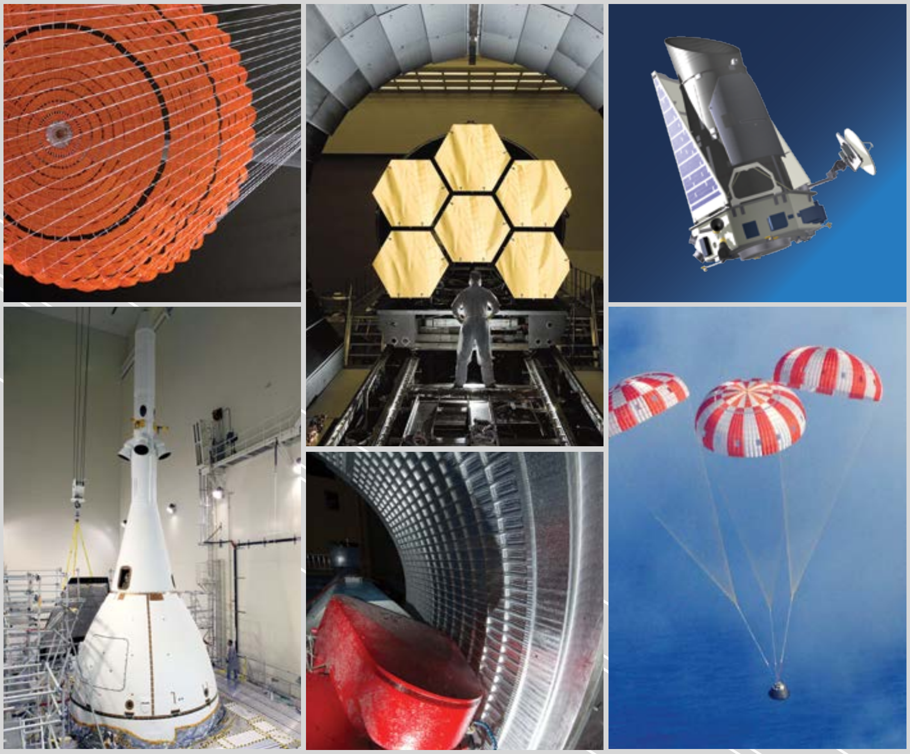
National Aeronautics and Space Administration

THE NESC

2014 TECHNICAL UPDATE



NASA Engineering & Safety Center

The NESC-designed Alternate Launch Abort System fairing shown integrated with the Orion spacecraft for the EFT-1 mission.

Timmy R. Wilson
Director

Michael T. Kirsch
Deputy Director

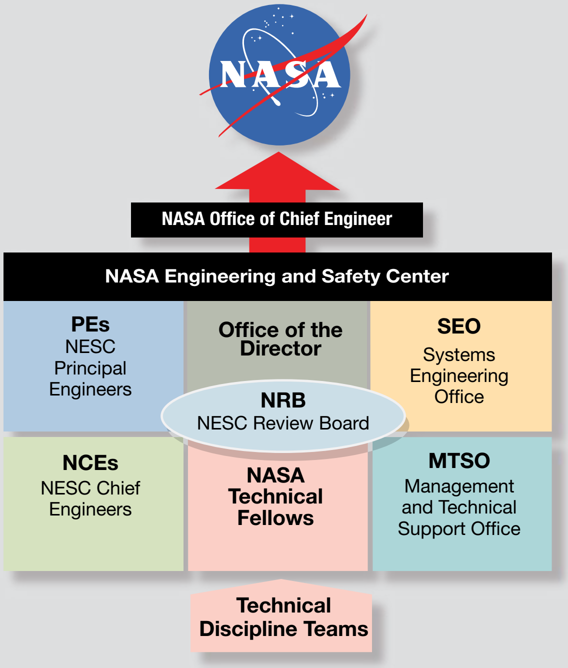
Moving into a New Era

The NASA Engineering and Safety Center (NESC) leadership team is pleased to introduce the 2014 NESC Technical Update. This publication is an example of one of the knowledge products we use to share discoveries, lessons learned, and technical solutions with the Agency and the broader engineering and technical community. This year, the NESC experienced a change in leadership with the departure of two of the driving forces behind the NESC since its inception in 2003. Ralph Roe, the NESC's first Director, was named the NASA Chief Engineer, and Dawn Schaible, the former manager of the NESC Systems Engineering Office, was named NASA Deputy Chief Engineer. They may have moved on, but their vision for the NESC endures as a world-class technical resource to address NASA's toughest problems and provide timely, value-added solutions to those problems. All members of the NESC management team, past and present, share that common vision. Tim Wilson now serves as the NESC Director, having served as the Deputy Director since 2006 and as an NESC Chief Engineer since NESC formation. Mike Kirsch now serves as the NESC Deputy Director, having briefly served as the Management and Technical Support Office Manager in 2013 and as an NESC Principal Engineer since 2004.

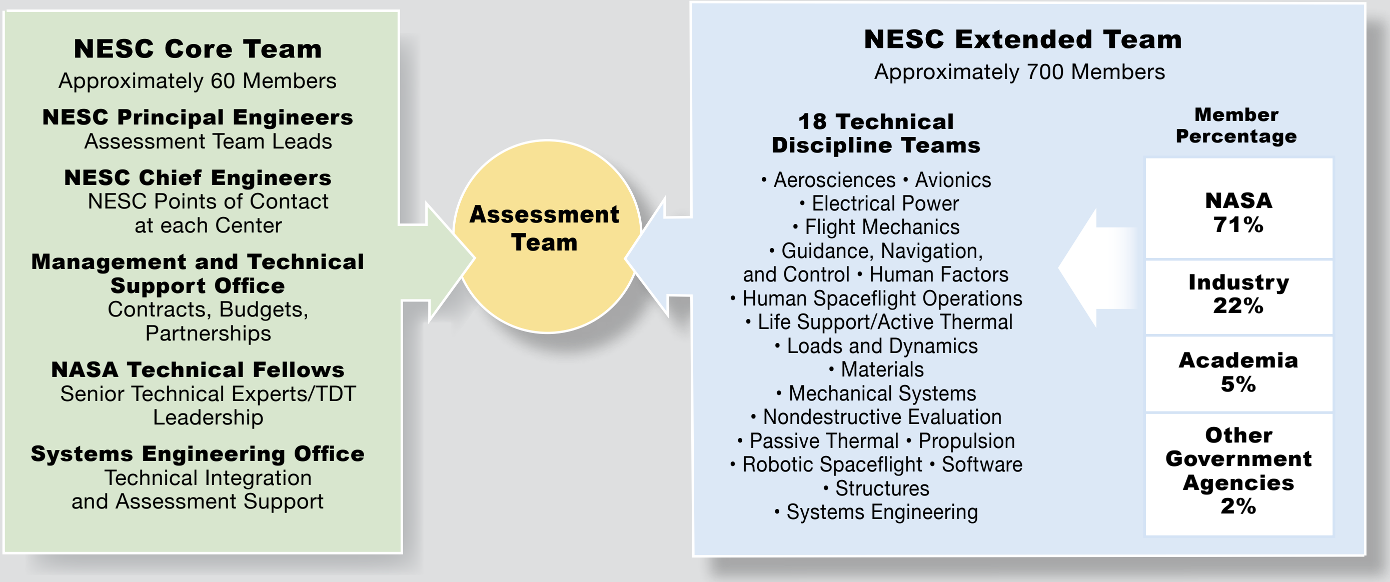
Conveying knowledge

Previous editions of the NESC Technical Update showcased a wide variety of NESC activities from the preceding year using short descriptions and illustrations. However, an objective of this year's publication is to show the reader how NESC assessments may be part of a broader picture than the scope of the original assessment, or connect some of the themes drawn from separate assessments. Consider the study the NESC performed on a 1967 X-15 flight accident. The objective of the study was to find lessons learned from that incident that could be applied to current NASA projects. A contributing factor to the accident was the X-15's adaptive flight control system, which has similarities to what NASA's Space Launch System will be employing and the focus of a separate NESC assessment. In addition, other NESC

The NESC Organizational Structure



The NESC Assessment Team Structure



teams have been evaluating the use of commercial-off-the-shelf (COTS) electronics components on spacecraft. The X-15 accident was attributed in part to the use of certain COTS equipment.

The NESC Review Board (NRB) is a unique element of the NESC, which is comprised of members from each of the NESC offices, and represents all 10 NASA Centers and each technical discipline.

Another objective of the NESC Technical Update is to serve as an introduction to the NESC through our accomplishments. From an organizational standpoint, the NESC falls under NASA's Office of the Chief Engineer. This arrangement separates the NESC from the NASA mission directorates, programs, projects, and Centers, and allows independence, objectivity, and flexibility when working with other NASA organizations.

The proven NESC structure

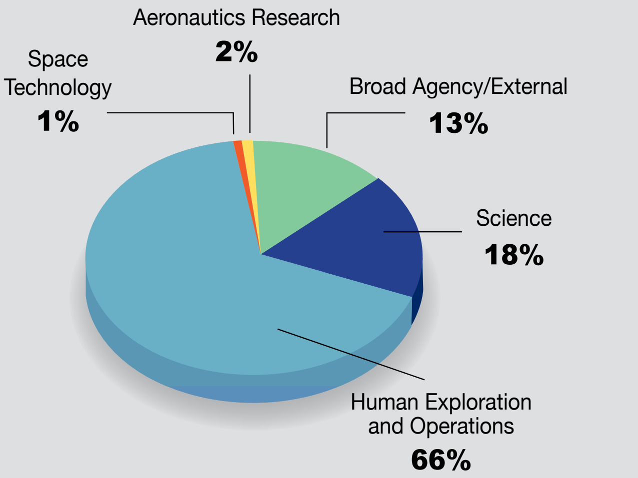
The NESC is structured to quickly and efficiently apply the concept of tiger teams (called assessment teams in the NESC) to address technical problems as they arise. NESC core team members are full-time employees of the NESC and form the nucleus of each assessment team. The NESC Principal Engineers, NESC Chief Engineers, NASA Technical Fellows, Systems Engineering Office, and the Management and Technical Support Office make up the core team, led by the NESC Director and his office. Members of Technical Discipline Teams (TDTs) form the NESC extended team. The TDTs are populated with engineers and scientists chosen for their technical knowledge and experience, and drawn from within NASA, academia, industry, or other government agencies. There are 18 TDTs, each focused on an engineering discipline, and led by a NASA Technical Fellow or TDT Lead. When the assessment lead determines the requirements for an assessment, he or she draws the appropriate personnel from the TDTs through the NASA Technical Fellows.

The NESC Review Board (NRB) is a unique element of the NESC, which is comprised of members from each of the NESC offices, and represents all 10 NASA Centers and each technical discipline. The NRB approves all technical products generated by the NESC and its assessment teams. The NESC is successful because a diversified technical experience base creates different vantage points from which to approach each issue — resulting in a robust decision-making process.

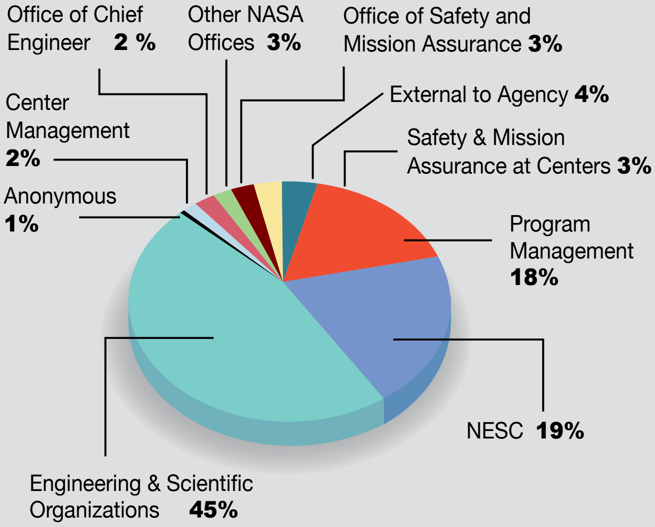
The NESC provides the framework and infrastructure to find and focus engineering talent. Any success the NESC has achieved is a testament to the extended NASA team and the limitless knowledge and experience its members provide as they tackle the Agency's most difficult technical challenges. □

Accepted Requests: 593 total

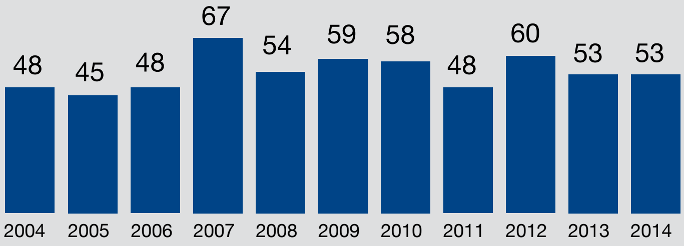
Accepted Requests by Mission Directorate



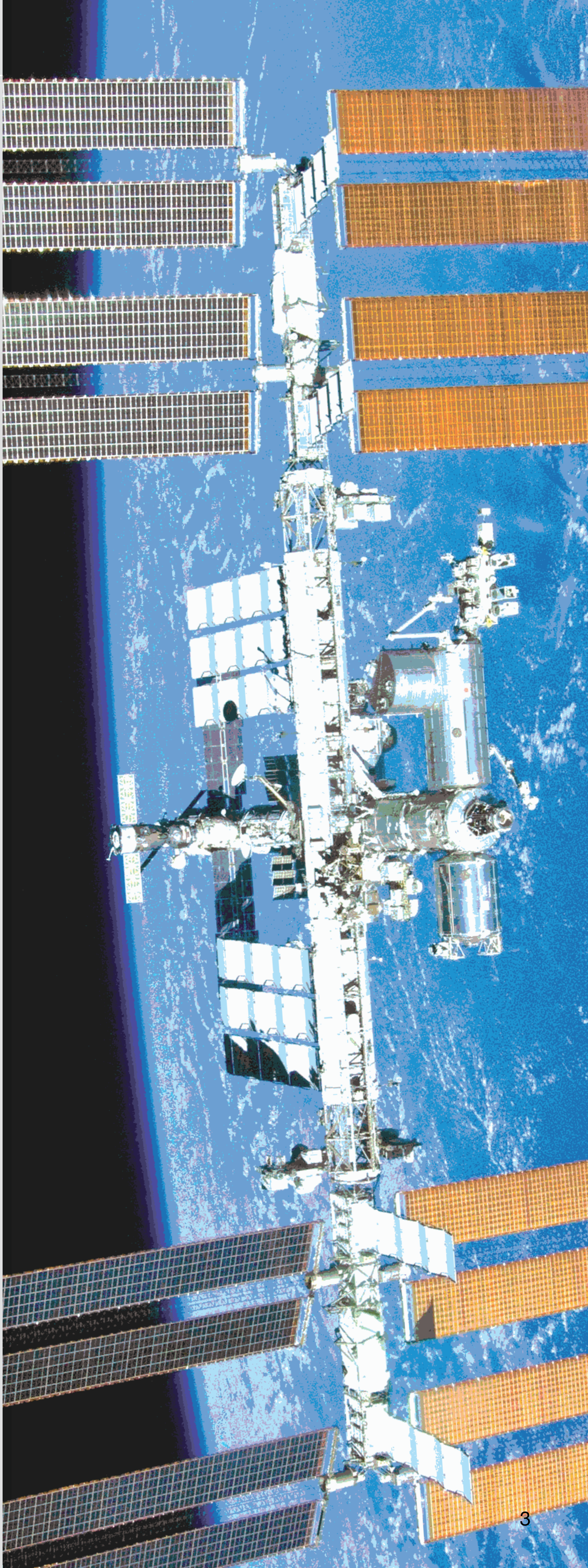
Sources of Accepted Requests



Accepted Requests by Year



All statistics as of December 31, 2014



Preserving Knowledge for the Future

The NESC takes a broad approach when it comes to sharing the knowledge it has accumulated from the hundreds of technical assessments conducted since its inception more than a decade ago. To capture and disseminate that knowledge to all who may need it — within NASA, industry, and academia — the NESC offers a wide variety of knowledge services and products that can be readily accessed and consumed. From technical assessments and reports to databases and videos, these products bring the data gathered in the field to the people it will benefit most, and capture that knowledge for generations to come.

Engineering reports

The detailed engineering and analyses generated from each assessment are captured in comprehensive engineering reports and converted into NASA Technical Memorandums (TM) for permanent archive and access. Capturing engineering analyses in formal reports instead of briefing slides has been on-going since the Columbia accident investigation. In 2014, more than 30 TMs were generated by NESC teams whose members span all 10 NASA Centers. TM topics touched on a broad range of NASA programs across all NASA mission directorates. All publicly available NESC reports are located at ntrs.nasa.gov.

ntrs.nasa.gov

Technical bulletins

Occasionally, significant and noteworthy data found during NESC assessments are turned into one-page technical bulletins. The bulletins condense new knowledge or best practices into quick and easy reads, while also linking to additional reference material. NESC Technical Bulletins are located at nesc.nasa.gov.

Technical update

At the end of each year, the NESC Technical Update serves as a summary of significant contributions to the Agency, and also serves as a way to communicate NESC knowledge products. The NESC Technical Update can be found at nesc.nasa.gov.

NESC knowledge products and summaries of our latest efforts can be found at nesc.nasa.gov.

nesc.nasa.gov

Lessons learned

An Agency-level lessons learned database called the Lessons Learned Information System (LLIS) is used to capture important and broadly applicable lessons learned. In some cases, the lesson may be significant enough that it is used to update a NASA standard. NESC and Agency lessons learned can be found at llis.nasa.gov.

llis.nasa.gov

Video academy

The NESC Academy is a website featuring nearly 300 informative lessons on topics relevant to current NASA issues and challenges. They offer the audience a virtual classroom experience on a myriad of technical topics, which this year ranged from fundamentals of aircraft engine control and metal fatigue to Kalman filtering and space situational awareness. NESC Academy videos have received more than 17,000 views since inception in 2012. In 2014, the Academy also featured 44 technical webcasts as a service to the discipline communities. Viewers could send in questions to the presenter during the live broadcast. The NESC is also processing major new content that includes over 60 videos from the JSC U.S. Spacesuit Knowledge Capture Series to make available on the NESC Academy. 2015 will bring even more capabilities to the website, including mobile access and personalized training. NESC Academy videos are found at nescacademy.nasa.gov.

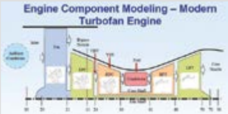
nescacademy.nasa.gov

Additional knowledge service products

Other knowledge sources to which the NESC contributes include the NASA Engineering Network, an online space for communities of practice, as well as workshops, forums, and technical interchange programs. The NASA Technical Fellow's communities of practice can be found at nen.nasa.gov.

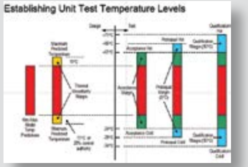
nen.nasa.gov

Top 10 Most Viewed NESC Academy Videos



1. Fundamentals of Turbofan Aircraft Engine Control

This presentation covers the basic principles behind modeling the engine system for control design and how the safety and operational limits are implemented in the engine control to provide safe and reliable operation.

