

# Crosslink®

A woman with long brown hair, wearing safety glasses and a white lab coat, is focused on her work. She is wearing a blue nitrile glove on her right hand, which is touching a large, circular, metallic component of a machine. The component has several oval-shaped holes. The machine itself is complex, with various metal parts, bolts, and a blue-painted section. The background is a solid blue color. The overall lighting is bright, highlighting the metallic surfaces and the woman's concentration.

The Aerospace Corporation magazine of advances in aerospace technology

Fall 2005

## Testing

Best Practices • Environmental Testing • Nanoscale  
3-D Imaging • Thermal Cycling • Electric Thrusters •  
Software Testing • Ground Systems

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On the cover: Gidget Ternet of the Materials Processing and Evaluation Dept. loads the optical scattering measurement facility, used to measure the BRDF (bidirectional reflectance distribution function) of optics, optical coatings, and contaminant films. Design by Karl Jacobs.

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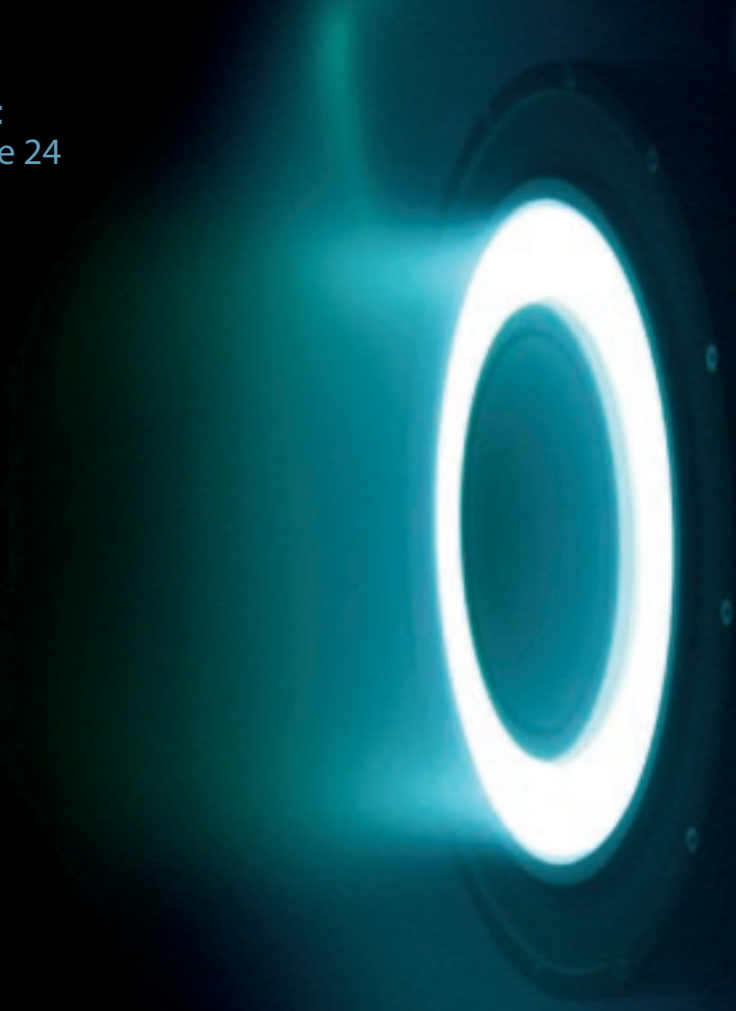
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In trying to reduce overall program cost and schedule, testing is often the first thing to get cut. And it's not hard to understand why. High-fidelity testing can take a long time—years, in some cases—and the end product is not some new gizmo or technological advance. When tests reveal no problems, program managers can be left wondering whether the testing was worth the time and effort—or worse, whether the tests were properly conceived and carried out. At best, testing can only confirm a program manager's worst fear: that something isn't working, and something needs fixing.

On the other hand, history has shown that a decrease in testing rigor equates with an increase in program risk. And a few important programs have felt the consequence of that risk.

Aerospace has traditionally been a vocal advocate of proper testing and has worked to make the process more efficient and reliable. Part of that work extends to phenomenology—what should a test be looking for?—and part of it extends to concepts and planning—how can we be sure a test will find the flaws it's supposed to?

Aerospace review of test plans and procedures can be crucial in ensuring that the testing process will find existing problems without introducing new ones. Investigations of life cycle performance help validate and improve testing models, instilling greater confidence in accelerated tests. Assessment of testing methods (especially across contractor boundaries) helps verify suitability and identify best practices. Given the company's traditional emphasis on testing, it's not surprising to find some unique and highly advanced facilities at Aerospace, including the ultrafast thermal cyclers and advanced propulsion diagnostics chamber featured in this issue.

Specifications and standards, which fell out of favor in the era of acquisition reform, are now back in style, much to the benefit of government space programs. The industry has come to realize that specs and standards do not arise arbitrarily, but represent the collective wisdom of numerous experts in diverse fields and eras. Aerospace has championed this return to standards and has been instrumental in revising outdated standards and developing new ones to reflect the latest manufacturing technologies and testing methodologies.

In some circles, the Aerospace name is synonymous with independent testing, validation, and verification. This issue illustrates the importance of testing and showcases some of Aerospace's important work in the field.

