the panel be willing to serve as reviewers and advocates for those recommendations?

Answer: There is interest and support. Please help us to understand what is needed. What can be done to help make the recommendations more effective? What can the community do to push forward? Experiences of the field should be brought to the designs/designers.

Key point raised by the panel: Our RFPs do not always reflect a good understanding of the capabilities that exist. We need visible and widely publicized demonstrations that confirm the strength and robustness of composite products.

For example, each year at the Indianapolis 500, full composites structures engage in a race. These cars are strong and light. How can such experience and demonstration of strength and functionality be projected to the space industries?

Audience follow-up to 'intelligent RFPs': Is the problem with RFPs a matter of ignorance of what could be done, or is it a matter of comfort with what has always been done?

Answer: Whatever the reason, the result is the same. As a community, we are not allowing our suppliers and our systems to get better because we design in the same capabilities and systems.

Answer: Perhaps the right approach is to 'simply' specify that composite components will be procured?

Comment: Unless a program office has a specific need, there is little reason or willingness for action. Until someone 'needs it right now' or has a specific requirement that cannot be met, there is no push. When the need is identified, the normal procedure is to do what has been done. This is the target of opportunity—to change that response from 'what has always been done,' to 'what should best be done.' It is important to remember that the culture is, appropriately, risk aversive, and we do not get incentivized to take risks!

Comment: Maybe the pathway to composites deployment is not in **requiring** composite alternatives, but by **allowing** composite alternatives.

Good observation: NASA should work to be sure that these opportunities are open, and industry can help. Industry has the opportunity to push back on a draft RFP to make NASA aware of possibilities.

Question: Program goals can be defined, in the form of upgrades, to require additional capability that mandates alternative materials and processes. Is this an avenue for composites deployment?

Answer: There is presently no requirement that mandates vehicle improvements. There are three communities that must embrace change. They include the program community, the engineering community, and the safety community. A program requirement that drives change is essential for change to happen. A requirement that cannot be met with traditional solutions opens the door for exploration and deployment of new capabilities.

Answer: We now baseline metals with composites buying its way on. Perhaps that baseline could be reversed by acceptance of best possible performance as a requirement.

Answer: We must do the development work well and completely. We must understand, accurately and precisely, the real and perceived risks, and we must systematically address and mitigate those risks. We require a recipe for certifying and qualifying composite components integrated in systems.

Comment: Most of the discussion has centered on launch systems, but it is not just about launch vehicles. There are other opportunities and other programs where composite solutions offer potential improvements. Composites should be a core competency across the organizations and programs.

There are examples where some of the limits are being pushed and capabilities from the commercial community are being applied. Presently, a NASA contractor is doing hydrostatic tests on a large tank. There are defects in that tank, and there will be a build repair. To satisfy the requirements for effective repair, we must define the possible damages, demonstrate damage tolerances, and establish acceptable boundaries (allowables) for characterized points of damage. There are some metrics available from which the foundation can be developed. The FAA has requirements. NASA has requirements and boundaries. The assertion that standards and requirements for composites manufacture and repair do not exist, as a baseline, and that this work is not being used by NASA is wrong and misleading.

Comment: Validated models can be important assets in gaining acceptance of composite alternatives. More emphasis on validated models is needed. It would be good to see more validation of the models ahead of application.

CLOSING REMARKS

John Vickers closed the Technical Exchange by expressing his pleasure and delight with the content that was shared at the meeting, and by thanking all who participated. He echoed the theme that composite development for space application has been underway for some time and great progress has been made since the early years. Many lessons have been learned. The capabilities and technologies have matured to the point that we must move to the next level of inclusion of composites in vehicle designs. To emphasize the message that the composites community must take the responsibility for product and process excellence and for educating the community, he stated, "We have met the enemy, and he is us." He highlighted three 'Cs' for our consideration:

Culture—There is lots of work left to do. The NASA culture is (appropriately) averse to risk. There is a perception that composites are exotic. There are perceived risks. These challenges must be met with good science and engineering to mitigate the risks and dispel the concern.

Confidence—As a community, we must have the confidence to address and mitigate the risks, and we must instill confidence in the decision makers. Industry has confidence in their ability to deliver components that satisfy requirements and perform. They provided the data, testing, and validated models to instill the confidence in those who must buy off on the decisions. That confidence must be (1) validated and justified, and (2) embraced across the space community.

Collaboration—Perhaps this is a beginning point. Perhaps the communication of this technical interchange will lead to improved collaboration and success.

Thanks to all who made the Technical Interchange a valuable event. In closing, there are three challenges that we all must embrace:

(1) We must change the <u>culture</u> by addressing the risks with good science and sound engineering to mitigate the risks.
(2) We must instill <u>confidence</u> in the decision making, and we must confidently address the challenges.
(3) We can achieve our goals through, and only through, <u>collaboration</u>.

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APPENDIX—LIST OF PARTICIPANTS

First Name	Last Name	Affiliation
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Malcolm	Wood	NASA's Michoud Assembly Facility
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14. ABSTRACT
Composite materials offer significant advantages in space applications. Weight reduction is imperative for deep space systems. However, the pathway to deployment of composites alternatives is problematic. Improvements in the materials and processes are needed, and extensive testing is required to validate the performance, qualify the materials and processes, and certify components. Addressing these challenges could lead to the confident adoption of composites in space applications and provide spin-off technical capabilities for the aerospace and other industries. To address the issues associated with composites applications in space systems, NASA sponsored a Technical Interchange Meeting (TIM) entitled, "Composites Materials and Manufacturing Technologies for Space Applications," the proceedings of which are summarized in this Conference Publication. The NASA Space Technology Mission Directorate and the Game Changing Program chartered the meeting. The meeting was hosted by the National Center for Advanced Manufacturing (NCAM)—a public/private partnership between NASA, the State of Louisiana, Louisiana State University, industry, and academia, in association with the American Composites Manufacturers Association. The Louisiana Center for Manufacturing Sciences served as the coordinator for the TIM.

15. SUBJECT TERMS
composites, composite materials, advanced manufacturing, cryogenic tanks

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