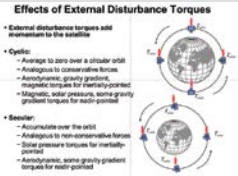


2. Rationale for Selected MIL-STD-1540E Thermal Test Requirements

Testing to MIL-STD-1540E requirements over past decades has demonstrated its value in support of military programs for identifying design workmanship issues early, providing realistic flight environments, and demonstrating flight worthiness.

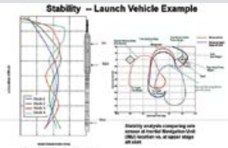
3. An Overview of Fastener Requirements in the new NASA-STD-5020

This presentation provides an overview of the contents of the new standard, including rationale for differences from NSTS 08307, and case studies to illustrate application of some of the concepts.



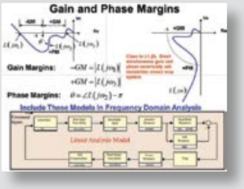
4. Fundamentals of Spacecraft Attitude Control

Spacecraft attitude control systems are onboard systems that autonomously orient a spacecraft relative to a target reference frame. An understanding of the disturbance environments in various flight regimes is critical to design choices.



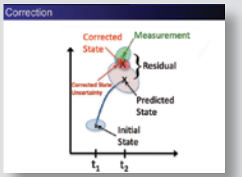
5. Fundamentals of Launch Vehicle Flight Control System Design

This presentation is intended to be an introductory overview of launch vehicle guidance, navigation, and control (GNC) for ascent. The video will look at the big picture of how these three disciplines are interconnected in a launch vehicle design.



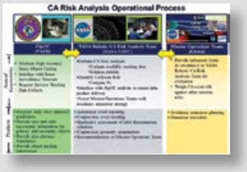
6. Fundamentals of Aircraft Flight Control

This short course covers the major control design issues and what to beware of in the design process and shows ways to design a robust control design method with some of the real world issues involved.



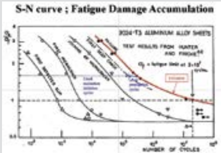
7. Fundamentals of Kalman Filtering and Estimation

Kalman Filtering and Least Squares Estimation have been at the heart of the GNC system design within the U.S. Space Program since its inception. Beginning with linear systems, the basic concepts will be introduced, and several examples will be presented.



8. NASA Space Situational Awareness (SSA) Overview

This talk describes the Agency's role in SSA, with particular emphasis on the robotic conjunction assessment effort. SSA policy, procedures, interfaces, and goals will be discussed.

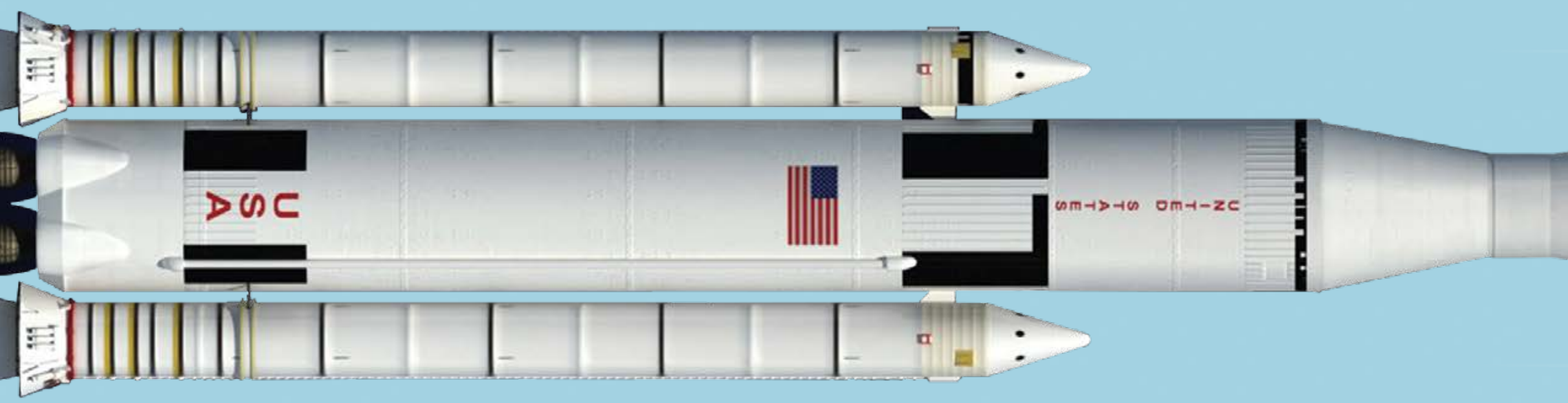


9. Metal Fatigue Part 1

This presentation provides a cursory overview of metal fatigue, which includes the basic elements of stress-life (S-N) fatigue, strain-life, and linear elastic fracture mechanics. Details regarding the micro- and macro-mechanics associated with metal fatigue crack nucleation, initiation, and propagation are also addressed.

10. The Evolution of Guidance, Navigation, and Control (GNC) in Mars Entry, Descent, and Landing (EDL)

This presentation describes the history of EDL GNC as represented by its functional and performance requirements, and the architectures and implementations needed to satisfy them. This video starts with the unguided Viking legged-landers, continues with the Mars Exploration Rover airbag-landers, and concludes with Curiosity's fully guided entry and SkyCrane-lander.



50 Years Later, the X-15 Is Still a Platform for Knowledge

An adaptive flight control system currently baselined for use on NASA's Space Launch System (SLS) borrows concepts from the design of the X-15, an experimental aircraft once operated by NASA and the U.S. Air Force. The manned hypersonic vehicle, which flew at speeds of up to Mach 6.7 and altitudes up to 350,000 feet, demonstrated new technologies including a "self-adaptive" control system. Though highly advanced for its time and successfully proven on previous flights, this control system contributed to a fatal X-15 accident in 1967. The initiating event for this accident was in essence an electrical anomaly, originating in an experiment payload, which coupled into the guidance, navigation, and control avionics creating a disastrous situation. And as is typically the case with accidents, additional compounding circumstances created a situation from which the pilot could not recover. ***See "Testing the SLS Adaptive Augmenting Control" – page 9.***

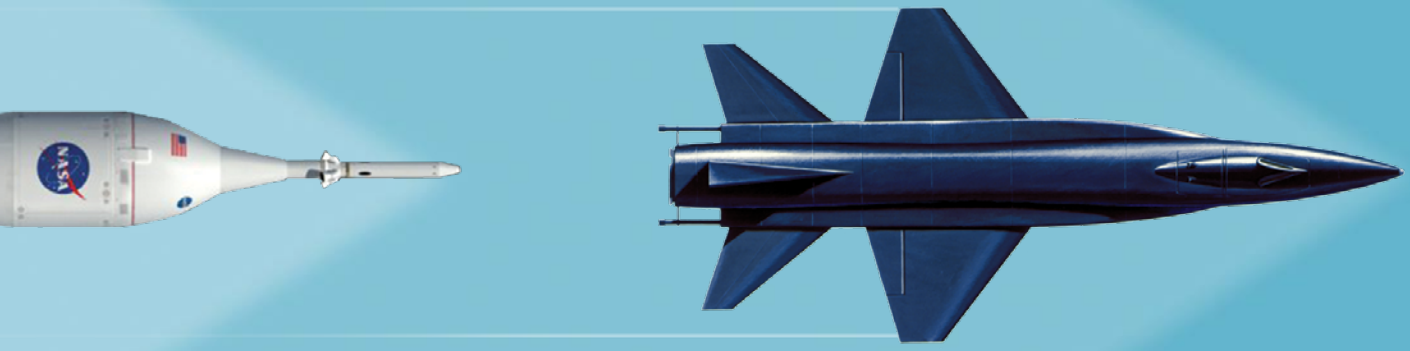
Learning from a 1967 accident

To more fully understand the role that the adaptive control system played in the accident, the NESC sponsored a comprehensive analysis of the X-15 mishap in parallel with the SLS adaptive control risk-reduction flight test effort that was conducted in 2013. The primary goal of the X-15 analysis was to evaluate the applicability of lessons learned not only to SLS but to other emerging aerospace systems. "New sub-orbital commercial concepts are proposing flight profiles similar to X-15 with fast reentries and high dynamic pressures, and will encounter similar flight control, system integration, and environmental challenges," said Dr. Jeb Orr of Draper Laboratory and a member of the NESC Guidance, Navigation, and Control Technical Discipline Team. "We need to understand to what extent lessons learned from the X-15 Program could be applied as risk mitigation to these emerging concepts." The X-15 analysis taught us about engineering, human factors, and design shortfalls that unfortunately resulted in a major accident. The SLS adaptive control algorithm design approach mitigated these shortfalls, and the 2013 flight test campaign advanced the technical maturity and flight readiness of the algorithm.

Test COTS equipment for use in its intended environment

Just before the 1967 accident, designers added a traverse probe experiment to the X-15 starboard wing pod to measure shock geometry. The experiment had flown previously on X-15 at lower altitudes without incident and was deemed acceptable for all flight environments. Unknown to designers, the probe's commercial-off-the-shelf (COTS) motor contained a high voltage component, which at higher altitudes caused arcing and introduced electrical disturbances into safety-critical aircraft systems. This started a chain reaction that led to the eventual breakup of the aircraft. ***See "COTS Components in Spacecraft Systems" – page 10.***

"A complacent culture develops that marginalizes risk," said Orr. As the X-15 had been flying for several years, it was viewed more as an operational versus experimental platform. Numerous X-15 modifications were added without a clear understanding of potential subsystem interactions with avionics hardware. Without the original design specifications for the motor, designers did not know the motor would generate high voltages. "They



“If today’s designers relied only on simulation, they may not have found this case”

—Dr. Jeb Orr

had put the experiment on another aircraft and didn’t see any problems and assumed, without doing rigorous analysis of hardware design, that it would be okay in all flight environments.” ***See “Protecting Against Failures from Nonessential Equipment” – page 8***.

For the X-15, the electronic hardware, combined with the pressure and temperature of the atmosphere at high altitude, led to the plane’s catastrophic electrical issues. Orr noted that ballistic space planes and crewed commercial concepts currently being developed are likely to spend more time in the same critical region as X-15 and experience the same types of environments.

Classical techniques can predict complex behavior

“There is a lot of insight to be gleaned from simple mathematical, rigorous analysis,” said Orr. To characterize the X-15’s flight control system, analysis techniques that were available during X-15’s operation were combined with new computer simulation tools to allow for quicker and more efficient evaluation of data.

Orr noted that today’s analysis methodology relies heavily on simulation, which has led to classical approaches falling out of favor. “Using approximation, or first order principles, to understand system behavior is absolutely paramount,” said Orr. “Then it can be coupled with simulation to understand the underlying physics.” Orr also noted that describing function (DF) analysis was used to understand the X-15 flight control system’s limit cycle oscillation behavior, which prevented the aircraft’s pitch recovery. “If today’s designers relied only on simulation, they may not have found this case,” said Orr. “DF analysis is thought of as a lost art, though it’s an insightful technique.” ***See “Describing Function” – page 8.***

Communication is key to situational awareness

During the X-15 flight, ground control staff did not communicate subsystem anomalies to the pilot, assuming the pilot had better situational awareness. In addition, not all flight data being telemetered was immediately available to ground control or required human analysis before recommendations could be made. This combination led to an overall lack of communication between the pilot and ground control, which contributed to confusion for the pilot, who also was receiving conflicting information from failing avionics systems. Orr noted that any anomaly of significance to aircraft safety should be relayed by ground control to the pilot or crew, even if it is redundant. This combination of events prevented the team from placing priority on restoring the X-15 to a safe state over the continuation of science objectives.

Design for the average human

“We need to design an interface for average humans, even if it is operated by astronauts,” said Orr. On the X-15, for example, the instrument panel had changed over time as

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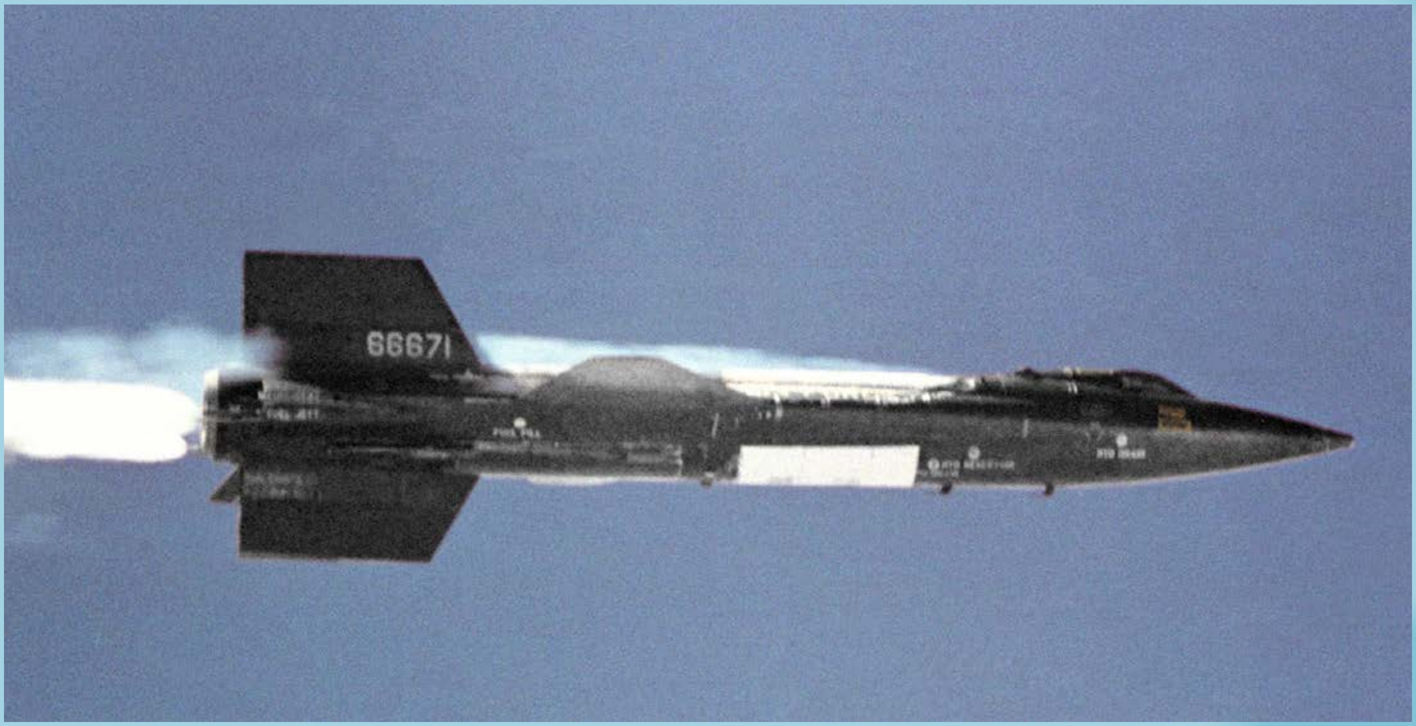


The X-15 was a high-altitude hypersonic research vehicle, operated by NASA from 1959 to 1968, used to support development of new technologies including propulsion, instrumentation, structures, thermal protection systems, and flight controls.

X-15, 50 Years Later

Continued

switches and indicators were added or moved, eventually leaving all three X-15 aircraft with different instrument panels. In addition, each aircraft had slightly different emergency procedures depending on what equipment was installed. "That was fine in 99% of flights, but when things went wrong, it led to confusion. Astronauts are highly trained, but in times of high stress, they need a simple interface that gives them an unimpeded ability to maintain the safety of the spacecraft and its crew." In the case of the X-15 accident, a primary contributing factor was a lack of mode indication on a critical flight instrument, which had been uniquely modified to support a specific science objective.

The X-15 accident followed a familiar pattern where several unrelated, but concurrent failures came together to create an unrecoverable event. Several subsystem anomalies occurred, which were considered benign in their individual subsystems, such as the limit cycle oscillation in the X-15's flight control system. "But because it was coupled with other failures, it did cause an accident," said Orr. "If things don't behave as expected, you have to be willing to stand down and understand the risk and threat before continuing flight operations." □

Reference NASA/TM-2014-218538

Describing function

Describing function (DF) analysis is a classical technique to predict the behavior of certain types of nonlinear control systems. The technique was developed in the early twentieth century partly to provide an analytical method to supplement the limited computer capabilities of the time. Now, combining classical theory with modern numerical simulations, DF analysis has re-emerged as a mathematically rigorous and powerful tool for helping control engineers understand why and under what conditions nonlinear control systems oscillate in undesirable ways.

Protecting against failures from nonessential equipment

NASA spacecraft and commercial aircraft designers now go to great lengths to protect flight-critical systems from potential hazards generated by "nonessential" systems such as experiments flying on the International Space Station or in-flight entertainment systems in commercial aircraft. Engineers also went to great lengths to protect flight-critical avionics in the Space Shuttles from problems with experiments that operated in the orbiter's payload bay.

Test trajectories flown repeatedly by NASA's F/A-18 while testing the SLS AAC.

Testing the SLS Adaptive Augmenting Control

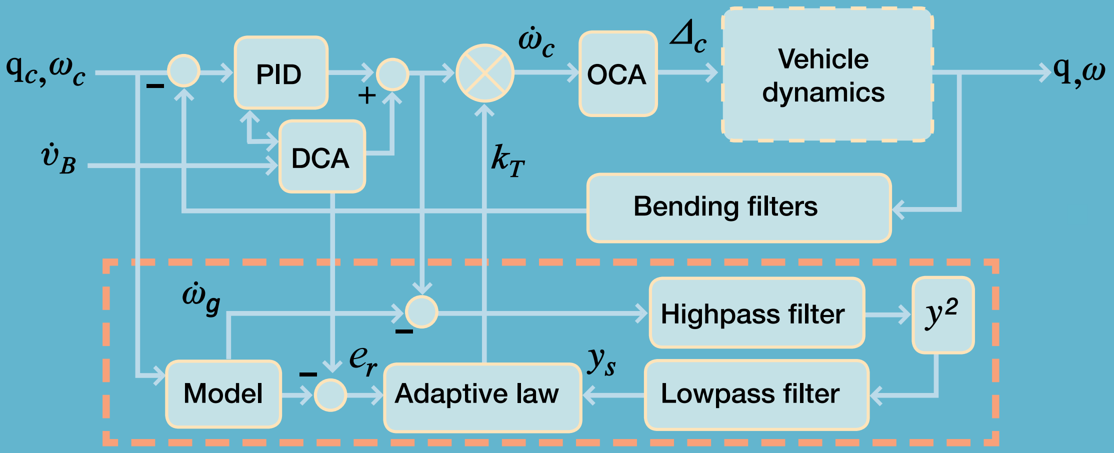
In 2013, a partnership of NASA organizations including MSFC, AFRC, NESC, and the Science and Technology Mission Directorate Game Changing Technology Office, conducted a series of F/A-18 research flights to test Space Launch System (SLS) prototype software, including the previously untested adaptive augmenting control (AAC) component.