## A Closer Look at Mars

Intriguing data from several recent missions to Mars suggest the planet may have once held surface water. But if so, where did it go? The successful launch of NASA's Mars Reconnaissance Orbiter may help bring an answer to that question. Launched from Cape Canaveral atop an Atlas V rocket in August, the probe will take about seven months to reach the red planet. Once there, it will survey the surface from low orbit with unprecedented detail, charting the topography, monitoring the climate, measuring gravity gradients, and presenting new clues about the planet's geologic history. Most important, the orbiter will scout out sites for future surface landers, identifying locales with the greatest potential for answering questions about the presence of water and the prospects for harboring life.

For example, images from the high-spatial-resolution camera—the most powerful ever sent to another planet—will be used to select a landing site for a future mobile science lab that would maximize the chance of drilling into sedimentary rocks that still preserve information about how they were originally formed. Hyperspectral image data will provide detailed maps of aqueous mineral traces, including deposits that are too small to be resolved through other means. Ground-penetrating radar will see roughly half a kilometer below Mars's surface, searching for underground layers of ice, rock, and maybe even melted water.

The Mars Reconnaissance Orbiter will also serve as a communications relay satellite for later surface landers.

Aerospace, in conjunction with NASA's Jet Propulsion Laboratory, contributed expertise during mission planning and launch. Trade-off studies at Aerospace revealed how variable data rates at selected orbital heights could yield greater data throughput when the orbiter begins functioning as a communications relay. Aerospace assisted in developing project-level risk-management strategies, similar to work performed for the successful Mars Rover missions. Aerospace also performed cost and technical evaluations for the numerous instrument proposals.

## Airborne Laser

The airborne laser (ABL) recently completed an important phase of testing. In May, the laser's conformational window was unstowed for the first time during flight, a maneuver necessary for the weapon system to complete its mission of shooting down a ballistic missile in flight.

Aerospace personnel in Albuquerque have been a part of the team that supports the ABL's Beam Control/Fire Control (BCFC) segment. This portion of the ABL is responsible for target tracking, aiming of the lasers, and compensating for atmospheric conditions. In everything from BCFC systems engineering, integration and testing, and performance evaluation, Aerospace has provided on-site support for the ABL team.

By the final month of last year, the ABL program accomplished both of its planned 2004 milestones: the first light of the high-energy laser system and the first flight of the integrated BCFC segment.



Image courtesy of JPL

The launch of the orbiter was the first U.S. government mission and the first interplanetary mission aboard the Atlas V vehicle. Aerospace provided technical insight into the development and qualification of the Atlas V family in support of the Air Force EELV program, contributing to the early string of launch successes, including the success of the Mars Reconnaissance Orbiter. To maintain awareness of the Atlas V fleet health, Aerospace supported all technical reviews and events leading up to launch and participated as an integral part of the launch team at Cape Canaveral and at the mission support center at Aerospace headquarters in El Segundo, California. This included review and disposition of the gyro and software issues that delayed the launch two days. The successful launch was preceded by a smooth, nominal count with no major issues.

## Last of the Titans

The last Titan IVB heavy-lift vehicle to launch from Cape Canaveral successfully lifted off on April 29, 2005, carrying a National Reconnaissance Office (NRO) payload. The historic launch closed the penultimate chapter in the Titan family saga, which began half a century ago with the Titan ICBM. Throughout these years, Aerospace provided integral support to the program. In all, 27 Titan IVs have been launched from Cape Canaveral and 11 from Vandenberg. The vast majority of these carried essential national security payloads for the Department of Defense and the NRO. The final Titan IVB is scheduled to launch from Vandenberg in late October, once again carrying an NRO payload.



Image courtesy of Lockheed Martin

## STS-114 Return to Flight

The crew of the space shuttle Discovery returned safely to Earth in August after two weeks in space. The mission, which marked the shuttle's return to flight after the Columbia disaster, was not without tension and drama. First, a large piece of insulating foam broke off from the external tank during liftoff. Later, astronauts performed the first-ever in-flight shuttle repair, removing protruding gap fillers from Discovery's heat shield.

Prior to this mission, Aerospace assisted NASA in identifying risk from space shuttle debris sources by developing an alternative probabilistic (Monte Carlo) approach for those cases where it was not possible to identify risk using a deterministic worst-on-worst analysis. NASA had asked Aerospace to analyze several external tank foam cases for the Discovery launch as a result of the April 2005 Debris Verification Reviews. Specifically, Aerospace analyzed the liquid-oxygen protuberance air load ramp, which consists of thick manually sprayed layers of foam, the liquid-oxygen tank-to-intertank flange, the liquid-hydrogen tank-to-intertank flange, and the liquid-oxygen and intertank ice/frost ramps. The intertank is the structural connection that joins the liquid-hydrogen and liquid-oxygen tanks, which are affixed to flanges at the top and bottom. After the two tanks are joined to the intertank, the flange is insulated with foam.

Aerospace conducted additional non-Monte Carlo analyses on the bipod region and the liquid-hydrogen tank-to-intertank flange cryo divots. After a series of internal and external technical reviews throughout May 2005, Aerospace presented the analyses in June 2005 at the final Debris Verification Review. The space shuttle program accepted the results.

Aerospace also provided support to the program during the mission. Aerospace was tasked to perform sensitivity studies on the large debris and also trajectory and impact analysis on the extruding protective blanket. The analysis results were used to assist in determining the need for an additional space walk.