Because SLS will deliver more payload to orbit and produce more thrust than any other vehicle, past or present, it opens the way to new frontiers of space exploration as it carries the Orion Multi-Purpose Crew Vehicle, equipment, and experiments into new territories. The addition of AAC to SLS offers significant benefits to the total attitude control architecture by providing the fixed gain control architecture with additional robustness. AAC increases flight control system (FCS) performance when excessive tracking error is present and decreases responsiveness to undesirable frequency content. It expands the envelope under which the FCS is capable of safely flying the vehicle, maximizing vehicle survivability and crew safety.

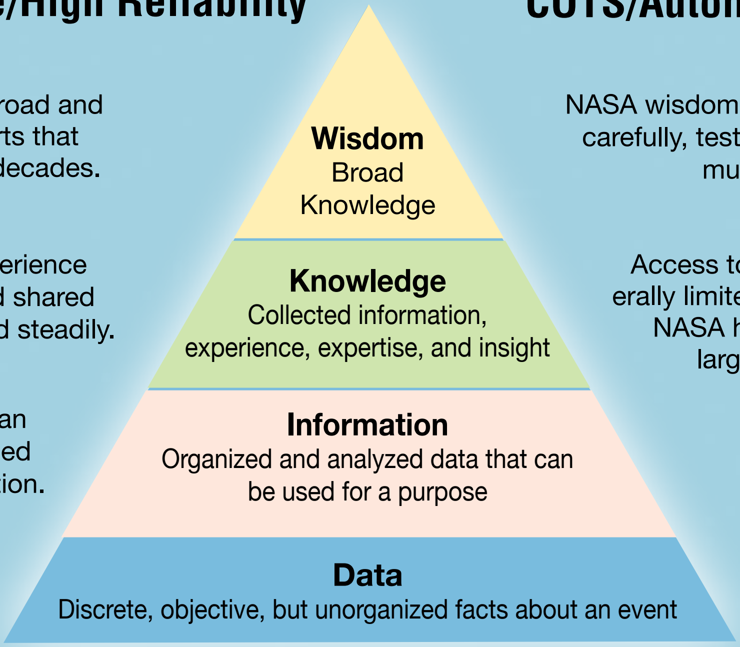
If there were no vehicle or environmental uncertainty, a fixed-gain controller could be optimized prior to flight with no need for adaptation; however, a review of historical reusable launch vehicle data from 1990 to 2002 revealed that over 40% of failures resulting from other malfunctions might have been mitigated by advanced guidance, navigation, and control technologies. Thus, an algorithmically simple, predictable AAC design with direct ties to classical stability margins was implemented for SLS. It was initially formulated and tested during the former Constellation Program, then refined as part of the baseline autopilot design and flight software prototype for SLS.

During flight testing on the F/A-18 Full-Scale Advanced Systems Testbed aircraft at AFRC, the aircraft completed a series of trajectories during multiple sorties with the SLS FCS enabled. The aircraft's pitch rate was matched to the SLS and matching attitude errors for various nominal and extreme SLS scenarios were incorporated through the use of a nonlinear dynamic inversion controller. The emphasis of the 100-plus SLS-like trajectories was on fully verifying and developing confidence in the AAC algorithm in preparation for the first uncrewed launch of SLS. □

Reference NASA/TM-2014-218528



Simplified block diagram of the SLS flight control system.



Military/Aerospace/High Reliability	COTS/Automotive/COTS Plus
NASA wisdom is based on broad and deep knowledge of these parts that has enabled reliable use for decades.	NASA wisdom says: use these parts very carefully, test extensively, and gather as much knowledge as possible.
Extensively documented experience (good and bad) collected and shared about parts that have evolved steadily.	Access to detailed information generally limited to important customers. NASA has limited experience with large-scale use of these parts.
Data generated over more than 40 years analyzed and reported to provide extensive information.	Market-focused reports available. NASA must generate own information.
NASA has ready access to mandated data, common to all suppliers.	Manufacturers supply extensive data aimed at their target market.

COTS Components in Spacecraft Systems: Understanding the Risk

NASA's Commercial Crew Program (CCP) is stimulating efforts within the private sector to develop and demonstrate safe, reliable, and cost-effective space transportation capabilities to the International Space Station. One initiative involved investigating the possible use of commercial grade electronic parts in launch vehicle and spacecraft designs. The CCP was interested in data that would help frame the technical, cost, and schedule risk trades associated with the use of electrical, electronic, and electromechanical (EEE) parts of a lower grade than traditionally used in most NASA safety-critical applications.

The fundamental question

The fundamental question is "Can commercial-off-the-shelf EEE parts with limited screening be used in crewed flight hardware systems?" The terms "commercial-off-the-shelf parts," or "COTS," and "screening" are broadly defined and not applied consistently. Automotive, commercial aviation, medical, and safety conscious consumer electronics industries engage in assurance processes within their supply chain to establish a basis for the quality and reliability of the EEE parts used in their products before assembling them into critical applications. These assurance processes, with inspections and tests possibly performed on a sample basis depending on criticality, are intended to identify defects and abnormalities that serve as warning signs of a potential for premature failure, reduced performance, and safety.

Parts screening approaches

There is a wide spectrum of approaches to parts screening. At one end of the spectrum, EEE parts used in critical space systems in general are subjected to 100% parts-level inspections and testing to provide high assurance of quality and reliability. At the other end of the spectrum are commercial catalog parts that have not been subjected to any testing other than those established by the manufacturer. An NESC team analyzed two COTS parts screening approaches: one that employs only card-level testing coupled with box-level and system-level testing versus the traditional approach of screening at the parts level prior to card, box and system-level testing. The team concluded that there are fundamental concerns with replacing parts-level screening and qualification with card and box-level or system-level testing only.

Assembling COTS EEE parts on circuit boards for space applications without proper parts-level qualification or additional screening could result in assembling good parts along with any weak parts (parts containing latent defects and infant mortals and/or parts not suitable for the application) into flight hardware, with the questionable assumption that board-, box-, and system-level testing can effectively identify parts that might fail during the anticipated mission lifetime. Proper parts-level qualification is essential to: 1) ensure the part technology, design, and construction is capable of predictable and required performance in the space environment and 2) identify parts that function properly in terrestrial applications but may not perform safely in the more extreme space radiation, vacuum, vibration, and thermal environments found in spaceflight applications. Card-level, box-level, and system-level testing cannot replicate accelerated failure factors that voltage, current, and temperature stresses can provide during parts-level screening prior to installation on a circuit board.

Commercial parts use at NASA

NASA has successfully used commercial parts in spacecraft for specific and sometimes mission-critical applications throughout the Agency's history. This has been achieved by careful selection, qualification, and screening. The level of screening required for commercial parts to ensure they will work successfully is highly dependent on the mission, intended application, environment, mission duration, and part technology. The level of screening is quite well characterized in existing NASA parts documents such as EEE-INST-002. NASA flies non-MIL (non-military) grade parts when the required functionality and/or performance is not available in MIL parts. If a MIL part can be used, they are preferred.

Initial qualitative analysis indicates significant differences in reliability and safety can result between screened MIL parts and unscreened commercial parts. Parts quality, architecture (including the selection of like or diverse backup systems), and mission duration are inseparable variables that must be traded in a mission design. One system architecture could use lower grade parts for short-duration missions (a few minutes to a few days) and possibly exhibit acceptable analytical system reliability. That same architecture may not provide the analytical reliability required for long-duration missions (a few weeks to many months) when using lower grade parts. Parts quality dominates system reliability in long-duration missions where environmental effects like space radiation and single event upsets are more likely to occur. A system design for long-duration missions is an example where NASA would typically employ in critical applications high reliability space-qualified military grade parts or use highly screened and qualified COTS parts.

Alternative approaches

Any alternative approach for the use of COTS EEE parts in critical applications other than those that have proven successful, such as described in EEEINST-002 or similar NASA documents, requires a firm basis for substantiation. Any approach based on architecturally similar redundancy and card-level, box-level, and system-level testing alone is not sufficient to enable widespread use of unscreened parts acquired from commercial catalog distributors in critical applications. To reduce the likelihood that parts failures result in unacceptable mission risk, standard practice dictates designers to: 1) develop and implement a systems engineering-oriented mission assurance program to address EEE parts derating, qualification, traceability, and counterfeit control, and demonstrate how it mitigates the risks associated with EEE parts applications, and 2) provide data supporting the effectiveness of the proposed screening approach, ensuring part failure rates are adequately bounded. □

Important definitions

COTS: An assembly or part designed for commercial applications for which the item manufacturer or vendor solely establishes and controls the specifications for performance, configuration, and reliability (including design, materials, processes, and testing) without additional requirements imposed by users and external organizations. For example, this would include any type of assembly or part from a catalog without any additional parts-level testing after delivery of the part from the manufacturer.

COTS Plus: A COTS part supported by test data available to end users establishing random failure rate assumptions, performance consistent with the manufacturers data sheet and methods to exclude infant mortal parts, parts with latent defects, weak parts, or counterfeit parts. For example, automotive electronics council-certified or compliant automotive parts are one type of COTS Plus.

Parts Qualification: Sample-based mechanical, electrical, and environmental tests at the piece parts level intended to verify that materials, design, performance, and long-term reliability of parts on the same production line are consistent with the specification and intended application until a major process change.

Parts Screening: A series of tests and inspections at the piece parts level intended to remove nonconforming and/or infant mortal parts (parts with defects that are likely to result in early and/or cluster failures) and thus increase confidence in the reliability of the parts selected for use.

Reference NASA/TM-2014-218261

Under Pressure: LPVs Feeling the Effects of Age

More than 300 layered pressure vessels (LPVs) are in operation at NASA facilities across the country. Gases such as helium, hydrogen, methane, nitrogen, and air are stored under high pressure in these LPVs and supply a variety of NASA test facilities like wind tunnels and engine test stands. The vessels vary widely in size and operate under a broad range of pressures and temperatures, but they all share one common denominator: age.

Past the 50-year mark

Built in the 1950s and 1960s, many have passed the 50-year mark and are now at risk for age-related concerns. "You start to worry about things like fatigue, cracks, corrosion, environmental degradation, and embrittlement," said Dr. William Prosser, NASA Technical Fellow for Nondestructive Evaluation (NDE). Also built prior to the inclusion of LPV construction methods in American Society of Mechanical Engineers boiler and pressure vessel codes, they are at a higher risk as "non-code" vessels.

To ensure the continued safe operation of LPVs at NASA, the NESC established a team of experts from across NASA Centers to develop a proposal for test and analysis methods to keep age-related concerns in check, a task made more difficult by the LPV design itself. "Because of this layered structure, it's hard to see into the layers to detect flaws in the welds," said Prosser.

Establishing consensus on a plan forward was a top priority. "Every Center had a different level of background and understanding of the nature of the problem, had tried different methods, and had different perspectives on what should be done," Prosser noted. ***See "A Brief History of LPVs" – page 13.***

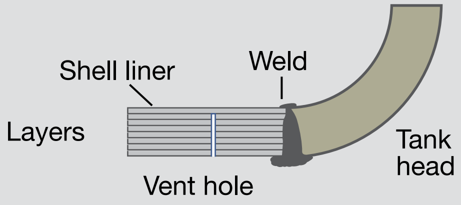
Assessing the future of LPVs

As for the LPVs themselves, many weren't originally built for NASA, but for the Department of Defense or other government entities, which meant little or no information existed on vessel history – how they were used, pressures they were subjected to, or materials they once contained.

The assessment began with reviewing any available inventory information, like manufacturer, age, condition, rated and operating pressure, contents, layer thickness,

Typical large facility layered pressure vessels can be pressurized to 5,000 psi.

Section of weld between layered tank cylinder and single layer tank head (top) with cut-away illustration (bottom).



and more. NDE history and inspection methods were reviewed, as well as risk mitigation methods used by each NASA Center. Locations within government and private industry were also surveyed. The goal was to prioritize risks and determine what could be done to “buy down the most risk,” said Prosser.

The assessment also involved testing and analysis. Material evaluations of tensile strength and fracture toughness of materials and investigations of the microstructure of weld regions were performed at MSFC. The MSFC NDE team also provided acoustic emission test support. Photogrammetric techniques to measure vessel deformations on an LPV not in service were conducted at GRC. Some phased array ultrasonic technique (PAUT) NDE development was done in coordination with MSFC, SSC, and LaRC.

In the end, several near-term and long-term recommendations were identified. Near-term recommendations could be implemented immediately, such as inspecting vent holes to ensure they aren’t blocked or corroded; monitoring for product loss, which could indicate an inner shell failure; imposing service restrictions; implementing physical barriers; and developing a standard Agency process for LPV usage and centralized information database.

Long-term recommendations included extensive materials testing and the development and validation of analysis methods and NDE techniques to address high-risk conditions. The assessment revealed that the PAUT technique holds promise for inspecting specific LPV welds. ***See “About PAUT” – above right.***

A brief history of LPVs

The LPV fabrication method was developed in the 1930s. As the need grew to hold liquids and gases at higher pressures, thicker-walled vessels were required, but building vessels from a single, thick plate of steel became difficult. Manufacturers discovered that high-strength thin steel plates had better material properties, could be easily rolled, and were less expensive to fabricate. These thin sheets were layered together and welded, creating an LPV that could withstand pressures up to 10,000 psi. While fewer than 24,000 LPVs have been fabricated, a number of known catastrophic failures have occurred in both code and non-code vessels.

About PAUT

Circumferential shell-to-head welds, which join the LPV domed single layer tank head to the cylindrical layered body, are of particular interest, since the area can develop cracks, which has led to catastrophic failure. PAUT inspection offers advantages over conventional ultrasonic inspection techniques. A phased array ultrasonic probe contains a number of elements that each emit an ultrasonic wave. By electronically varying the timing of the excitation of the different transducer elements, the resulting ultrasonic beam can be “steered” in different directions. This approach indicated the shell layers intersecting the shell-to-head weld region had a number of flaws in a test vessel.

While simply replacing aging LPVs would eliminate the most risk, the cost and schedule impact would soar into the billion dollar range, Prosser said. “It’s a problem we’re not going to immediately take care of by replacement. We’ve got to better understand these vessels to manage our risks effectively.” Government and industry users of LPVs are already requesting copies of the assessment results. “They were very interested in learning from our experience,” he said.

Working together with the NASA pressure systems managers as well as experts in materials, inspection, and structural analysis from the NESC Technical Discipline Teams, Prosser said the insight gained during the assessment was invaluable. “It was certainly a challenge,” he acknowledged, “but the opportunity to learn about critical engineering issues, new technologies, and applications is always fun.” □

Reference NASA/TM-2014-218505

Tackling Hybrid Control is Right in the GNC Wheelhouse

The NESC's Guidance, Navigation, and Control (GNC) Technical Discipline Team (TDT) is sharply focused on the development of hybrid attitude control approaches and techniques for NASA spacecraft. The necessity for such hybrid techniques has grown in the last several years as science spacecraft, some working in extended mission operations, have been rendered nonfunctional or placed in jeopardy after crippling reaction wheel failures. ***See "Reaction Wheel Basics" – page 16.***

"Failures have occurred both before and after primary mission completion," said Mr. Neil Dennehy, the NASA Technical Fellow for GNC. "Fortunately, many project teams were able to successfully develop and implement a hybrid attitude control scheme, using both the remaining functional wheels and the thrusters. This allowed these spacecraft to continue in a scientifically productive mode using nonstandard mixed-actuator techniques to obtain three-axis control with only two wheels."

The story of hybrid control

The challenge in implementing hybrid attitude control, said Dennehy, is manipulating the physics of an under-actuated space vehicle, harnessing the remaining attitude control actuators, and often exploiting naturally occurring disturbance torques. "The project teams that have faced the challenges of dealing with failed reaction wheels have responded with clever and implementable solutions for hybrid attitude control. What they accomplished is a great feat of engineering and flight operations innovation," Dennehy said. The end result is a restructured, but effective, configuration and operating mode for these spacecraft, though one likely not envisioned by the designers of the original attitude control system (ACS).

With billions of dollars invested in spacecraft assets, which are collecting invaluable science data, the need to keep those spacecraft operational for as long as possible, in today's economic climate, is a clear-cut goal. "NASA has a history of trying to squeeze more and more out of its science spacecraft," said Dennehy, putting the development of successful hybrid ACS at the top of the GNC "to do" list.

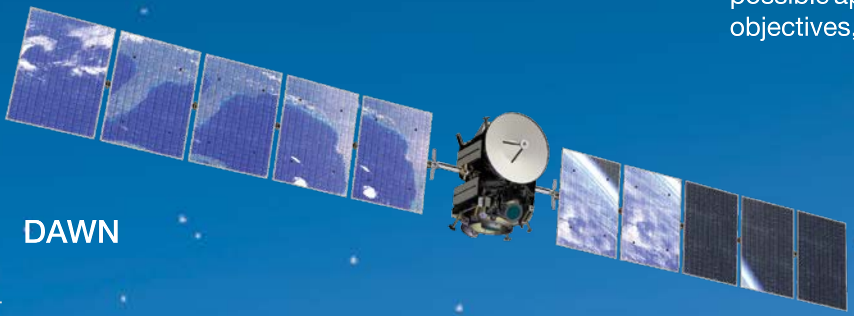
Since reaction wheel problems began emerging in 2001, efforts have been underway to address the issue. In early 2007, NASA formed a tiger team to investigate the wheel anomalies and failures occurring on spacecraft, and in spring 2013, the NESC sponsored a NASA workshop on Hybrid (Mixed-Actuator) Spacecraft Attitude Control, gathering key personnel from across NASA Centers and industry for a 2-day delve into contingency spacecraft attitude control techniques.

At the workshop, discussions revolved around previously successful hybrid control techniques developed by the ACS teams for spacecraft such as Far Ultraviolet Spectroscopic Explorer (FUSE) and Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED). Brainstorming sessions were held to tackle current issues faced by Kepler, Dawn, and Mars Odyssey spacecraft.

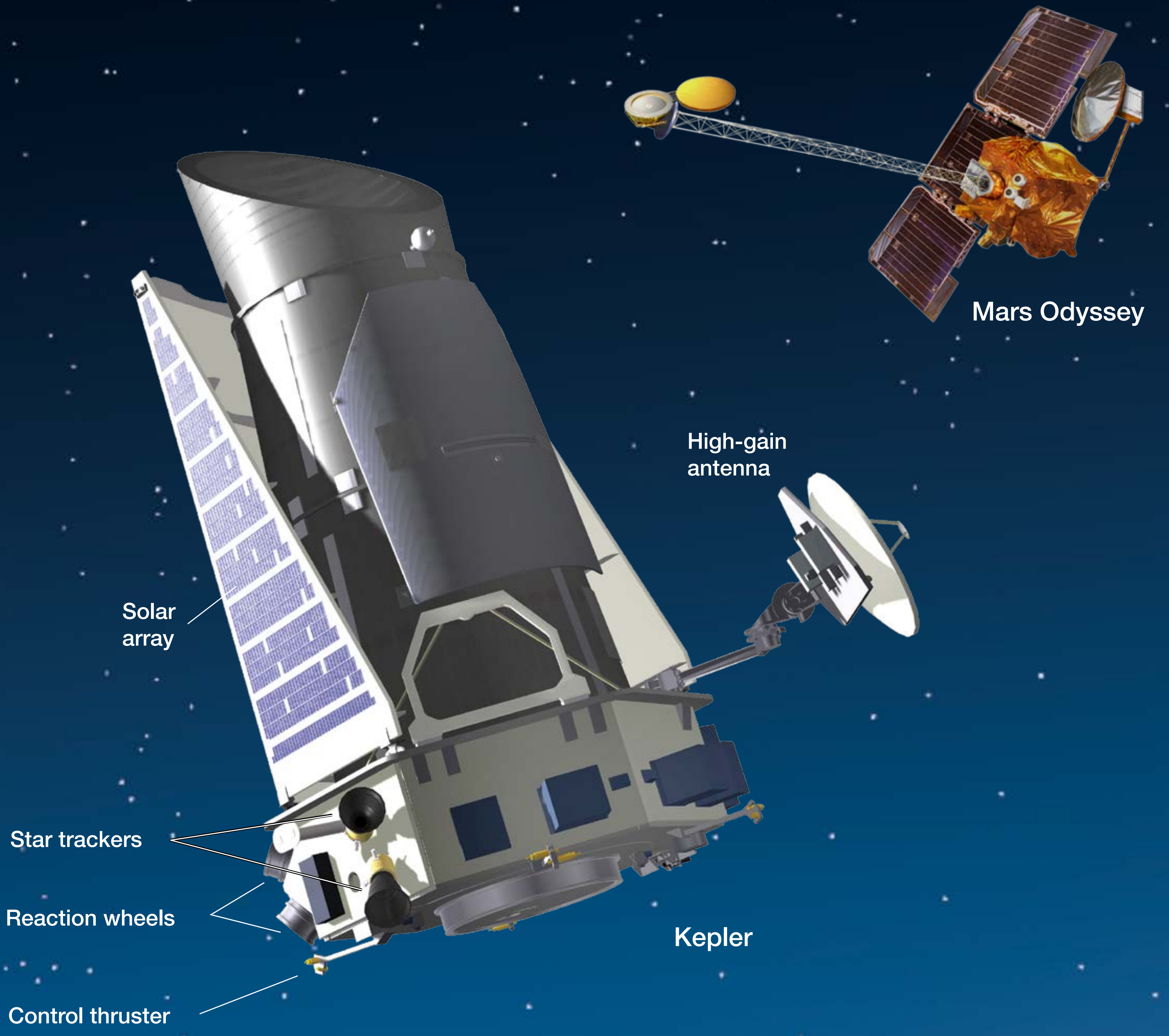
Seven different spacecraft were discussed at the workshop, and Dennehy said that the range of hybrid control implementation challenges was just as varied. What they quickly discovered was that a mission's operational requirements, a spacecraft's physical configuration, ACS architectures, and more, all play a huge role in the development of a successful hybrid approach. As presentations and discussions ensued, a revealing list of lessons learned emerged, some of which came into play sooner than expected. ***See "Top Five Takeaways for Hybrid Control" – page 16.***

Extending the Kepler Mission

Not long after the workshop, Kepler suffered the loss of a second reaction wheel, leaving the spacecraft with only two operational wheels. After issuing an open call seeking innovative hybrid attitude control ideas for possible application in repurposing Kepler for new science objectives, the NESC coordinated a spacecraft pointing



DAWN



technical interchange meeting (TIM) to evaluate those ideas. Today, after the successful development of a new two-wheel/thruster hybrid controller by the spacecraft's prime contractor, Kepler is once again collecting valuable science data. ***See "About Kepler" – page 16***.

"Initially it looked like the Kepler Mission was done," said Dennehy. "But the project team and the GNC community felt something could be done to regain three-axis attitude control. We used the pointing TIM as a forum for the project to hear and evaluate a wide variety of hybrid control ideas from the community that could potentially help accomplish new types of Kepler science observations. It was a real group effort to get Kepler back on the air, pointing sufficiently to perform science. Collectively we were able to accomplish that, and that's a big deal. Kepler isn't collecting exactly the same science data as it was originally, but it's doing some very scientifically valuable observations."

The future of hybrid control

Following Kepler's success, research continues at the Naval Postgraduate School, under NESC sponsorship, to evaluate nonlinear hybrid attitude control concepts, ideally for Kepler, but which may have broader applicability to other NASA under-actuated spacecraft. These concepts would work without the use of propellant-consuming thrusters, employing only the two remaining functional wheels.

In the near future, Dennehy envisions a second workshop to continue efforts in developing hybrid ACS techniques. "Hybrid attitude control has a background that dates back more than a decade, and it is still a dynamically evolving area of research and practice," he said. "This is the kind of challenging problem a GNC engineer likes to work on." □

Reference NASA/TM-2014-218539


TIMED

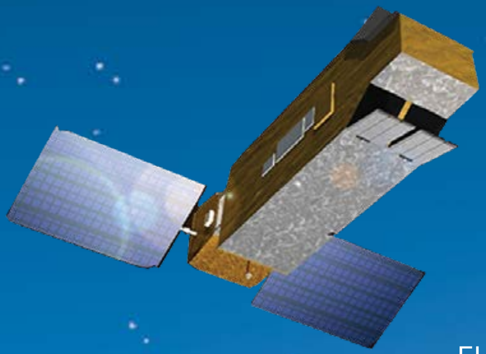
About Kepler

Launched in March 2009, the Kepler spacecraft was tasked with performing a photometric survey of approximately 100,000 stars in a section of the Milky Way near the constellation Cygnus. Its mission was to detect planets and determine the prevalence of Earth-sized planets in or near the habitable zone. Planet detection required Kepler to maintain a pointing stability of better than 9 milliarc-seconds for science observation periods longer than 30 minutes.

Near the end of Kepler's 3.5-year prime mission, a reaction wheel failed when its friction increased beyond the attitude control law's torque command. A second wheel was lost in May 2013, which prompted the Kepler Project to request support from the NESC GNC TDT and spurred the development of a two-wheel hybrid controller at Ball Aerospace (the Kepler prime contractor). A known challenge, GNC engineers at Jet Propulsion Laboratory had already conducted a hybrid control feasibility study that showed achieving Kepler's original long-term pointing stability with only two wheels would be unlikely.

In parallel with Ball Aerospace, members of the GNC TDT independently worked to analytically demonstrate the feasibility of a bias-momentum hybrid control approach for Kepler. Results obtained by Ball engineers and the GNC TDT compared favorably, and the new Ball-designed two-wheel/thruster hybrid controller was implemented on the repurposed Kepler observatory, called K2.

K2 is now successfully collecting science data using this hybrid attitude control. The momentum bias, created by the combination of the two remaining wheels, will be oriented normal to the Kepler spacecraft's orbital plane so targets in that plane can be tracked by modulating the bias. K2 will be pointed in the ecliptic plane to exploit the solar radiation pressure disturbance torque rather than fight it. In December 2014, the K2 mission logged its first exoplanet discovery of a planet 2.5 times the diameter of Earth, named HIP 11645b, proving K2 is once again performing valuable science.


FUSE

Reaction wheel basics

Reaction wheel (RW) technology provides spacecraft attitude control torque and momentum management functions. RWs rotate the spacecraft and are frequently used for stabilizing, slewing/orienting, and precision pointing spacecraft platforms. Typical RW actuators consist of a rotating inertia flywheel, a wheel suspension system (almost exclusively lubricated bearing balls), a wheel drive motor, and wheel drive electronics encased in a wheel housing/enclosure. RWs are used in Earth and Mars orbiting spacecraft as well as on interplanetary vehicles, with a typical complement of four RWs providing a redundant three-axis attitude control capability. While the failure of one RW can typically be managed, the failure of two wheels poses a significant challenge for accomplishing some form of three-axis attitude control.

Top five takeaways for hybrid control

No one hybrid solution is applicable to all spacecraft, but some key lessons learned are applicable to all ACS hybrid design.

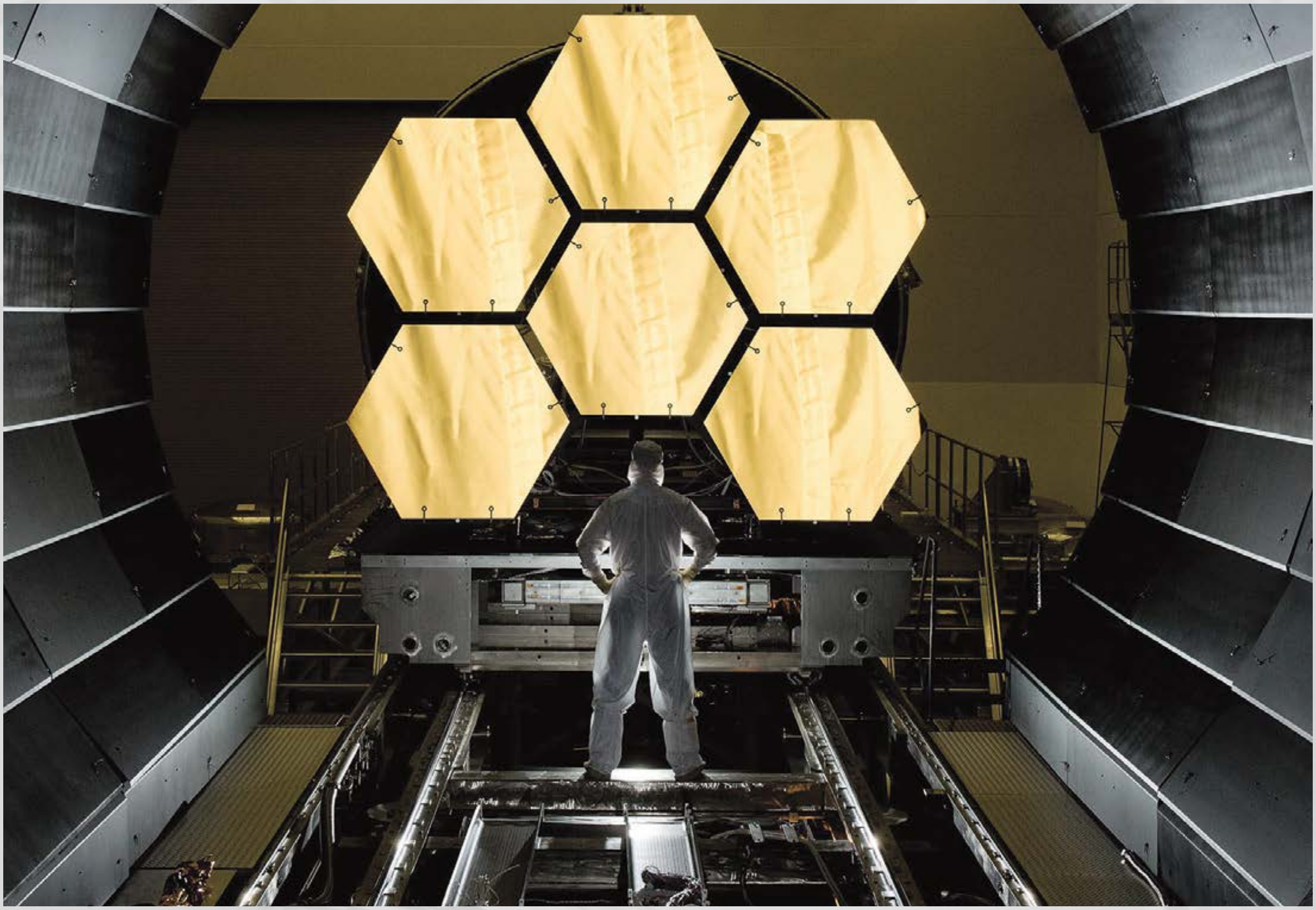
1. While successful hybrid (mixed actuator) ACS techniques have extended the science productivity of several NASA spacecraft, prelaunch considerations for implementing hybrid attitude control were nearly non-existent. ACS architectural considerations early in system development may facilitate hybrid control implementations in the later stages of mission life.

2. There are advantages to considering a bias-momentum approach when designing a two-wheel-based hybrid control system, as was successfully implemented on the repurposed Kepler.

3. Spacecraft fault management/safing/safe mode aspects should be carefully considered when designing new hybrid control modes.

4. Maintaining ACS flight software testbeds whenever possible will aid in flight readiness recertification efforts in the face of wheel in-flight anomalies.

5. On-orbit testing of spacecraft attitude controllers in hybrid ACS configurations, especially near the end of life, is wise and will likely benefit future spacecraft missions.



Ball Aerospace

The first 6 of 18 segments that will form the James Webb Space Telescope primary mirror.

Preparing to See into the Past

The James Webb Space Telescope (JWST) will be the world's largest infrared, space-based observatory. It features a more than 21-foot primary mirror and is expected to launch in 2018. A successor to the well-known Hubble telescope, JWST will be able to see back to the beginnings of the known universe, the earliest formation of galaxies, and the birth of planetary systems. To allow JWST to look back in time, the software development team at GSFC took an integrated computer-aided software engineering (CASE) approach to design the complex software. The team employed a modern suite of modeling and development tools based on the Unified Modeling Language (UML). ***See "Model-Based Systems Engineering" – page 20.***

Enhancing systems integration

Two critical systems, the integrated science instrument module (ISIM), which integrates all the hardware and software to support the JWST science instruments, and the core command and data handling (C&DH) software, were developed this way, as were all the applications controlling the specific science instruments. "The use of an integrated CASE tool suite for development was primarily to reduce the complexity of integration of all the independently developed instrument software," said Mr. Michael Aguilar, NASA Technical Fellow for Software. Several NASA Centers, along with partners from industry, academia, and the European Space Agency were involved in the software development at their individual facilities, following their own review processes.

Standardized development tools

The project team standardized the use of IBM's Rational Rose CASE tool for the JWST software design, coding, testing, as well as integration. Taking full advantage of the tool, "The ISIM Flight Software Development Team was one of a few organizations in the high reliability spaceflight environment to use the tool's auto-source code generation aspects," Aguilar added. The team coded within the UML

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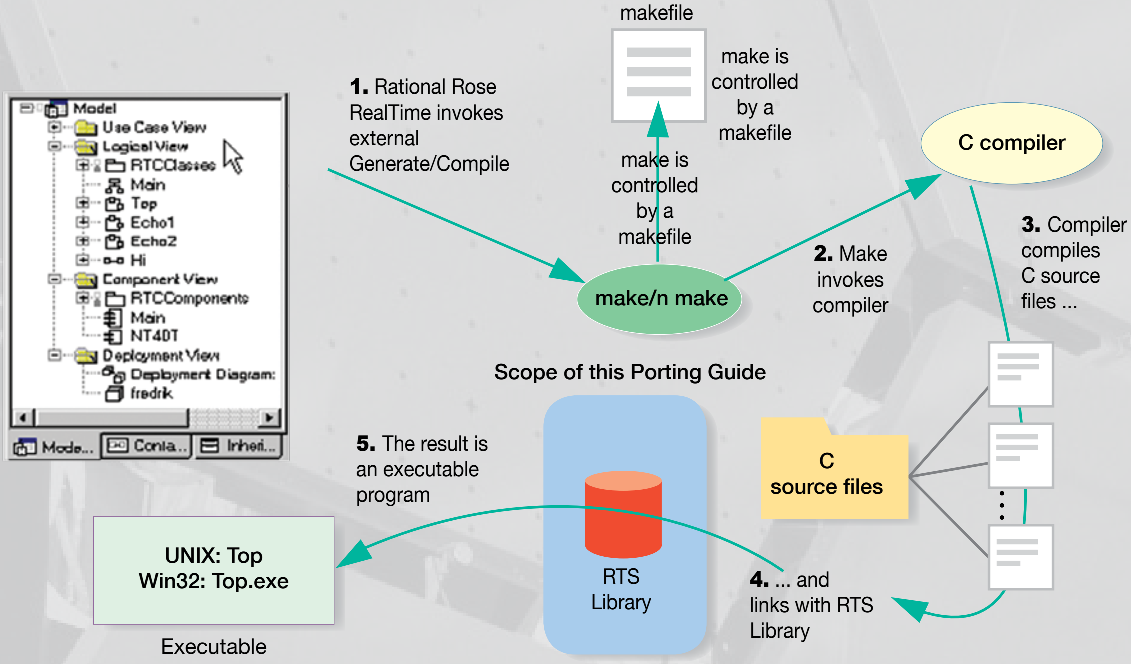


Software development environment provided by IBM's Rational Rose CASE tools.

design model elements, ensuring code and design were always in sync, significantly increasing productivity as design and code reviews no longer required resource-intensive review material preparation.

A built-in software documentation tool and document templates were used for automated creation of code and design review documentation using model elements and database contents. The IBM Rational Requisite Pro tool suite was used for requirements management. Requisite Pro was part of the integrated tool suite that provided links to the configuration management and defect tracking tools and enabled traceability down to the source code implementation levels. "The tools helped facilitate concurrent development by the multi-developer teams," Aguilar noted.