Image courtesy of NASA

## A Positive Impact

On July 4, 2005, NASA's Deep Impact mission slammed a tiny spacecraft into comet Tempel 1, kicking up a spectacular cloud of dust and debris that was recorded by a second mission spacecraft. Scientists will pore over the resulting gigabytes of data to learn more about the solar system's formative years.

Aerospace played key developmental roles in this remarkable mission, lending personnel to the flight project engineering team for launch vehicle mission design. Aerospace also provided analyses on launch probability that helped determine the length of the launch window. These analyses led to the decision to accommodate two launch opportunities for each day of the launch window. Aerospace verified trajectory information supplied by the launch service provider and wrote both the final target specification document and the day-of-launch documentation used by the launch director.

During development of the Deep Impact spacecraft, two serious technical questions emerged. The first concerned the integrity of the mounting welds on the spacecraft inertial reference unit, and the second involved timing and back-plane contention issues with the spacecraft control unit. To address the weld problem, Aerospace evaluated material samples and performed nondestructive testing and analyses, ultimately confirming that the weld strength was within acceptable limits. To address the timing and back-plane contention issues, Aerospace analyzed the problem and recommended a number of flight software changes that mitigated the risk during flight.



Image courtesy of JPL

# What Happened?

**A little detective work—and a lot of advanced technology—helps Gary Stupian trace the root causes of electronic system failure.**

**Donna J. Born**



Gary Stupian, senior scientist.

**G**ary Stupian, a senior scientist in the Microelectronics Technology Department, came to The Aerospace Corporation in September 1969 after completing two years as a post-doctoral researcher at Cornell University. For Stupian, Aerospace offered opportunities to continue his scientific research in a variety of technical areas. "Aerospace has always stressed research, even in lean times," he said. "It's a very diverse environment, which is what makes it a very interesting place to be."

He has worked on many programs during his years at Aerospace, but since the mid-1980s, his focus has been root cause analysis, the systematic investigation into a problem or an anomaly to find the underlying physical cause in order to fix it and prevent its recurrence. Stupian said such analysis has historically been part of the corporation's work in maintaining currency in space technology. "Root cause analysis covers all programs. Like an undertaker in a small town, we eventually get everyone's business."

One of the company's leading authorities in this area, Stupian described this work as technically challenging, eventually involving "the application of essentially every scientific discipline that one has studied." Space programs do have failures, and most of the technical staff inevitably will spend much of their time trying to understand and correct them, he said. "They will get down to the atomic scale to find out what's going on."

"That's what we do, myself and other people in the labs," he explained. "We generally drive for the absolute 'for sure' cause of why something didn't work, why it failed. You can often do that, but sometimes you have to be satisfied with the probable cause. You don't want unverified failures—everyone lives in fear of an unverified failure. You don't know whether it's going to come back again. You'd like to know what really did happen, and then you can either work around it or take corrective action."

Investigating the cause of anomalies is tied to the very beginnings of the corporation, when one of its earliest assignments was to assume system engineering for the Atlas launch vehicle and improve its reliability from 85 to 99.9 percent to make it safe for human flight. The Atlas, destined to carry the first astronaut into space, had already failed twice, once just a week before the corporation was formed in June 1960. Comprehensive design analyses led to modifications that

improved the reliability of the launch vehicle, and the Atlas successfully lifted John Glenn into his historic three-orbit flight aboard the Mercury capsule in February 1962.

Designers try to catch failures during testing before launch, Stupian said: "In space nothing is really repairable." Testing does cost money, and tests have to be designed with great care, he cautioned. The number of parts that can be tested under temperature and vacuum, for example, are limited, and testing has to be "accelerated," most commonly with elevated temperatures, so results are timely enough to be useful. The spacecraft is made up of components, and each one has to be reliable. Catching problems at the component level is the least expensive solution. Fixing problems becomes progressively more expensive at higher levels of integration and as launch dates approach, he explained.

Failures revealed by testing are examined carefully using advanced laboratory techniques. Stupian said that analysts will ask questions such as: Are the failures in an accelerated test representative of real, end-of-life failures that will limit a mission, or did inappropriate testing break the parts in some other way that won't be a problem in the application? If a failure involves a component installed in hardware, maybe even on the launchpad, what went wrong? Is there a generic problem that will affect all similar parts, or can the failure be attributed to mishandling that is not likely to be a recurring difficulty?

"You hope you have only one failure, but you must know the root cause if mission success is to be guaranteed," he said. "Sometimes, failures result from some very familiar physical mechanism; in other cases, the failure may result from a process that hasn't previously been responsible for anomalies. The ones that are not totally routine are more interesting, as a rule, but you have to look at everything."

In recent years, root cause analysis has acquired even greater importance, Stupian said, because of the decline of military influence on the electronics industry, reduced funding, and to some extent, offshore fabrication. Military requirements used to drive the supplier industries, especially the semiconductor market, but with the growth of consumer and industrial electronics, the small aerospace industry has little clout to dictate what suppliers are willing to provide. Manufacturers can change designs anytime—a component that previously

worked may no longer do so; a change to facilitate production may be disastrous for military space but inconsequential for consumer applications.

"I think in the present age, when we are switching emphasis to commercial parts, Aerospace is needed more than ever. We must look at the roots of failures to help understand how to make these commercial parts viable to ensure the success of space missions."