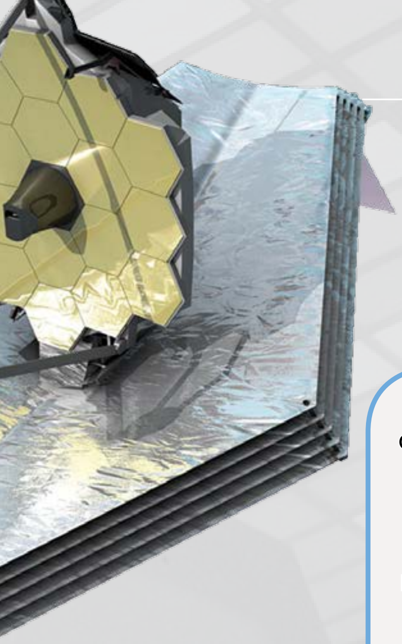
Accruing benefits

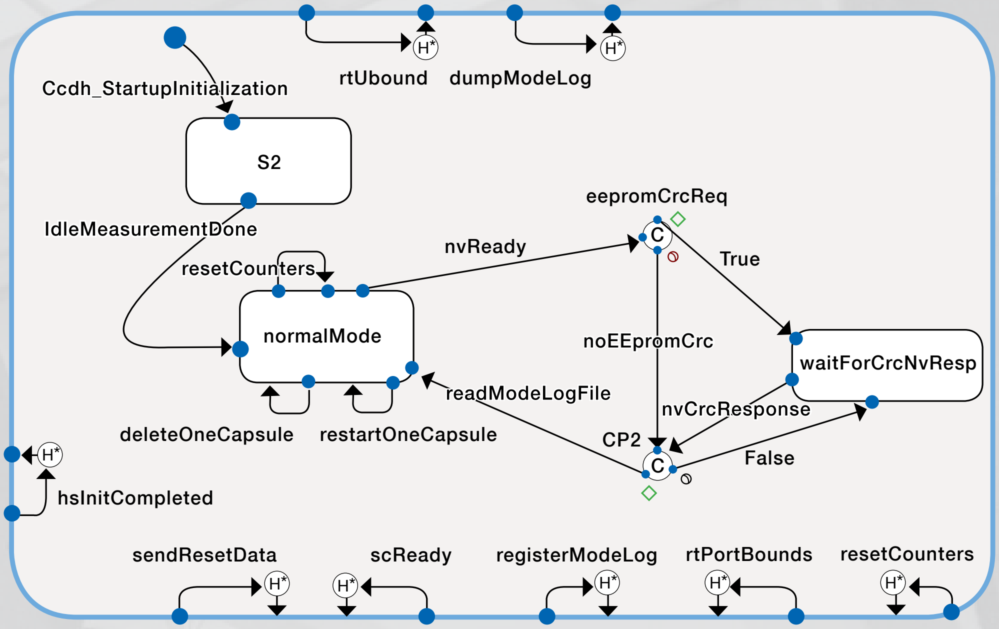
The ISIM Ground System Support Team delivered more than 21 commercial-off-the-shelf-based development, test, and integration systems to validate and qualify flight instrument hardware for space. ISIM flight software was used to qualify flight hardware for space through formal box-level environmental testing, test procedure development and operator training, and to develop and certify operational scripts for spaceflight use. "The cost and effort in the development and maintenance of these test systems paid off when the effort of integration of all the software completed within 1 week of delivery," said Aguilar.

The code generated by the CASE tool was found to be acceptable for the mission. The compiled code passed unit, subsystem, and system testing in an environment identical to previous mission testing environments. Static code checkers performed source code analysis to ensure specific standards were being followed, coding language issues were addressed, and coding errors were identified.

Over the course of the project, about 25 software build cycles were required for the ISIM and C&DH code, with each build encompassing a feature that could be functionally tested. Each software build was verified with a build integration test quality check before being passed to the test team, which performed an independent functional build verification test in parallel with the next software build. Similar build cycles occurred across the partner teams developing the science instruments. This overlapping schedule continued until all required features were implemented.

Ultimately, the choice of a common set of development tools and incremental and iterative software development processes could respond to changes in requirements rapidly and fit into the NASA system-level project waterfall requirements and schedule. □





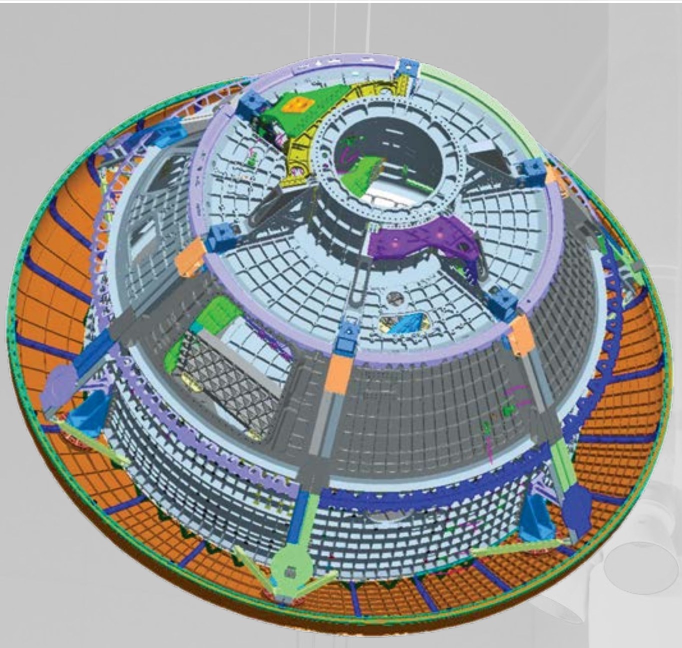
Example of UML statechart used on JWST for state machine modeling.

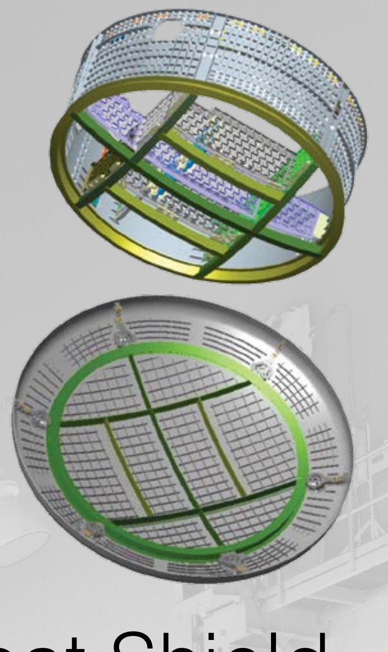
Model-Based Systems Engineering (MBSE)

MBSE is a formalized methodology for implementing the processes and practices of systems engineering through the use of models and modeling. In practice, it is the application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. MBSE encompasses requirements, behavior, architecture, and the validation and verification in one system-level model, regardless of hardware or software implementation.

Model-based engineering has been practiced for years in discipline-specific areas. Examples include computer-aided design for developing two or three-dimensional models of physical objects, finite element models to examine the physical behavior and response of structures, and electronic circuit simulation tools to examine circuit performance are just a few examples. Current MBSE efforts are working to incorporate the discipline-specific models into the system-level model for increased accuracy of system-level performance predictions. To deal with the rise of software-intensive systems, a new concept of designing software was introduced in the ‘70s, called computer-aided software engineering (CASE). This term is used for a new generation of tools that applies rigorous engineering principles to the development and analysis of software specifications, which have now evolved to cover the complete software engineering lifecycle process. The term integrated computer-aided software engineering (I-CASE) was introduced and includes tools capable of generating entire executable applications from design specifications.

These new methodologies enable rapid prototyping techniques to develop systems faster, at lower cost and higher quality. By using a prototype, the developed system can be tested more often in between the development phases. Design decisions can be validated, and design errors can be detected and corrected early in development to produce systems more efficiently and effectively. □





Far Left: **Proposed titanium orthogrid heat shield carrier mounted to crew module pressure vessel.**
Left: **Heat shield carrier structure** *(top)* **and corresponding lower portion** *(bottom)* **of pressure vessel with "H-beam" backbone interface structure.**

An Alternate Orion Heat Shield Carrier Structural Design

To carry astronauts beyond near Earth orbit to rendezvous with asteroids, the Moon, or Mars, the Orion Multi-Purpose Crew Vehicle (MPCV) must be as light as possible, and spacecraft engineers are always looking for ways to "take mass" out of a design. Weighing in at over 3,000 pounds and just over 16 feet in diameter, the Orion crew module (CM) heat shield carrier structure offered the best opportunity to shave off a bit of weight – about 800 pounds in fact, or 25% of its mass. While the Orion MPCV Team worked hard to reduce mass in this area, the Orion MPCV Chief Engineer requested the NESC study the heat shield carrier and develop alternate designs to the structure.

The carrier structure must hold the thermal protection system heat shield securely to the Orion CM while facing launch, reentry, and splashdown impact loads, including 4,800° F reentry temperatures. Its baseline construction, made of titanium and composite carbon graphite skin to hold the Avcoat ablator thermal protection system, was an agile design that could be easily manipulated and changed, but the Orion MPCV Program needed to know if it was the most mass-optimum design.

Mr. Michael Kirsch, NESC Deputy Director who was then an NESC Principal Engineer, led the NESC assessment team that included members from industry, contractor partners, and NASA Centers including JSC, GSFC, LaRC, and MSFC. The team developed several alternative concepts, including designs that incorporated load sharing with an H-beam configuration, and switched the composite carbon graphite skin to a titanium orthogrid skin. By down-selecting to the titanium orthogrid option, the team had already saved over 1,000 pounds. The design was developed by processing thermal, aerodynamic, and water landing loads through finite element models of the titanium orthogrid structure. The team designed, built, and tested a 20-inch-diameter subscale heat shield orthogrid test article and visited titanium forging facilities, electron beam welding facilities, and large-scale titanium machining facilities to improve confidence that the final design solution could be manufactured.

The final NESC design was estimated to save about 1,600 pounds over the baseline, far exceeding the original goal of 800 pounds. Encouraged by the NESC team's weight savings, the Orion CM baseline design had been undergoing revisions and had significantly reduced its mass, eliminating about 1,100 pounds.

The Orion MPCV Program ultimately stayed with its composite carbon graphite design, versus the titanium option proposed by the NESC for several reasons. While weight savings were a significant factor in design selection, so was schedule. Orion's first exploratory mission is expected in 2017, and the NESC design required financial commitments for material procurement and manufacturing and had a tight schedule for construction. Further, the baseline design had already demonstrated the full-scale manufacturing process, which lowered manufacturing risks, nonrecurring financial commitment, and a shortened delivery timeline.

Even though the NESC's alternative design was not selected by the Orion MPCV Program, it promoted the aggressive redesign of the current baseline and the net result was a significant reduction of overall mass. □

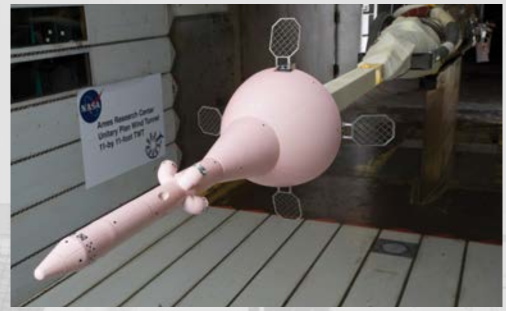
Successful launch of the Orion Multi-Purpose Crew Vehicle on the Delta IV Heavy for Exploration Flight Test-1.

Changing the Shape of Launch Abort Systems

In December 2014, NASA's Orion Multi-Purpose Crew Vehicle (MPCV) Program successfully conducted Experimental Flight Test-1 (EFT-1), the first orbital flight test of the Orion spacecraft. Close observers may have noted that the spacecraft had an updated shape from the concepts included on the previous Ares I-X and Orion Pad Abort 1 flight tests. In reality, the Orion crew module (CM) shape has not changed substantially since these flights, but the Orion Launch Abort System (LAS) has changed.

Reducing structural loads

In September 2006, during a peer review of the NESC Composite Crew Module (CCM) Assessment, an Alternate Launch Abort System (ALAS) was conceived to reduce structural loads carried by the CCM during a flight abort. To further investigate the feasibility of the ALAS concept, Dr. Charles Camarda (then NESC Deputy Director for Advanced Projects) sponsored a study to evaluate promising approaches to improve overall Orion CM mission performance. This short, 5-week effort developed the concept of a multifunctional boost protective cover (MBPC) for the Orion CM, with analyses that demonstrated a system mass reduction due to the improved load transfer characteristics of the ALAS concept. An additional benefit the team discovered, which was not initially anticipated, was that the aerodynamically contoured forward fairing over the CM significantly reduced the overall launch vehicle drag – so much that the reduced drag provided even more payload-to-orbit increase than the improvement in structural load path.



Above: **ALAS fairing mounted atop a United Launch Alliance Delta IV Heavy Rocket for the EFT-1 launch.** *Below:* **After developing the ALAS shape, the NESC performed further testing in the ARC Unitary Plan Wind Tunnel to investigate stability augmentation provided by grid fins.**

Additional ALAS benefits investigated

Based on the promising phase 1 results, the NESC extended the effort designating Dr. Stephen Scotti, ALAS phase 1 lead, and Dr. David Schuster, NASA Technical Fellow for Aerosciences, to co-lead a second phase of the ALAS study team to further refine the concept. Starting in December 2006, they performed aerodynamic, structural and controls analyses, as well as a number of wind tunnel experiments, to obtain the data required to validate the concept.

"We found that adding a fairing improved the aerodynamic shape significantly," said Schuster. "It reduced drag during ascent, as well as weight by providing a separate load path around the crew module." In addition to better quantifying the aerodynamic, performance, and structural improvements, a major new focus investigated using the ALAS MBPC to reduce aeroacoustic loads on the Orion CM. "Current predictions of Orion acoustic loads far exceeded what was assumed in the design of the Orion subsystems," said Scotti. "And the project hoped that the ALAS approach would help solve that problem and eliminate the need to redesign and requalify all the subsystems."

The team developed a suite of aerodynamic shapes for the MBPC from a simple conic that would be easy to manufacture to the final Sears-Haack fairing offering the greatest drag reduction. A diverse family of ALAS configurations were evaluated using high fidelity computational fluid dynamics simulations in concert with wind tunnel testing. In total, 11 ALAS designs were evaluated along with 10 revisions to the 11th ALAS concept. Each design offered its own level of performance, stability, and acoustic advantages, but there were tradeoffs. For example, improvements in performance in some of the designs added additional complexity with the addition of fins and ducted abort motors. "The combination of high fidelity fluid dynamics analyses and the wind tunnel tests was essential to the design process because it positively identified the sources of noise in the flow" said Scotti. "We didn't have that capability during Apollo. Now instead of blindly trying design modifications, we knew exactly what changes would help and where to make them."

Mercury and Apollo spacecraft used launch abort towers without aerodynamically and structurally beneficial fairings.

The third revision of ALAS 11 made the final cut with the Orion MPCV Program and became the baseline configuration for the LAS design. Though other designs had higher performance improvements, ALAS 11 was a good compromise that offered considerable aeroacoustic load relief. “That’s the one that could fly without fins, yet remain controllable, and offer aeroacoustic protection and aerodynamic benefit. It was also relatively easy to incorporate,” said Schuster. Wind tunnel testing confirmed the ALAS-11 had the best blend of aerodynamic and aeroacoustic performance with the required launch abort vehicle stability characteristics.

In parallel to the development of ALAS, the NESC was also pursuing a towerless LAS, known as the Max Launch Abort System (MLAS), to tackle development challenges with regard to the tower design on the Orion MPCV. While those challenges were later overcome, the MLAS, based on the new ALAS shape, pushed the boundaries of the LAS design even further. ***See “Launch Abort System Evolution” - page 24.***

ALAS proven on EFT-1

Ultimately, ALAS offered benefits beyond what was expected and in December 2014, ALAS successfully flew for the first time on EFT-1. “Something that was effectively a research study became the baseline—the main geometry—for the Orion vehicle,” said Schuster, who didn’t realize back in 2006 that ALAS would help redefine the concept of the LAS at NASA. Since timing of the ALAS development didn’t mesh with either the ARES 1-X test flight or the first pad abort test for the Orion MPCV Program, “The Orion EFT-1 was the first time flying with the ALAS design,” Schuster said. This would finally allow the Orion MPCV Program and the NESC team to collect and analyze real-time flight data on the new configuration. It was a big moment for everyone involved, he said. “We could point to the top of the vehicle and say ‘We designed that shape.’” □

Reference NASA/TM-2014-217155

Lockheed Martin

Unpainted ALAS fairing used to protect the Orion crew module during Exploration Flight Test-1.

Launch Abort System Evolution

A critical component of crewed spacecraft, the launch abort system (LAS), allows for rescue of the crew in the event of a catastrophic malfunction while the spacecraft is sitting on the launch pad or on its way into orbit. For a successful rescue, however, the LAS must perform several critical maneuvers in rapid-fire succession. First, the launch abort motors must be powerful enough to fly the fairing and crew module (CM) to a safe distance away from the launch vehicle. Next, it must reorient and fly in a carefully controlled heat shield-forward attitude. Finally, it must release the CM, enabling the CM's parachute landing system to deploy for a safe return of the crew.

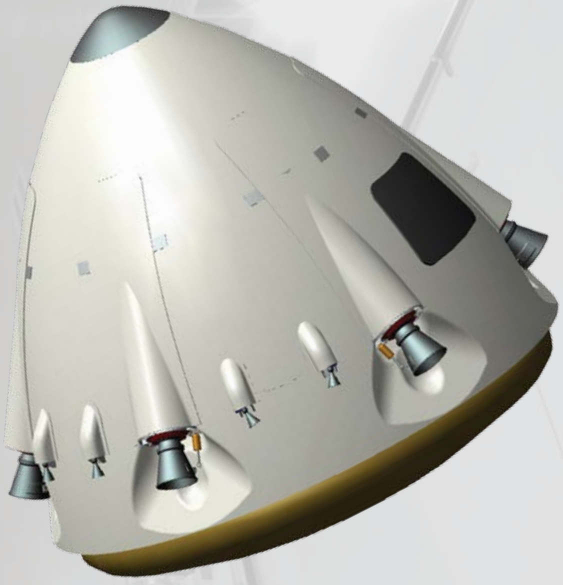
LAS begins with Project Mercury

Since the time of Project Mercury and the Apollo Program, the LAS has maintained its traditional tower configuration. But as spacecraft design has evolved, so has the need for a new LAS. The Orion Multi-Purpose Crew Vehicle launched on December 4, 2014, featured a new Alternative Launch Abort System (ALAS) shape and structure that enhanced the aerodynamic and aeroacoustic performance of the spacecraft. But while the NESC was spearheading efforts on the ALAS design, it was also developing the Max Launch Abort System (MLAS), a follow-on to the ALAS design that incorporated the ALAS shape while fundamentally changing the LAS from a tower to a towerless design.

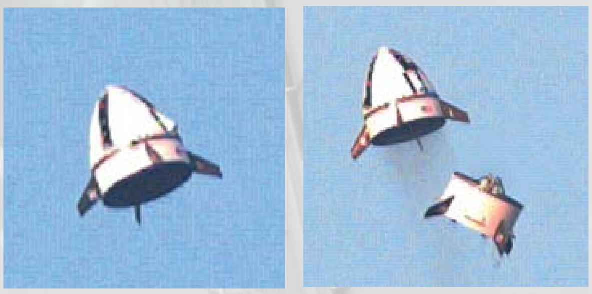
Named in honor of Maxime Faget, developer of the original Mercury launch escape system, MLAS was a 2-year effort that culminated in a full-scale flight demonstration. The initial goal of MLAS was to keep the ALAS advantages while pursuing a LAS concept that eliminated the tower and did not require active attitude control or stabilization following escape motor burnout. A key design constraint was avoiding structural changes to the CM if MLAS was substituted for the launch abort tower.

From napkin sketch to flight test

From a napkin sketch design drawn by the NASA Administrator at the time, which featured six side-mounted escape motors attached to the service module, the NESC team focused on key issues such as the number and placement of motors, separation dynamics, stability following motor burnout, and CM extraction from the fairing. This concept became the basis for the MLAS flight test vehicle, which would be boosted to abort test conditions to prove MLAS was passively stable, could be reoriented with parachutes, and safely release the CM for crew recovery. Launched from NASA Wallops Flight Facility in July 2009, the MLAS successfully demonstrated all flight test objectives.



Propulsively stabilized MLAS concept.