Stupian predicts that smaller parts will bring further challenges to root cause analysis: "Semiconductor feature sizes are shrinking. We're at about 0.25 micrometers now. By way of comparison, a human hair is about 75 micrometers in diameter. You can stack 300 such tiny objects (e.g., transistors) side by side and just span a single hair. Devices with 90- and 45-nanometer feature sizes will be used in systems now being built. We're able to do some rather remarkable things, including complete 3-dimensional reconstruction and modeling of nanoscale structures and chemical analysis on the nanometer scale. This sort of challenging work will grow in importance."

His work in the area of reliability and root cause of reliability problems earned him the Aerospace President's Distinguished Achievement Award in 1994. His expertise is regularly in demand, and he has been involved in numerous investigations. For example, hybrid circuits in the Milstar flight computer were replaced based on evidence he collected working with Tom Hoskinson of Aerospace's Milsatcom Division. His work with microfocus radiography (also called X-ray microscopy), which provides real-time imaging of details of the internal structures of specimens, is well known in the contractor community.

Stupian has been with Laboratory Operations during his entire career at Aerospace (and has kept the same metal desk through several organizational changes), where in addition to his work with root cause analysis he has been involved in many aspects of surface science, "including Auger spectroscopy and scanning tunneling microscopy." He regularly publishes in scientific journals, including articles this year on fabricating a photonic crystal and on high-pressure physics.

He considers some of his most interesting, "albeit rather tangential," work to be in forensic science. He has assisted investigations with the California Highway Patrol and the Los Angeles Police Department. In one murder case, he and Neil Ives, also of the Microelectronics Technology Department, worked with the coroners' investigators using X-ray computed tomography ("similar to a medical scan where you take a cross-sectional view and then you can stack the sliced images to form a complete 3-dimensional model") to examine the vertebra of a murder victim.

He was the first to look at the isotopic composition of bullet lead to characterize bullets, and published papers on the subject in 1975 and 2004. The nuclei of lead atoms can have different numbers of neutrons; that is, there are different isotopes, he explained. The four main stable isotopes of lead are found in varying relative amounts in nature because of differences in the initial chemical compositions of the precursor radioactive minerals. Lead from different geologic sources will show differences in the isotopic ratios.

"This has become controversial now," Stupian said. "Some laboratories have made very strong assertions about their ability to do this type of analysis. They were looking also at variations in elemental

composition, but the same principle applies. The trouble is that the lead used in bullets may be recycled, so it's very hard to vouch for its uniformity."

From the time he was 10 years old, he wanted to be a physicist. Although his long working hours leave him with little free time, he spends much of it keeping up with developments in physics outside his area of concentration—for instance, dark matter and dark energy in the universe—"because a physicist ought to know these things." His three academic degrees are in physics (with specialization in condensed-matter physics): B.S. from California Institute of Technology and M.S. and Ph.D. from the University of Illinois at Urbana/Champaign.

He has been active in helping young scientists and recruiting them to Aerospace through his work with the corporation's university affiliates program, which promotes the exchange of technical information, expertise, and research with selected universities. As the technical liaison between Aerospace and Caltech, he is largely responsible for obtaining funding for six undergraduate research fellowships each summer. The students work on the Caltech campus with faculty, graduate students, and postdoctoral fellows over a 10-week period during the summer. The six company-sponsored students are asked to



Stupian discusses a forensic investigation with members of the local police force.

present their work in seminars at Aerospace at the end of the summer. They get to see the Aerospace campus and gain a broader awareness of the company's role in national security space. The Aerospace Institute, the division of the corporation that administers the university affiliates program, has recognized his significant contributions to the program with four annual achievement awards.

"Aerospace is a good place for young scientists to pursue a career," Stupian believes, "because it is one of the few places where you actually have the possibility to do research. We're involved in the practical things, and we try to do some more fundamental things. There are not very many places where you can do that. We don't do as much research as we would probably like, but I have a lot of satisfaction in helping space programs by applying physics and material science to solving problems." ●

# A Successful Strategy for Satellite Development and Testing

An Aerospace study of satellite development practices has reaffirmed the needs of the traditional approach based on uniform standards and rigorous testing.

Bill Tosney and Steve Pavlica

In 1986, the President's Blue Ribbon Commission on Defense Management completed an in-depth assessment of the defense acquisition process. The recommendations of this commission resulted in a series of policy reforms geared toward a "faster, better, cheaper" acquisition strategy. One of these new policies, codified in the Military Specifications and Standards Reform Program issued by the Secretary of the Air Force for Acquisition in 1995, effectively ended the use of military specifications and standards—despite arguments that these standards represented best practices compiled through decades of costly and arduous trial and error. Commercial best practices were deemed suitable alternatives, even though in the space industry they were mostly nonexistent or unproven.

In the ensuing years, the number of late-build-cycle and on-orbit failures surged. Commercial satellite programs alone had a 146-percent increase in failures between 1998 and 2002. This increase in failures, assumed by many to be caused by deficiencies in testing, alarmed the government acquisition community. As a result, Aerospace was tasked in 2002 to conduct a comprehensive assessment of satellite testing practices to answer the question: Is testing technology failing to keep pace with changes in development methodologies, manufacturing improvements, technology upgrades, and material advances?

Right away, it became clear that very few recent problems could be attributed to the failure of testing technology to keep pace with development technology—most problems arise from deeper system-wide deficiencies, particularly systems engineering shortcuts. The study found that testing is resource-intensive, but it can accommodate new technologies, when properly applied. The scope of the study was, therefore, expanded to include a comprehensive assessment of satellite acquisition and development practices, a task that Aerospace was uniquely capable of performing thanks to its comprehensive database of detailed factory and orbital data going back several decades. This allowed analysts to compare and contrast important programmatic and engineering variables affected by the acquisition changes that had taken place since 1995.

## A Decline in Testing Rigor

A comparison of programmatic and engineering practices affected by the acquisition changes found that much of the growth in late-build-cycle and orbital failures occur because proven mission-assurance practices were either greatly relaxed or discarded in the wake of acquisition reform. Entrusted with more autonomy, the government and industry had grown more concerned with managing near-term cost and schedule risk than long-term performance risk—and one clear way to trim cost and schedule in the near term was by shortchanging quality, particularly testing thoroughness and issue resolution during development.

For example, development times had grown as a result of increased system complexity, and the pressure to minimize schedule slip prompted some developers to reduce test perceptiveness and thoroughness of unit, subsystem, and system-level testing and to increase the use of test surrogates instead of actual flight units in system-level tests. The time to conduct a typical system-level test, for example, had declined by an average of 30 percent since 1995. This raised questions about the rigor of the functional and performance testing employed: Was it indeed perceptive enough?

Another notable decline in test rigor was seen in the area of unit or black-box thermal testing. Contractors consistently cut back on environmental stress screening at the unit level, decreasing the number of thermal cycles by as much as 50 percent to save time. The consequence, however, was an increase in unit failures after the satellites were fully assembled and subjected to the system-level thermal vacuum test (where the cost of the failure dramatically increases).

The space industry generally recognizes that all units (black boxes) and space vehicles should be tested under environmental and performance conditions as close to flight-like as possible—a philosophy known as "test like you fly." However, complete flight-like testing is not always feasible. There are often physical factors limiting what can be done on the ground (for example, recreating zero-gravity effects, providing the star field

and environment for testing the attitude control system, providing solar illumination in vacuum for fully extended solar arrays, and fitting large systems into a relatively confined vacuum chamber). But even in light of these acknowledged limitations, Aerospace found an increasing trend away from applying flight-like testing methodologies where they were previously considered routine, such as in unit and subsystem performance testing and software compatibility with hardware in the loop. Similarly, intersegment testing between the ground and space segments was often eliminated entirely or greatly reduced in scope.

The decision to omit or scale back these tests must be accompanied by a clear assessment of the attendant risks. Where there is significant risk exposure by not being able to test appropriately, mitigation strategies can be developed early in the life cycle. Aerospace found these risks were not always well understood, and consequently, mitigation strategies were not effectively applied.

Aerospace found that best practices for flight-like testing had not been codified in the industry. There was a general lack of practical guidance for determining how well or poorly the testing was conducted. This was particularly true for “day in the life” operational testing.

Traditionally, issues and problems uncovered during satellite development and testing would result in design and process changes, which would in turn be scrutinized for insights that very often improve the development and verification process. As a third-party observer, Aerospace could look across contractor boundaries and identify key lessons and practices, which could then be used to help prioritize the reintroduction of industry-wide specifications and standards. With the cancellation of these standards in the mid-1990s, contractors were left on their own to accommodate technological changes and lessons learned into their own processes—with variable success.

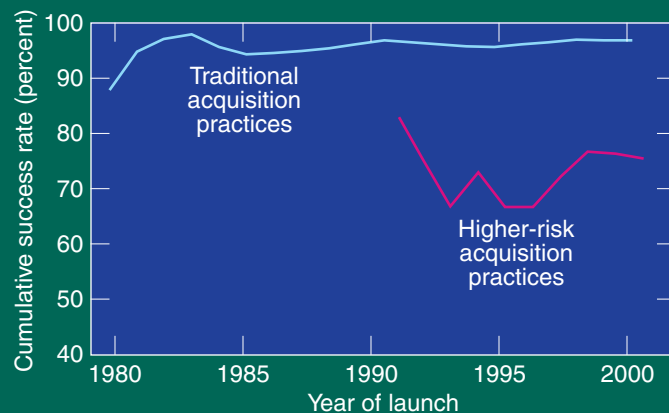
## A Leap in Complexity

While verification rigor had dropped, overall satellite complexity rose, often exponentially, as a result of advances in electronics technology and software. Not only were these systems using more parts, but the parts themselves were often far more complex, requiring much more stringent design verification and qualification practices. The greater use of field-programmable gate arrays (FPGAs) and application-specific integrated circuits (ASICs), with millions of embedded transistors on a single device, poses an even greater testing challenge.