Left: Successful launch abort test of the passively stabilized MLAS flight test vehicle. *Right:* Spent test booster can be seen falling away after launch.

During the flight test, dummy motors were incorporated into the MLAS fairing alongside the CM. This preserved space for the next flight test concept, which was to use the six abort motors with thrust vector control to perform active stabilization and eliminate the large exterior fins used on the first flight test. Thrust vector control would allow the MLAS to steer in the best direction for safety during the boost phase of an abort, then reorient for safe release of the CM. This MLAS objective system design was completed to a point where it could be built and tested if needed in the future.

More than 150 people from across NASA, as well as industry partners, had a hand in bringing the MLAS flight test to fruition, not only meeting the mission objectives, but developing and building a full-scale prototype vehicle from which invaluable experience was gleaned for future NASA projects. □

Machining of orthogrid pattern into tank shell at MSFC to be used for test factor in the NESC Shell Buckling Knockdown Factor Assessment.

EXPLORATION

Spin Forming Aluminum Lithium CM Metallic FPVBH

The NESC explored producing a single-piece crew module (CM) forward pressure vessel bulkhead (FPVBH), integrating the forward bulkhead, cone, and barrel into a single component. The spin forming fabrication method could simplify FPVBH fabrication and enhance CM design. The work addressed key attributes of the single-piece pressure vessel design that would be relevant to produce a full-sized, optimized single-piece demonstration FPVBH. NASA/TM-2014-218163

Spin Forming CM Pressure Bulkhead Phase II, Aft Bulkhead and Cone

The Multi-Purpose Crew Vehicle (MPCV) Chief Engineer requested the NESC assist in developing a spin forming fabrication process for the manufacture of the Orion CM aft pressure vessel bulkhead and cone. The spin forming process will enable a single piece aft bulkhead and single piece cone versus multiple-piece welded construction, simplify CM fabrication, and lead to an enhanced design.

CPAS Wake Deficit Wind Tunnel Testing

The Orion MPCV Chief Engineer requested the NESC acquire flowfield measurements of the wake behind the Orion MPCV capsule in subsonic and transonic flight conditions to support Crew Exploration Vehicle Capsule Parachute Assembly System (CPAS) parachute design and performance prediction and to also support validation of computational fluid dynamics tools. NASA/TM-2014-218171

An SLS model in LaRC's Transonic Dynamics Tunnel.

FPVBH manufactured by spin forming.

Orion TPS Margin Study (Phase II)

The Orion MPCV Program requested the NESC provide an updated approach for thermal protection system (TPS) margin that accounts for material property and thermal model uncertainties. The current margin implementation of designing to an artificially reduced bondline temperature needs to evolve in the interest of mass optimization and TPS reliability. NASA/TM-2013-218262

Launch Abort Vehicle Transonic Stability Augmentation

The former Constellation Program Flight Performance Systems Integration Group requested the NESC support in addressing the potential benefits of grid fins for vehicle stabilization during transonic abort. NASA/TM-2014-218522

Transonic Shock Reflections in SLS Wind Tunnel Testing

The Space Launch System (SLS) Program requested the NESC assist with performing a transonic test at LaRC's Transonic Dynamics Tunnel to determine the effects of tunnel-reflected shock waves on SLS aerodynamic loads. Previous testing in other tunnels indicated that shocks reflected from the wind tunnel walls could be impacting the test article and contaminating the measured aerodynamic loads. NASA/TM-2014-218269

Review of GSDO Tools for Verifying Command and Control Software

The Exploration Systems Development Standing Review Board requested the NESC perform an independent review of the Ground Systems Development and Operations (GSDO) plan for integrating models and emulators to create tools for verifying its command and control software. NASA/TM-2014-218278

Review of ESD Integrated Hazard Development Process

The Exploration Systems Development (ESD) Chief Engineer requested the NESC perform an independent assessment of the ESD integrated hazard development process, focusing on a review of the integrated hazard analysis process and identifying any gaps/improvements.

SLS Block I Booster Insulation Characterization

The SLS Booster Element Manager requested the NESC address specific, identified weaknesses in the fundamental understanding of SLS Program Block I five-segment reusable solid rocket motor polybenzimidazole insulation age life and material performance.

Flight Testing of the SLS Launch Vehicle AAC Algorithm

The MSFC Flight Mechanics and Analysis Division requested the NESC partner with the SLS Program and the Space Technology Mission Directorate Game Changing Development Program to flight test the adaptive augmenting control (AAC) algorithm on a manned aircraft to raise the technology readiness of the algorithm. The MSFC-developed AAC algorithm was baselined as part of the SLS flight control system. NASA/TM-2014-218528

A Comprehensive Analysis of the X-15 Flight 3-65 Accident

Draper Laboratory performed an analysis to investigate the role of the MH-96 self-adaptive flight control system in the fatal accident of an X-15 vehicle in November 1967. As the AAC is part of the baseline SLS vehicle flight control system, a comprehensive analysis was necessary to understand the causes and evolution of the accident to reduce risk to emerging aerospace vehicle concepts. NASA/TM-2014-218538

X-15

SPACE OPERATIONS

EMU Lithium-Ion Battery Assessment

The International Space Station (ISS) Program Manager requested the NESC perform an independent review of the ISS Extravehicular Mobility Unit (EMU) long-life batteries (LLB). The NESC performed an LLB review in 2009, however, recent issues with commercially used lithium batteries led to the additional review request. NASA/TM-2014-218164

MMOD Design and Analysis Improvements

The NESC identified the need to address ways to improve micrometeoroid and orbital debris (MMOD) protection and analysis highlighted by previous NESC assessments. NASA/TM-2014-218268

ISS ORU Wet Storage Risk Assessment

The ISS Program Chief Engineer's Office requested the NESC evaluate the risk of storing ISS orbital replaceable units (ORU) that have been serviced with deionized water for long periods of time (years) before being used on orbit. NASA/TM-2014-218172

ISS PCU Utilization Plan Assessment Update

The ISS Systems Manager for Space Environments requested the NESC extend a previous assessment to include additions to the ISS plasma contactor unit (PCU) utilization plan. The previous assessment investigated whether leaving PCUs off during non-extra-vehicular activities presented any risk to the ISS through assembly completion. NASA/TM-2014-218512

SPACE OPERATIONS

Continued

Raven Impact on ISS Visiting Vehicles

The ISS Program Manager requested the NESC perform an independent assessment to evaluate the impact of the Raven payload experiment's light detection and ranging vision navigation system on ISS visiting vehicles during proximity operations.

ISS ETCS Loop A PM Jettison Options Assessment

After the ISS experienced a failure of the external thermal control system (ETCS) Loop A pump module (PM), the NESC identified the need to independently evaluate jettison options being considered by the ISS Trajectory Operations Officer and provide recommendations for a safe jettison of the PM working within the minimum number of extravehicular activities required to replace the PM. NASA/TM-2014-218542

Reverse Polarity Capacitor Installation Anomaly on the ISS ExPRESS Logistics Carrier Simulator

The GSFC Electrical Engineering Division Chief requested the NESC evaluate the electrical ground support equipment simulator and flight build of the ExPRESS (Expedite the Processing of Experiments to the Space Station) Carrier Avionics (ExPCA) Experiment Control Module to investigate the failure of the ExPCA simulator at KSC in October 2012.

CCP Ascent Abort Model Review

The Commercial Crew Program (CCP) Program Manager requested the NESC perform a peer review of the CCP-funded independent abort simulation capability, the Generic Abort Simulation Package (GASP). The independent GASP simulation tool is intended to provide CCP with the means to check and evaluate abort simulation products provided by the CCP partners.

Electronic Components in Safety-Critical Avionics Systems

The CCP Deputy Chief Engineer requested the NESC to review reliability analyses methodology and assumptions for flight avionics, focusing on the current or planned practices of aviation and commercial space providers. The goal was to establish boundaries for the impact these practices have on overall system reliability metrics.

The Use of COTS Electronic Components

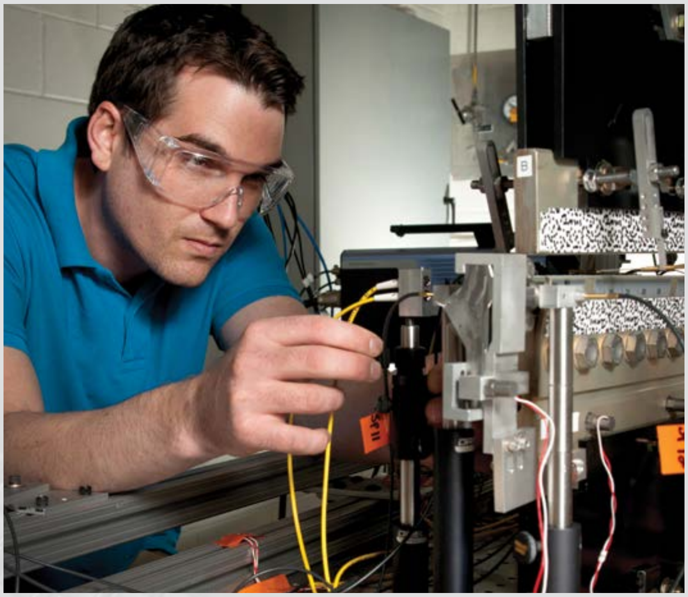
The ISS System Manager for Space Environments requested the NESC compare the suitability and possible benefits of alternative approaches for the use of commercial-off-the-shelf (COTS) electronic components in safety-critical avionics systems intended for use in human-rated commercial crew spacecraft. NASA/TM-2014-218261

Alternative Software Programming for Human Spaceflight

The Office of the Chief Engineer requested the NESC determine whether a path forward exists to certify or validate alternatively developed software for human spaceflight, and if none exists, propose a path forward for human spaceflight certification.

Assessing Risks of Frangible Joint Designs

The CCP Chief Engineer requested the NESC conduct an assessment of risks associated with designs of frangible joints (FJs). Recent Launch Services Program losses attributed to FJs have raised concerns about FJ designs, especially those that are zero-fault tolerant. A Phase II effort is underway with testing of joint mechanisms.



Instrumenting a frangible joint for testing.

SCIENCE

ARM SEP Analysis of Alternatives

The Space Technology Mission Directorate requested the NESC lead an independent analysis of alternatives of the solar electric propulsion (SEP) component proposed for the Asteroid Retrieval Mission (ARM) by reviewing the underlying assumptions used in the study and examining alternative methods for achieving mission success. NASA/TM-2014-218159

HST System Reliability Review

The Hubble Space Telescope (HST) Program Systems Management and Engineering Manager requested the NESC evaluate the current HST system reliability model to determine if it can be enhanced or replaced with an alternate method and/or approach, allowing the HST Program to predict the likelihood of performing viable science as a function of time. NASA/TM-2014-218161

JWST Sunshield Venting Analysis Assessment

The James Webb Space Telescope (JWST) sunshield membrane systems engineer requested the NESC provide an independent assessment of the venting analysis of the JWST sunshield. NASA/TM-2014-218173

Review of SEXTANT and DSAC Technology Demonstration Projects

The Space Technology Mission Directorate requested the NESC perform an independent assessment of two of their technology demonstration projects, Station Explorer for X-ray Timing and Navigation (SEXTANT) and Deep Space Atomic Clock (DSAC). NASA/TM-2014-218270

OSIRIS-REx TAG Onboard Navigation Capability

The Origins Spectral Interpretation Resource Identification Security – Regolith Explorer (OSIRIS-REx) Project Manager requested the NESC perform an independent assessment of the OPNAV Natural Feature Tracking hardware/software system being added to OSIRIS-REx as the backup guided touch-and-go (TAG) navigation solution. NASA/TM-2014-218277

MMS High Voltage Optocoupler Assessment

The Magnetospheric Multiscale Mission (MMS) fast plasma instrument's dual electron spectrometer (DES) sensor had experienced ground failures during integration and test, while its dual ion spectrometer (DIS) sensor did not. The NESC identified the need to examine the possible effects of the circuit differences between the DES and DIS instrument applications and examine potential effects of part differences.

SCIENCE *Continued*

NASA Workshop on Hybrid (Mixed-Actuator) Spacecraft Attitude Control

The Science Mission Directorate Chief Engineer requested the NESC conduct a workshop on lessons learned and current developments in hybrid attitude control mode design, test, and operations. Cross-Center lessons learned were shared among NASA and industry subject matter experts. NASA/TM-2014-218539

Ground Wind Loads Uncertainty for Mars Insight Lander

The Insight Project systems engineer requested the NESC perform predictions of the ground wind loads on the Mars Insight Lander following landing and solar array deployment. Winds at the landing location could be as high as 75 meters per second and wind loads could damage the solar panels and/or flip the vehicle.

Assessment of Combustion Instability in BB Motors

The Sounding Rocket Program Office requested the NESC provide technical expertise in combustion stability modeling and analysis for its workhorse sounding rocket, the Black Brant (BB) motor. The scope of the assessment included updating existing combustion stability analyses and developing stability predictions for the BB proposed propellant. NASA/TM-2014-218160

AERONAUTICS

ACCESS Probing Aircraft Flight Test Hazard Mitigation

The Alternative Fuel Effects on Contrails and Cruise Emissions (ACCESS) Project Integration Manager requested the NESC to independently assess the Falcon 20 structural failure risk associated with flying in the wake of the DC-8 and identify potential flight test hazard mitigations. Follow-on work involves independent analyses of vortex crossing to corroborate project predictions. NASA/TM-2013-217995

View of DC-8 from Falcon 20.

GENERAL

NESC Enhanced Melamine Foam Acoustic Test

The NESC performed an acoustic characterization test program of melamine foam, including testing with enhanced designs intended to increase the low frequency acoustic benefit. Multiple NASA and industry projects could benefit from the tests. NASA/TM-2014-218162

COPV Stress Rupture Reliability and NASA CPVWG

The Composite Pressure Vessel Working Group (CPVWG) has been working to develop strategies, approaches, or methodologies to minimize technical risk for the use of composite pressure vessels. This task examined shortfalls in the current understanding of composite overwrapped pressure vessel (COPV) mechanics, resulting in an NESC Technical Bulletin 14-03 describing issues with COPV modeling. NASA/TM-2014-218260

CAD Tools to Support Human Factors Design Teams

The NESC identified the need to develop a database or library of human model behavior primitives, which may be used for human factors analyses in launch vehicle design trade decisions and requirements verification. Database users would include NASA, contractors, and commercial partners.

Evaluation of Agency Non-Code LPVs

The Office of Safety and Mission Assurance requested the NESC formulate a consensus draft proposal for the development of additional testing and analysis methods to establish the technical validity, and any limitation thereof, for the continued safe operation of non-code layered pressure vessels (LPV) used at NASA. NASA/TM-2014-218505

SOFIA Cryo Helium Dewar Heat Flux Evaluation

The Stratospheric Observatory for Infrared Astronomy (SOFIA) Project requested the NESC evaluate and determine the maximum boil-off rate of the cryo helium Dewar after a loss of vacuum jacket thermal protection. NASA/TM-2014-218540

Check-Cases for Verification of 6 Degree-of-Freedom Flight Vehicle Simulations

The NESC identified the need to provide verification of common elements of flight vehicle trajectory simulations, focusing on generic components of flight simulation dynamics. The assessment's scope generated check-case data for 6 degree-of-freedom simulation tools, including equation of motion and gravity models.

1. United States Navy Multi-Stage Supersonic Target Assessment
2. Vehicle Integrated Propulsion Research Experiment Impacts on the C-17 Engine-Pylon Interface Assessment
3. Space Launch System Program Booster Element Qualification Motor-1 Aft Segment Support
4. Unplanned/Unintended Event or Condition Investigation
5. Ground Testing to Assess the International Space Station Ultrasonic Leak Location Concept Assessment
6. Effects of Humidity on Dry Film Lubricant Storage and Performance Assessment
7. Review of Exploration Systems Division Integrated Hazard Development Process
8. Curiosity Wheel Consultation
9. Risk Reduction of Orion Crew Module Government Furnished Environmental Control and Life Support
10. Subscale Low Density Supersonic Parachute Wind Tunnel Test
11. Human Vibration Modeling for the Multi-Purpose Crew Vehicle
12. Abort Environments Update for Blast Fragments/Debris Support
13. International Space Station Extra Vehicular Activity Lithium-ion Battery Thermal Runaway Severity Reduction Measures Assessment
14. Ground Operations Human Factors Task Analysis Support
15. NESC Modeling of Crawler/Transporter, Mobile Launcher, and Forcing Functions
16. Peer Review of Space Launch Systems and Orion Multi-Purpose Crew Vehicle Programs Modal Test, Development Flight Instrumentation, and Dynamic Model Correlation Plans
17. Joint Polar Satellite System Micrometeoroid/Orbital Debris Assessment
18. International Space Station Anomalies Trending Study
19. Orion Crew Module and Commercial Crew Window Wavefront Measurement Assessment
20. Composite Overwrapped Pressure Vessel Liner Inspection Capability Assessment
21. Technical Support to the Multi-Purpose Crew Vehicle Capsule Parachute Assembly System Pendulum Assessment Team
22. Support to NASA MagicDraw Cloud License Project
23. Soil Moisture Active Passive Reflector and Boom Assembly Deployment Risk Assessment
24. Launch Vehicle Buffet Verification Testing
25. Simplified Aid for Extra Vehicular Activity Rescue Battery Assessment
26. Stability and Flight Readiness of the Space Launch System Flight Control System with Adaptive Augmentation
27. Independent Assessment of the Backshell Pressure Field for Mars Science Laboratory Entry, Descent, and Landing Instrument for Mars 2020
28. Model of the Space Launch System – Multi-Purpose Crew Vehicle – Ground Systems Development and Operations Stack on the Pad
29. Support to NASA Standard 5009 Development
30. Stratospheric Aerosol and Gas Experiment-III Interface Adaptor Module Subsystem Anomaly Support
31. Nonlinear Slosh Analysis Techniques for Launch Vehicles Assessment
32. Support for the Ames Research Center Arcjet Rectifier Snubber Failure Mishap
33. Robonaut Battery Safety Assessment
34. Portable Fire Extinguisher for International Space Station Evaluation
35. Independent Assessment of the Multi-Purpose Crew Vehicle Parachute Riser Loads
36. RAD750 Single Board Computer Qualification Testing Assessment
37. Support Airborne Observation of Automated Transfer Vehicle-5 Reentry
38. Development of a Manned Vehicle Reentry Thermal Protection System Damage Assessment and Decision Plan
39. Evaluation of the Orbital Debris Engineering Model 3.0 with Available On-Orbit Assets
40. Implementation of JR-A Methodology into the NASGRO/Fracture Analysis by Distributed Dislocations Codes to Improve Crack Instability Analysis
41. Technical Support for Space Launch System Vibroacoustics Plans and Analysis
42. International Space Station Columbus Interface Heat Exchanger Thermal Response
43. Layered Pressure Vessel Technical Consultation
44. International Space Station Plasma Contactor Unit Utilization Plan Assessment Follow-on
45. Review of Fatigue Cycle-Counting/Fatigue Spectra Cycle Counting Methodology
46. Technical Support to Space Technology Mission Directorate Brazing Tiger Team
47. Independent Computational Fluid Dynamics Analysis of Aero/Reaction Control System Interaction on Commercial Crew Provider Vehicles

As of December 31, 2014

technical bulletins

This year the NESC produced three technical bulletins that condense new knowledge and best practices into a one-page, quick and easy read. Links are included to reference additional material on the subject. NESC technical bulletins can be found at nesc.nasa.gov.

TB 14-01: Flying Through Periods of Instability

An NESC assessment of the Ares 1 flight control sensitivity to slosh dynamics in the Orion service module raised questions for Neil Dennehy, NASA Technical Fellow for Guidance, Navigation, and Control (GNC), about stability margins, the degree of conservatism flight control system (FCS) engineers put into designs, the linear and nonlinear analysis tools they use, and how it all related to safely flying a vehicle through brief periods of control instability. As stability is a mantra for GNC experts, Dennehy began capturing what the GNC community was learning about stability margins with respect to control instability, resulting in this technical bulletin that suggests FCS designers not limit themselves, and look beyond the frequency domain approach when designing flight control systems.

TB 14-02: Aerodynamic Reaction Control System (RCS) Orientation and Jet Interaction (JI) Model Validation

A historical perspective on jet interaction prediction issues combined with NESC analysis gleaned from a Mars Science Laboratory assessment led to this technical bulletin's guidance on the placement and orientation of reaction control system (RCS) jet thrusters on hypersonic entry vehicles. Dr. David Schuster, NASA Technical Fellow for Aerosciences, concluded that taking the proper precautions in the development of an RCS system, paired with computational fluid dynamics calculations and wind tunnel testing, yields a more accurate view of controllability and the flow characteristics behind those vehicles.

TB 14-03: COPV Mechanical Model Validation

When issues surrounding the understanding of composite overwrapped pressure vessel (COPV) mechanics surfaced in two previous NESC assessments, Dr. Lorie Grimes-Ledesma of the Composite Pressure Vessel Working Group discovered that even with the availability of vendor-supplied finite element tools, there was a lack of accuracy in understanding COPV liner and composite response. And that lack of accuracy was propagating in subsequent fracture and stress rupture analysis. A look back to fundamentals in understanding autofrettage and a subsequent correlation study between finite element analysis and measured response on COPVs led to this technical bulletin's best practices for COPV model validation.

National Aeronautics and Space Administration

NASA Engineering and Safety Center Technical Bulletin No. 14-01

Designing for Flight Through Periods of Instability

For completeness, it is imperative that Flight Control System (FCS) designers use both complementary time and frequency domain techniques to address periods of instability. Use of standard frequency domain synthesis techniques alone may not always yield an FCS design with sufficient gain and phase stability robustness margins while simultaneously satisfying performance requirements.

Instability Cause and Consequence

Analysis and evaluation must be performed of any potential source of instability (e.g., propellant slosh, flexible structure, or aerodynamics), while flying through periods of rapidly changing dynamics. A large body of experience has been accumulated regarding successfully flying through not only degraded margins, but also relatively brief periods of linearized model instability. These instabilities occur as the flight environment and vehicle dynamics undergo rapid changes. When linearized stability robustness margin requirements cannot be satisfied, alternative methods are then needed to ensure that deficient stability margins do not present a high risk of losing control during the mission.

The Orion launch abort system successfully flew through brief periods of instability. Known instabilities and risks were evaluated prior to flight using best practices.

Best Practices for Flight Control System Design

FCS designers should consider employing non-linear system requirements that capture both stability and performance aspects. Occasionally, it may be necessary to set aside the traditional frequency domain gain and phase stability robustness margins in favor of another technique. The tried-and-true guideline that stability always comes before performance in the design process remains the same. However, since real flight systems behave in a non-linear manner, "stability" should be understood as control of the vehicle never being lost while simultaneously achieving attitude control performance requirements.

Consider four complementary recommendations for certifying FCS designs with deficient stability margins:

1) Accept some Relaxed or even Negative Stability Margins: additional analysis may not be required if a stability margin fails the requirement for only a brief time. Seek out prior experience with similar configurations and conditions.

2) Evaluation of Uncertainties: reassess whether the uncertainties input into the analysis are realistic. In certain cases, the effects of correlated variables can be taken into account to reduce the level of uncertainties used in the analysis.

3) Checking the Time to Double Amplitude: determine if the vehicle will fly through the region of concern before the oscillations reach unacceptable amplitudes, in which case a relaxed or even negative margin may be acceptable.

4) Use of Non-Linear Time-Domain Simulations: exploit the complete non-linear time-domain models to prove that the vehicle exhibits acceptable behavior, even with programmed test inputs to excite oscillations. Additionally, the loop gains and/or time lags can be adjusted in the simulation to evaluate the gain and phase stability margins remaining from a non-linear perspective.

Historically, some launch vehicles have been successfully flown with the known threat of slosh instabilities. The Atlas-II was successfully flown with linearly unstable (as viewed from a purely linear frequency-domain perspective) slosh modes.

An FCS designer should question the application of linear stability requirements and not rely exclusively on the frequency domain approaches to verify stable flight. The use and application of the frequency-domain synthesis and analysis tools must be balanced with the non-linear time-domain performance simulation tools and the Time to Double Amplitude criteria.

References

1. NASA/TM-2011-217183, NESC-RP-09-00602 v2.0, Independent Review of the Ares-I Control Sensitivity to Orion Service Module Tank Slosh Dynamics, Oct. 2011

2. NASA Document Number: EAM-CEV-09-001, Shuttle Ascent and Entry GN&C Stability Verification, Edgar Medina (PA-1 Flight Dynamics Team), Jan. 23, 2009

3. NASA/SP–2010–3408, Space Shuttle Entry Digital Autopilot, Section 9.0 Lessons Learned, Larry McWhorter and Milt Reed, Feb. 2010

For information contact the NESC at nesc.nasa.gov

National Aeronautics and Space Administration

NASA Engineering and Safety Center Technical Bulletin No. 14-02

Aerodynamic Reaction Control System (RCS) Orientation and Jet Interaction (JI) Model Validation

Careful consideration should be given to placement and orientation of RCS jet thrusters on hypersonic entry vehicles in order to minimize adverse RCS JI. Modern state-of-the-art computational fluid dynamics (CFD) tools should be able to predict the RCS effectiveness and JI accurately when coupled with verification and validation studies, including the use of appropriately designed experimental wind tunnel testing.

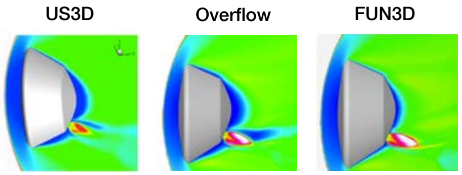
Applicability

Development of experimental techniques and CFD predictive capabilities to determine proper placement and orientation of RCS jet thrusters on hypersonic entry vehicles to minimize adverse RCS JI.

Historical JI Prediction Issues

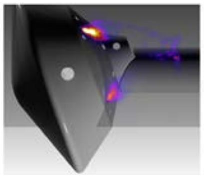
Historically, the prediction of hypersonic entry RCS effectiveness and associated JIs with surrounding flowfields has been a challenging CFD problem. For example, during the bank maneuvers of the first space shuttle orbiter reentry, the rolling moment that occurred when the forward yaw thrusters were fired was less than expected, resulting in greater RCS fuel usage than anticipated. The cause of this discrepancy was attributed to improper scaling of wind tunnel derived RCS interaction correlations to the flight condition.[1] In a more recent example, CFD analyses of the RCS JI on the Mars Phoenix entry vehicle indicated the possibility of uncontrollable adverse JI, enough so that the project chose to not use the RCS during portions of the entry phase, increasing the landing footprint and the overall mission risk.[2]

The Mars Science Laboratory (MSL) mission was plagued by similar issues in the early design phases. The entry vehicle aerodynamics was based on a combination of experimental results, CFD calculations, and comparisons with estimates of flight aerodynamics from previous Mars missions. Estimates of the RCS effectiveness and RCS JI with the aftbody flow-field were originally developed based primarily on CFD calculations, indicating the potential for large, undesirable RCS JI. Recommendations were made to change the RCS jet locations and orientations in an attempt to reduce plume impingement on the spacecraft, jet-to-jet plume interactions, and to minimize undesirable interaction torques. Given the uncertainties associated with the wake flow predictive capabilities of current CFD codes, a wind tunnel test was designed and executed in the Langley Research Center 31-Inch Mach 10 Wind Tunnel to provide experimental data for the new MSL RCS thruster configuration design.[3] This data served to provide validation results specific to MSL and, at the same time, the experimental test techniques developed would potentially be of benefit to other projects and programs employing blunt body entry aeroshell designs with aftbody RCS jet thrusters (e.g., Orion/Multi-Purpose Crew Vehicle or commercial crew vehicle designs). Additional CFD calculations were made on the new thruster configuration to assess effects of the aerodynamics and RCS interactions.[4] Results indicated generally good agreement between the experimental data and CFD predictions of the RCS JI. This, along with recommended conservative uncertainty values for RCS JI, provided an appropriate degree of confidence to the MSL Project on the adequacy of the new thruster configuration and overall robustness of the entry flight control system.



Comparison of MSL Aero/RCS interaction using 3 different CFD codes.

MSL model in LaRC 31-Inch Mach 10 Wind Tunnel.



Experimental flow image of MSL RCS jets.

Conclusions and Guidance

Appropriate consideration must be given to RCS thruster locations and orientations to minimize impingements and interactions. Modern CFD tools should be used in conjunction with well-designed experimental testing early in development to accurately predict the RCS JI and overall control effectiveness.

References

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2. Dyakonov, A. A., Glass, C. E., Desai, P. N., and Van Norman, J. W.: "Analysis of Effectiveness of Phoenix Reaction Control System," AIAA Paper 2008-7220.

3. NASA/TM-2013-218023, NESC-RP-10-00613 Mars Science Laboratory (MSL) Reaction Control System (RCS) Jet Interactions (JI) Testing and Analysis, July 2013

4. Schoenenberger, M., Van Norman, J. V., Rhode, M., and Paulson, J.: "Characterization of Aerodynamic Interactions with the Mars Science Laboratory Reaction Control System Using Computation and Experiment," AIAA Paper 2013-097.

National Aeronautics and Space Administration

NASA Engineering and Safety Center Technical Bulletin No. 14-03

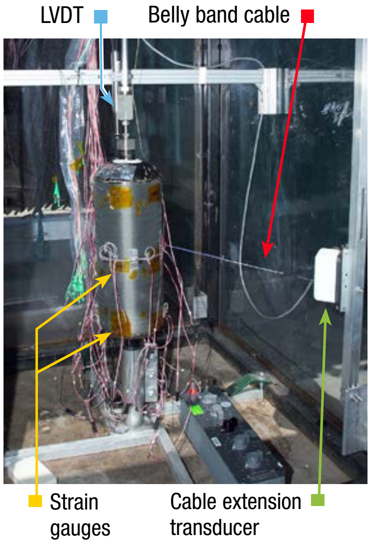
NESC tech bulletin

COPV Mechanical Model Validation

Global and local deformation measurements should be incorporated into the composite overwrapped pressure vessel (COPV) design and analysis process to allow correlation of these measurements with finite element analysis (FEA) models. This correlation improves understanding of liner, liner/overwrap interface, and composite deformation response in COPVs. The improved accuracy reduces error in subsequent analyses, such as fracture, fatigue, and stress rupture that are critical for COPV qualification.

Current Obstacles to COPV Mechanical Model Validation

Mechanics models and FEA of COPVs developed by manufacturers have not always been adequate to provide accurate general deformation response and to pinpoint areas of stress concentration in the composite shell and liner. This lack of accuracy has been an obstacle to determining risks associated with failure modes, such as stress rupture and fatigue crack growth. Key phenomena in the understanding of COPV liner and composite response include overwrap stress-deformation states, liner mechanics, and liner/overwrap interface mechanics. Accurate quantification of the interference strain between the liner and overwrap is difficult to capture without measurement and model correlation.



Model correlation study test fixture.

While closed-form solutions and FEA models with simple liner-overwrap interface assumptions may be calibrated to conservatively bound hoop strain response, they cannot accurately capture the complete multi-axial stress and deformation state to simultaneously correlate with all axial, circumferential, and volumetric deformation measurements, especially in the presence of an interface gap. The cited reference identifies ways in which measurements and model correlation can be performed. Global measurements taken from axial linear variable differential transducers (LVDTs), belly bands, and volumetric measurements, along with local measurements of axial and hoop strain from strain gages and laser profilometry measurements, were all demonstrated to be helpful in understanding the complex mechanical response of the COPV. COPVs are classified into 3 levels, and guidelines for measurements are suggested.

Best Practices for Validation of COPV Models

Three levels of measurements are recommended based on design burst safety factors and are intended to serve as guidelines for measurements on flight pressure vessels.

Level 1: Burst factor > 3.0

Determine composite and liner response based on analysis of the vessel per the as-built specifications and demonstrated burst pressure. Alternatively, determine composite and liner response based on closed-form analysis of a measured fiber strain response (nominal or local) as a function of pressure to burst.

Level 2: 2.0 < Burst factor < 3.0

Determine composite and liner response based on fully verified FEA. Measurements needed as a function of applied internal pressure include:

1. **Global measurements:** Axial elongation by LVDT and internal volume growth.
2. **Local measurements:** Hoop and axial strain at equator and other carefully referenced positions by foil strain gages and/or full-field methods of optical metrology.

Level 3: Burst factor < 2.0

Determine composite and liner response based on fully verified finite element model. Measurements needed:

1. **Global measurements:** Axial elongation by LVDT and internal volume growth.
2. **Local measurements:** Hoop and axial strain at equator and other carefully referenced positions by foil strain gages and/or full-field methods of optical metrology.
3. **Interior Laser Profilometry:** Unwound liner, wound liners prior to overwrap cure, wound liner post-overwrap cure prior to autofrettage, and cured COPV post autofrettage.

References

Thesken, J.C., et. al., Composite Pressure Vessel Working Group (CPVWG) Task 4: A Theoretical and Experimental Investigation of Composite Overwrapped Pressure Vessel (COPV) Autofrettage, December 19, 2013. TM-2014-218260.

2014 award recipients left to right: Pat Forrester (NESC Chief Astronaut/presenter); Michael Fowler (JSC); Daniel Wentzel (WSTF); Stan Bouslog (JSC); Koushik Daata (ARC); Chris Miller (AFRC); Mike Kirsch (NESC Deputy Director/presenter); Kevin Bonanne (JPL); Joseph Ruf (MSFC); James Reeder (LaRC); Kimberly Simpson (JPL); Chris Iannello (NESC); William Prosser (NESC); Eric Stoneking (GSFC); Donald Kessler (Independent Consultant); Scott Cryan (JSC); Kelly Barlow (ManTech International Corp.); Anup Katake (JPL); Bruno Munoz (Ball Aerospace Corp.); Vitali Volovoi (Independent Contractor); Lorie Grimes-Ledesma (JPL); Michael Vanek (LaRC); Justin Jones (GSFC); Tim Wilson (NESC Director/presenter)
Not pictured: Kevin Roscoe (LaRC) and James Smith (JSC).

NESC Leadership Award

Stan A. Bouslog

In recognition of outstanding leadership and technical support of the Multi-Purpose Crew Vehicle Avcoat Study.

Koushik Datta

In recognition of outstanding technical leadership of the Hubble Space Telescope Observatory System Reliability Review.

Michael E. Fowler

In recognition of outstanding leadership and technical support of the Multi-Purpose Crew Vehicle Avcoat Study.

Joseph H. Ruf

In recognition of outstanding leadership in identifying potentially inaccurate liquid engine nozzle acoustics and conducting scale model tests to confirm ignition acoustics environments for the Space Launch System booster design.

Kimberly A. Simpson

In recognition of outstanding leadership of the exploration systems development software interface mapping.

NESC Engineering Excellence Award

Scott P. Cryan

In recognition of engineering excellence to the Raven Vision Navigation System impact on International Space Station visiting vehicles.

Lorie R. Grimes-Ledesma

In recognition of engineering excellence for composite pressure vessel risk reduction efforts.

Justin S. Jones

In recognition of engineering excellence in support of the human space program by conducting critical nondestructive evaluation tests of failed extravehicular mobility unit components driving toward the return to extravehicular activity operations.

Anup B. Katake

In recognition of engineering excellence to the Raven Vision Navigation System impact on International Space Station visiting vehicles.

Chris J. Miller

In recognition of engineering excellence to the F/A-18 Full-Scale Advanced Systems Testbed Space Launch System Launch Vehicle Adaptive Control Project.

Bruno F. Munoz

In recognition of engineering excellence to the human space program by conducting critical non-destructive evaluation tests of failed extravehicular mobility unit components driving toward the return to extravehicular activity operations.

James R. Reeder

In recognition of engineering excellence to the Multi-Purpose Crew Vehicle Avcoat Team leading to advancements in testing and analysis of Avcoat material used in the Orion heatshield.

NESC Engineering Excellence Award

Continued

Kevin P. Roscoe

In recognition of engineering excellence to the Atlantis Kennedy Space Center visitor center display and the Multi-Purpose Crew Vehicle Underway Recovery Tests Assessment.

James P. Smith

In recognition of engineering excellence to the Multi-Purpose Crew Vehicle Avcoat Team leading to advancements in modeling and analysis of Avcoat material used in the Orion heatshield.

Eric T. Stoneking

In recognition of engineering excellence to the innovative dynamics and control contributions to the solution of the spacecraft hybrid attitude control problem for the repurposed Kepler mission.

Michael D. Vanek

In recognition of engineering excellence to the Raven Vision Navigation System impact on International Space Station visiting vehicles.

Vitali Volovoi

In recognition of engineering excellence to the NESC for reliability and modeling expertise including significant contributions to NESC Hubble Space Telescope tasks.

NESC Administrative Excellence Award

Kelly E. Barlow

In recognition of exceptional and dedicated support to the NESC Review Board and the NESC Technical Update.

NESC Group Achievement Award

Battery Thermal Runaway Severity Reduction Testing Team

In recognition of outstanding support in the testing and development of design methods that will improve the safety of batteries for NASA human spaceflight missions.

Composite Overwrapped Pressure Vessel Strand Stress Rupture Test Rig Development Team

In recognition of creativity, flexibility, and expeditiousness in designing strand test rigs, protocols and infrastructure to meet and exceed performance, schedule, and cost requirements.

Members of the NESC team.

Exploration System Development Software Interface Mapping Team

In recognition of outstanding system modeling efforts, training support, model analysis, review board support, and tool assessment for multiple NESC assessments.

Joint Polar Satellite System Micrometeoroid and Orbital Debris Assessment Team

In recognition of outstanding contributions to understanding the micrometeoroid and orbital debris environment models and risk for the Joint Polar Satellite System.