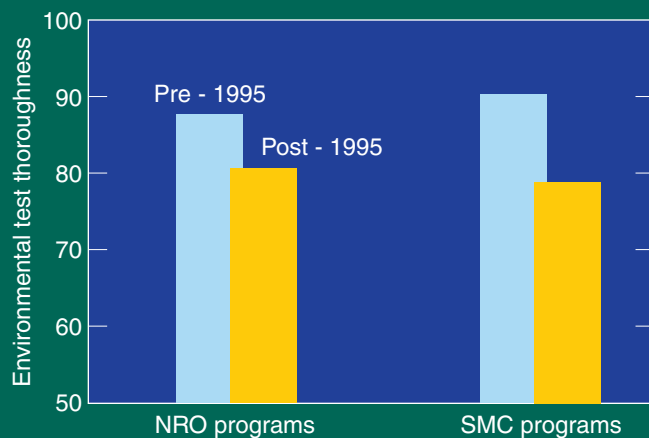
Not only does increasing complexity pose a challenge to the verification process, but it also implies an increase in the likelihood of latent design and workmanship defects. Given the increases in complexity, the corresponding pressures on the verification processes, and the increased failure potential, the industry and government had embarked on a path of conflicted logic that resulted in numerous problems that were often not detected until late in development cycle, or even on orbit.

Under acquisition reform, the government did not always specify requirements for qualifying the parts used in space systems. The manufacturers assumed responsibility for piece-part qualification, based on the application and the performance requirements at the system level. This led to problems for several reasons.

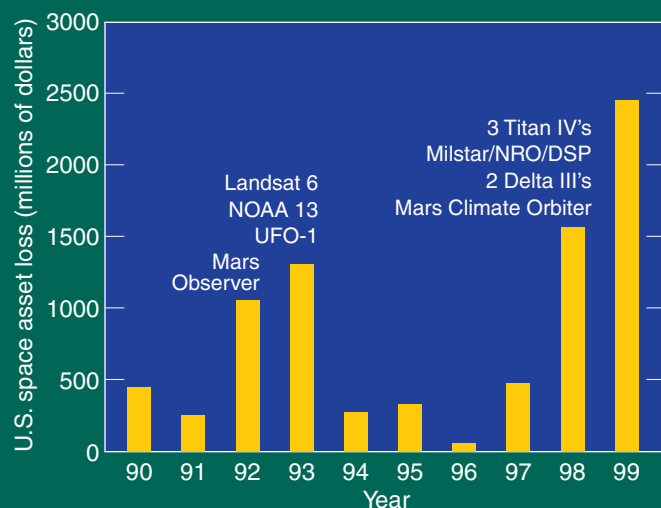
Acquiring qualified parts had become more difficult as suppliers focused on commercial markets at the expense of the military space market (which, although relatively small, typically requires



Out of a sample of more than 450 vehicles manufactured in the United States, those developed using traditional acquisition practices show a consistently higher success rate in the first year of operations. In contrast, vehicles developed using higher-risk acquisition approaches show markedly lower success rates in the first year of operations.



Acquisition reform in the national security space arena reduced verification rigor, as illustrated in the drop in environmental test thoroughness.



This chart shows the value in dollars of U.S. space assets lost during the 1990s. Recent independent studies have shown that reducing technical verification rigor and diminishing the role of independent technical oversight in the development of government and commercial space systems results in greater problems, as evidenced by higher failure rates and cost and schedule overruns.

## A Return to Standards

The Air Force Space and Missile Systems Center (SMC) and the National Reconnaissance Office (NRO) have established policies that embrace the use of government, industry, and professional society specifications and standards to define program technical baselines. The effort includes the processes for the evaluation, selection, and preparation of documents and also the processes and ground rules for implementation as compliance documents in requests for proposals and contracts.

Aerospace plays an integral role in the review of existing technical standards, the development and publication of new standards in several engineering disciplines, and the implementation of standards in the acquisition process for new systems. Aerospace, NRO, and SMC compiled a list of the key standards and have kept the list updated and published as an Aerospace technical report. Eventually, appropriate documents will be revised and reissued as military, industrial, or international standards. For example, five Aerospace standards were recently issued as AIAA standards. In the meantime, Aerospace technical reports will be used as compliance documents.

—Valerie Lang, Joe Meltzer, and Jacqueline Unitis

stricter parameter control, higher reliability, wider temperature ranges, higher dynamic response, radiation hardness, and similar traits). In addition, as suppliers switched from a product qualification model to a process qualification a model, both primary contractors and government lost insight and traceability into parts because suppliers were not required to provide technical data for qualification and traceability. The government had even less insight, with fewer people to track problems and less oversight into manufacturing details.

Cost and schedule assumed a greater role in determining which tests and analyses should be used to demonstrate that a device was acceptable and could meet system requirements. Because of inadequate resources and shifting priorities, only new or problematic suppliers were evaluated or closely

monitored. Verification of compliance was less disciplined for subtier contractors, and the prime contractor's role changed from "right of approval" to "right of rejection."

Flight software complexity had increased even more, and it is now statistically impossible to find all possible defects in large software systems. Despite continuing advances, debugging code remains time-consuming: up to 50 percent of a programmer's time can be spent debugging code. Furthermore, testing requires a test plan, detailed test procedures, and scripts for providing input to an automated testing tool—an effort that can be just as prone to error as the code it purports to test. Altogether, complex software entails meticulous verification planning and software development, a challenge that is not addressed in development and budget allocations. This underscores the need for a

## Reemerging Part Specifications

Based on a number of recent problems, experience clearly indicates that a more stringent and consistent approach to parts, materials, and processes—including qualification—must be followed. One major objective is to establish a revised standard that defines the necessary characterization, qualification, and screening tests for microelectronics and other piece-part commodities (e.g., hybrids, capacitors, resistors, relays, and connectors) that would clear them for use in space applications. This includes government participation to ensure that risks are not solely quantified on cost and schedule, but life performance as well. A rewrite of technical requirements for space parts, materials, and processes is under way based on previously existing military standards.

rigorous independent assessment of inter-related software and hardware requirements development early in the process.