Layered Pressure Vessel Assessment Team

In recognition of outstanding contributions towards defining testing and analysis developments necessary to reduce the risk associated with continued operation of critical Agency layered pressure vessels.

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2014 publications

1.	Multi-Purpose Crew Vehicle (MPCV) Drogue Parachute High-Altitude Qualification	NASA/TM-2013-218140/Volume I
2.	Multi-Purpose Crew Vehicle (MPCV) Drogue Parachute High-Altitude Qualification - Appendices	NASA/TM-2013-218140/Volume II
3.	Cassini Plasma Spectrometer (CAPS) Short Circuit Anomaly	NASA/TM-2014-218047
4.	Independent Assessment of External Pressure Field Predictions Supporting Constellation Program Aeroacoustics	NASA/TM-2014-218058
5.	Asteroid Retrieval Mission (ARM) Solar Electric Propulsion (SEP) Other Trades Study (OTS)	NASA/TM-2014-218159
6.	Assessment of Combustion Instability in Black Brant (BB) Motors	NASA/TM-2014-218160
7.	Hubble Space Telescope (HST) Observatory System Reliability Review	NASA/TM-2014-218161
8.	NASA Engineering and Safety Center (NESC) Enhanced Melamine (ML) Foam Acoustic Test (NEMFAT)	NASA/TM-2014-218162
9.	Spin Forming Aluminum Alloy Crew Module (CM) Metallic Forward Pressure Vessel Bulkhead (FPVBH) - Phase I	NASA/TM-2014-218163
10.	International Space Station (ISS) Program Extravehicular Mobility Unit (EMU) Lithium Ion (Li-Ion) Battery Assessment	NASA/TM-2014-218164
11.	Orion Multi-Purpose Crew Vehicle (MPCV) Capsule Parachute Assembly System (CPAS) Wake Deficit Wind Tunnel Testing	NASA/TM-2014-218171
12.	International Space Station (ISS) Orbital Replaceable Unit (ORU) Wet Storage Risk Assessment	NASA/TM-2014-218172
13.	James Webb Space Telescope (JWST) Sunshade Venting Analysis	NASA/TM-2014-218173
14.	SRTMV-N2 Plume Impingement Test Panel (PITP) Risk Mitigation Experiment Technical Assessment Report	NASA/TM-2014-218255
15.	Composite Pressure Vessel Working Group (CPVWG) Task 4: A Theoretical and Experimental Investigation of Composite Overwrapped Pressure Vessel (COPV) Autofrettage	NASA/TM-2014-218260
16.	Use of Commercial-Off-The-Shelf (COTS) Electronic Components in Safety-Critical Human-Rated (Commercial Crew) Space Avionics Systems	NASA/TM-2014-218261
17.	Orion Thermal Protection System (TPS) Margin Study, Phase 2	NASA/TM-2014-218262
18.	Computer-Aided Design (CAD) Tools to Support the Human Factors Design Teams	NASA/TM-2014-218263
19.	Micrometeoroid and Orbital Debris (MMOD) Design and Analysis Improvements	NASA/TM-2014-218268/Volume I
20.	Micrometeoroid and Orbital Debris (MMOD) Design and Analysis Improvements - Test Reports	NASA/TM-2014-218268/Volume II
21.	Transonic Shock Reflections in Space Launch System (SLS) Wind Tunnel Testing	NASA/TM-2014-218269
22.	Review of Deep Space Atomic Clock (DSAC) Technology and Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) Demonstration Projects	NASA/TM-2014-218270
23.	OSIRIS-REx Asteroid TAG Onboard OPNAV Capability	NASA/TM-2014-218277
24.	Review of Ground Systems Development and Operations (GSDO) Tools for Verifying Command and Control Software	NASA/TM-2014-218278
25.	Benefits of Shell Buckling Knockdown Factor (SBKF) Project	NASA/TM-2014-218281
26.	Evaluation of Agency Non-Code Layered Pressure Vessels (LPVs)	NASA/TM-2014-218505/ Volume I
27.	Evaluation of Agency Non-Code Layered Pressure Vessels (LPVs) Appendices	NASA/TM-2014-218505/ Volume II
28.	International Space Station (ISS) Plasma Contactor Unit (PCU) Utilization Plan Assessment Update	NASA/TM-2014-218512
29.	Flight Testing of the Space Launch System (SLS) Adaptive Augmenting Control (AAC) Algorithm on an F/A-18	NASA/TM-2014-218528
30.	A Comprehensive Analysis of the X-15 Flight 3-65 Accident	NASA/TM-2014-218538
31.	NASA Workshop on Hybrid (Mixed-Actuator) Spacecraft Attitude Control	NASA/TM-2014-218539
32.	Maximum Expected Wall Heat Flux and Maximum Pressure after Sudden Loss of Vacuum Insulation on the Stratospheric Observatory for Infrared Astronomy (SOFIA) Liquid Helium (LHe) Dewars	NASA/TM-2014-218540
33.	James Webb Space Telescope's (JWST) Near-Infrared Spectrograph (NIRSpec) Micro Shutter Subsystem (MSS) Alternate Materials and Coatings	NASA/TM-2014-218541/Volume I
34.	James Webb Space Telescope's (JWST) Near-Infrared Spectrograph (NIRSpec) Micro Shutter Subsystem (MSS) Alternate Materials and Coatings Appendices	NASA/TM-2014-218541/Volume II
35.	International Space Station (ISS) External Thermal Control System (ETCS) Loop A Pump Module (PM) Jettison Options Assessment	NASA/TM-2014-218542
36.	Alternative Software Programming for Human Spaceflight	TM-2014-218546
37.	NASA Engineering and Safety Center (NESC) Independent Review and Support of the International Space Station (ISS) Extravehicular Activity (EVA) Water Anomaly and EVA Recovery Team (ERT) Failure Investigation	TM-2014-218547

Opposite: Carlie Zumwalt from LaRC inspects a supersonic parachute model in the LaRC Transonic Dynamics Tunnel as part of the NESC Subscale Low Density Supersonic Parachute Wind Tunnel Test.

Recent NESC Scholarly Papers and Conference Proceedings

1. Ayari, L.; Kubitschek, M.; Ashton, G.; Johnston, S.; Debevec, D.; Newell, D.; Pellicciotti, J. W.: GMI Instrument Spin Balance Method, Optimization, Calibration, and Test. Presented at 42nd Aerospace Mechanisms Symposium, May 14-16, 2014, Baltimore, Md.
2. Dennehy, C. J.: Spacecraft Hybrid (Mixed-Actuator) Attitude Control Experiences on NASA Science Missions. Presented at ESA Conference on Guidance Navigation and Control, June 2-6, 2014, Porto, Portugal.
3. Dennehy, C. J.; Brady, T.; Greenbaum, A.: Identifying Trends in Spacecraft GN&C Components: The Development and Application of an Open-Source GN&C Component Data base. Presented at 8th ESA Workshop on Avionics, Data, Control and Software Systems, Oct. 27-29, 2014, Noordwijk, Netherlands.
4. Gilbert, M. G.: The Max Launch Abort System – Concept, Flight Test, and Evolution. Presented at 7th IAASS Conference, Oct. 20-22, 2014, Friedrichshafen, Germany.
5. Hanson, C.; Miller, C.; VanZwieten, T.; Gilligan, E.; Orr, J.; Wall, J.: Launch Vehicle Manual Steering with Adaptive Augmenting Control: In-Flight Evaluations using a Piloted Aircraft. AIAA SciTech Guidance, Navigation, and Control Conference, Kissimmee, Fla., 2015.
6. Null, C. H.: Autonomy: The Role of HSI. Presented at Dept. of Defense Human Factors Engineering Technical Advisory Group Meeting 68, May 19-22, 2014, Aberdeen, Md.
7. Null, C. H.: DOD Human Factors - Verification. Presented at Department of Defense Human Factors Engineering Technical Advisory Group Meeting 68, May 19-22, 2014, Aberdeen, Md.
8. Prosser, W. H.: Spacecraft NDE. Presented at IEEE Autotest 2014, Sept.15-18, 2014, St. Louis, Mo.
9. Rickman, S. L.: A History of Spacecraft Thermal Analysis. Presented at Thermal and Fluids Analysis Workshop (TFAWS) 2014, Aug. 4-8, 2014, Cleveland, Ohio.
10. Rickman, S. L.: Introduction to On-Orbit Thermal Environments. Presented at Thermal and Fluids Analysis Workshop (TFAWS) 2014, Aug. 4-8, 2014, Cleveland, Ohio.
11. Schuster, D. M.: MAX Launch Abort System Flight Test. Presented at Seminar at the University of Cincinnati, Oct. 31, 2014, Cincinnati, Ohio.
12. Schuster, D. M.: NASA Computational Aerosciences. Presented at AVIATION 2014 (The Aviation and Aeronautics Forum and Exposition), June 16-20, 2014, Atlanta, Ga.
13. Shockey, D.; Piascik, R. S.; Jensen, B. J.; Hewes, L. S.; and Sutter, J. K.: Textile Damage in Astronaut Gloves. Journal of Failure Analysis and Prevention, Volume 13, No. 6, Dec. 2013, p. 748-756.
14. VanZwieten, T.; Gilligan, E.; Wall, J.; Orr, J.; Miller, C.; Hanson, C: Adaptive Augmenting Control Flight Characterization Experiment on an F/A-18. AAS Guidance, Navigation, and Control Conference, Breckenridge, Col., AAS 14-052, 2014.
15. Wall, J.; VanZwieten, T.; Gilligan, E.; Miller, C.; Hanson C.; Orr, J.: In-Flight Suppression of an Unstable F/A-18 Structural Mode Using the Space Launch System Adaptive Augmenting Control System. AIAA SciTech Guidance, Navigation, and Control Conference, Kissimmee, Fla., 2015.

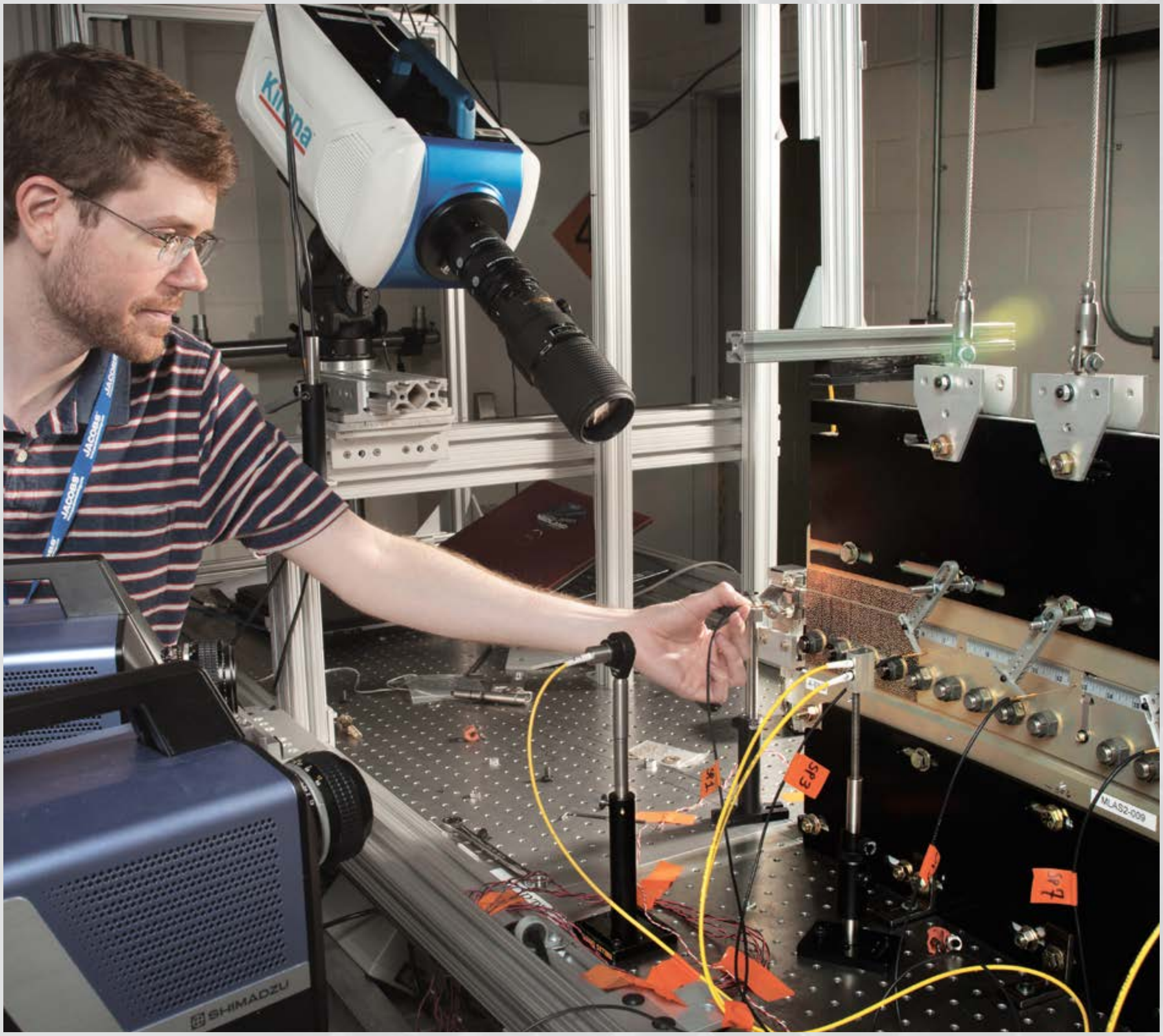
Recent NESC Technical Discipline Team Member Scholarly Papers and Conference Proceedings

1. Allgood, D.: Predicting Blast Wave Propagation in Rocket Test Facilities Using a Simplified Source Model. 60th JANNAF Joint Propulsion Meeting, April 29-May 3, 2013, Colorado Springs, Col.
2. Brauckmann, G. J.; Streett, S. L.; Kleb, W. L.; Alter, S. J.; Murphy, K. J.; and Glass, C. E.: Computational and Experimental Unsteady Pressures for Alternate SLS Booster Nose Shapes. Submitted for AIAA SciTech, Jan. 5-9, 2015, Kissimmee, Fla.
3. DellaCorte, C.; Moore III, L. E.: Launch Load Resistant Spacecraft Mechanism Bearings Made from NiTi Superelastic Intermetallic Materials. Proceedings of the 42nd Aerospace Mechanisms Symposium, May 14-16, 2014, NASA Goddard Space Flight Center, Md.
4. Forsgren, R. C.: APPEL - Developing the Technical Workforce. Presented at NASA Virtual PM Challenge, Dec. 2, 2014, Hampton, Va.
5. Jackson, E. B.; Shelton, R.; Jackson, A. A.; Castro, M. P; Noble, D. M.; Madden, M. M.; Litton, D. K.; Powell, R. W.; Queen, E. M.; Schidner, J. D.; Sellers, W. A.; Striepe, S. A.; Aguirre, J.; Zimmerman, C. J.; Lewis, E. K.; Reardon, S. E.; Vuong, N; Weinstein, M. J.: Development of Verification Check-Cases for Six Degree-of-Freedom Flight Vehicle Simulations. AIAA SciTech Guidance, Modeling and Simulation Technologies (MST) Conference, Jan. 2015, Kissimmee, Fla.
6. Krantz, T.: Reducing Wear of Steel Rolling Against Ti6Al4V Operating in Vacuum. 42nd Aerospace Mechanism Symposium, May 14-16, 2014, Baltimore, Md.
7. Ku, J.; Robinson, F.: Testing of a Neon Loop Heat Pipe for Large Area Cryocooling. Paper No. ICES 2014-35, 44th International Conference on Environmental Systems, July 13-17, 2014, Tucson, Ariz.

Recent NESC Technical Discipline Team Member Scholarly Papers and Conference Proceedings

Continued

8. Ku, J.; Robinson, F.: Testing of a Neon Loop Heat Pipe for Large Area Cryocooling. Spacecraft Thermal Control Workshop, March 25-27, 2014, El Segundo, Calif.
9. Orr, J. S.: A Critical Analysis of the X-15 3-65-96 Accident – Part I: Aircraft Systems and Flight Control. Presented at Aerospace Control and Guidance Systems Committee Meeting #114, Oct. 14, 2014, Cleveland, Ohio.
10. Wilder, M. C.; Bogdanoff, D. W.; Saunders, D. A.: Heat Transfer Measurements on the Afterbody of Spheres in Hypersonic Free-Flight in Air and Carbon Dioxide. Submitted for consideration to AIAA Aviation 2015, June 22-26, 2015, Dallas, Texas (submission status expected in late Feb. 2015).
11. Yang, K.; Peabody H.: Preliminary Development of a TSS and SINDA/FLUINT to ESARAD/ESATAN Thermal Model Converter. Paper Number TFAWS2014-PT-03. Presented at the Thermal & Fluids Analysis Workshop, Aug. 5, 2014, Cleveland, Ohio.
12. Yen, J. C.; Akers, S. A.: A C-4 Blast Simulation Using a Hybrid Source-Propagation Approach by CTH and JUSTUS Codes. 60th JANNAF Joint Propulsion Meeting, April 29-May 3, 2013, Colorado Springs, Col.



Kevin A. Lett of Jacobs Technology at WSTF instruments a Max Launch Abort System frangible joint for testing. Frangible joints can be used as the structural interconnection between stages of a launch vehicle and spacecraft.

The end of the successful Exploration Flight Test-1. The NESC performed numerous assessments for the Orion Multi-Purpose Crew Vehicle Program.

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10
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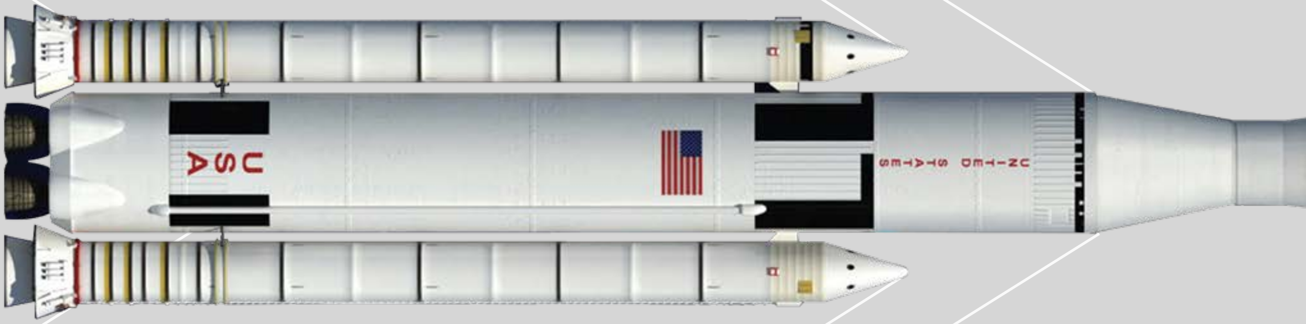

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