Today's satellite systems involve multiple user nodes. The increasing number and complexity of interfaces led to a rise in interface problems during system-level and end-to-end testing among ground, user, and space segments. These complex interfaces present a challenge to simulation tools and limit the accuracy of design-margin predictions and verification by use of models and simulations.

## A Breakdown in Systems Engineering

In addition to finding problems with verification and testing, the Aerospace study identified numerous problems with systems engineering practices, including source selection, requirements definition and flowdown, system design, engineering requirement verification, manufacturing and integration support, and scheduling.

Data analyzed pointed to a number of systems engineering deficiencies that resulted in numerous late-build-cycle problems, highlighted by the large increase in design flaws (detected in system-level testing) since 1995. Specific deficiencies include marginalizing the peer design review process and related documentation, descopeing preliminary and critical design processes, and marginalizing the risk management process. In general, Aerospace found that systems engineering processes were fragmented.

Several additional systems engineering challenges were also discovered—most notably, personnel shortfalls, flawed assumptions regarding the insertion of commercial products in a given design, less emphasis on achieving flight-like testing, and greater emphasis on cost and schedule versus performance and reliability.

Spacecraft are extremely complex, and program managers have always felt pressure to reduce costs and head count. Coupled with the aging demographics of the space industry workforce, the pressure to minimize staffing levels had decimated government and contractor systems engineering teams—sometimes depleting teams from five or six deep to one individual who may not have enough technical breadth to understand the potential impact of design issues and the many problems that occur during production. This increased the chances that design errors would go unidentified (and uncorrected) until they caused a failure. The lack of personnel also led to a reduction in oversight of the

prime contractors by the government and of the subcontractors by the prime contractors. This increased the likelihood that problems caused by streamlined design and verification process changes at one level would not be communicated to another.

Another common shortfall in systems engineering and verification planning involved overly optimistic assumptions about the use of commercial off-the-shelf (COTS) or heritage components. In many cases, the developer assumed that a commercial or heritage product was suitable for a new application without giving sufficient scrutiny to the intended design use conditions. In reality, commercial or heritage products almost always require more modifications than expected, and this adversely affects program schedule. Sometimes, problems with these products were overlooked until they caused costly failures in ground testing or even on orbit because assumptions regarding the suitability of the original design to the new application's actual design environment and operational scenarios did not pan out.

## A Get-Well Road Map

The Aerospace study concluded with a series of specific recommendations for the national security space community. In particular, acquisition managers must:

- strictly adhere to proven conservative development practices embodied in best-of-class specifications and standards;
- apply rigorous systems engineering, including disciplined peer design reviews and clearly traceable verification processes;
- emphasize requirements verification and testing of all hardware and software, focusing on the early development phase and lower-level unit design;
- apply updated and consistent software development and verification processes, including meaningful metrics;
- instill effective closed-loop design and communication processes, with special attention to new technology insertion, application of COTS components, and detailed assessment of operational data and lessons learned;
- strengthen the qualification and verification of parts, materials, and processes;
- develop a pyramidal and flight-like requirements verification policy and assess the risk of deviations from this policy;

## The Testing Handbook

Aerospace is developing a comprehensive test and evaluation handbook that will codify best practices for planning a successful qualification and acceptance test strategy. This handbook will deal with the up-front planning and production phase as well as orbital checkout. The list of guidelines includes lessons learned from the study, such as:

- Base schedules on realistic and executable models that account for system production maturity, reasonable levels of integration returns, and realistic problem resolution.
- Plan a test program that implements a pyramidal requirements verification approach.
- Test all high-power electronic units, including RF hardware, in thermal vacuum prior to system-level testing.
- Ensure a conservative retest philosophy on all anomalous hardware that accounts for fatigue life from prior test exposures.
- Develop an EMI/EMC control plan that ensures pertinent EMI/EMC testing at unit and appropriate levels of assembly and always conduct a system-level EMI/EMC test prior to the thermal vacuum test.
- Perform early interface and harness compatibility checks on all hardware, preferably during development.
- Plan for intersegment testing at the spacecraft level of assembly and include all flight hardware.
- Plan for a rigorous verification and checkout of ground support equipment well in advance of qualification testing.
- Plan for a disciplined anomaly tracking and resolution process that determines root cause on all anomalies and includes all factory, subcontractor, launch-base, and operational anomaly data.

- develop a set of engineering handbooks written from the perspective of the system program office;
- manage the product life-cycle data within the system program office and across the enterprise and learn from it.

When these practices are applied together throughout development, they have historically resulted in successful program acquisitions and mission success. Recommendations from major government review panels are largely consistent with Aerospace conclusions regarding the proper application of industry best practices and lessons learned. Moreover, the Aerospace study provides detailed evidence as to why national security, long-life, space acquisition—and more pointedly, the verification process—requires a different approach than that of a purely commercial space program. As a result, acquisition leaders are once again emphasizing a more traditional, proven, and disciplined approach to engineering space systems.

One critical part of such an approach is to ensure that appropriate specifications and standards are applied on a given contract. Specifications and standards arise from an often painful and costly evolutionary process, and in a sense, they form the embodiment of decades of lessons learned and best practices. These specifications, standards, and guidelines therefore form the cornerstone of traditional best practices that help ensure successful execution of a satellite program. Realizing this, Aerospace has already helped introduce revised and new national security space standards for space systems development, which draw upon the previously canceled military standard with enhancements to bring them up to date with current best practices.

Additional best practices related to a successful qualification and acceptance test strategy will be defined in a comprehensive test and evaluation handbook under development at Aerospace. In addition, Aerospace is developing and publishing handbooks that

General Design and Verification	Former	Current
Test Requirements for Launch, Upper Stage, and Space Vehicles	MIL-STD-1540C	SMC-TR-04-17 <sup>1</sup>
Test Method Standard for Environmental Engineering Considerations and Laboratory Tests	MIL-STD-810F	MIL-STD-810F
Software Development Standard for Space Systems	MIL-STD-498	Aero. TOR-2004(3909)-3537, Rev. A
Test Requirements for Ground Equipment and Associated Computer Software Supporting Space Vehicles	MIL-STD-1833	MIL-STD-1833
Verification Requirements for Space Vehicles	—	Aero. TOR-2005(3901)-4243 <sup>2</sup>
Domain-Specific Design and Verification	Former	Current
Electromagnetic Compatibility Requirements for Space Systems	MIL-STD-1541A	Aero. TOR-2005(8583)-1
Electromagnetic Emissions and Susceptibility, Requirements for the Control of EMI	MIL-STD-461D	Aero. TOR-2005(8583)-1
Wiring Harness, Space Vehicle, Design and Testing	DoD-W-8357A	DoD-W-8357A
Space Battery Standard	—	Aero. TOR-2004(8583)-5, Rev. 1
Qualification and Quality Requirements for Space-Qualified Solar Panels	—	AIAA S-112-2005 <sup>1</sup>
Electrical Power Systems, Direct Current, Space Vehicle Design Requirements	MIL-STD-1539A	Aero. TOR-2005(8583)-2
Moving Mechanical Assemblies for Space and Launch Vehicles	MIL-A-83577C	AIAA S-114-2005 <sup>1</sup>
Space Systems - Structures Design and Test Requirements	—	AIAA S-110-2005 <sup>1</sup>
Space Systems - Flight Pressurized Systems	MIL-STD-1522A	Aero. TOR-2003(8583)-2896
Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components	MIL-STD-1522A	AIAA S-080-1998 <sup>1</sup>
Composite Overwrapped Pressure Vessels	MIL-STD-1522A	AIAA S-081-2000 <sup>1</sup>
Solid Motor Case Design and Test Requirements	—	Aero. TOR-2003(8583)-2895, Rev. 1
Criteria for Explosive Systems and Devices Used on Space Vehicles	DoD-E-83578A	AIAA S-113-2005 <sup>1</sup>
Mass Properties Control for Satellites, Missiles, and Launch Vehicles	MIL-STD-1811	Aero. TOR-2004(8583)-3970
Part-Level Design and Verification	Former	Current
Qualification and Quality Standards for Space-Qualified Solar Cells	—	AIAA S-111-2005 <sup>1</sup>
Electronic Parts, Materials, and Processes Control Program Used in Space Programs	MIL-STD-1547B	Aero. TOR-2004(3909)-3316, Rev. A
1. These specifications have been converted to AIAA specifications based on Aerospace technical domain expertise submitted to AIAA technical committees via Aerospace TORs.		
2. Not included on SMC compliance list. Included with NRO standards.		

This table lists the specifications and standards that are being introduced or reintroduced into the national security space acquisition process that relate specifically to design and verification requirements. General design and verification specifications and standards typically apply to multiple levels of assembly and include some discussion of requirements oriented toward the integrated system-

level architecture. Domain-specific standards are oriented toward environmental, functional, or hardware type testing and include requirements for batteries, solar panels, mechanisms, and structures. Part-level standards typically focus on space-related items. For details, see Aero. TOR-2003(8583)-2, Rev. 4, "Systems Engineering Revitalization Specifications and Standards Implementation Plan and Status."

provide technical rationale, methodology, and tailoring guidance for mission assurance and space vehicle systems engineering.

## Summary

The findings of the Aerospace study are helping spur national security space initiatives to establish more disciplined systems engineering, verification, and mission-assurance strategies. The assessment of development practice changes, together with an analysis of on-orbit and factory test failures, provided a greater degree of insight into the effectiveness of the integration and testing processes, the critical role of the systems

engineering process, and the sensitivity of design and verification processes to the consequence of acquisition policy change. The study also shed new light on the relationships among test parameters, levels of assembly tested, test effectiveness, test-related fatigue, and the resulting influence on cost, schedule, and mission success.

Successful space systems in the past adhered to a rigorous requirements flowdown process that was tied to a comprehensive and disciplined verification process that ensured each requirement was properly verified and traceable to a specific test, analysis, or inspection document. By reemphasizing veri-

fication and testing at the lowest level and testing under flight-like conditions, the government is underscoring the importance of applying technical rigor in areas where conflicting and often marginally successful verification methods were being applied because of the lack of paradigmatic specifications and standards. Systems engineering and mission assurance revitalization initiatives are well attuned to the urgency to correct the lapses in the acquisition strategy and have consolidated efforts to accelerate development of a common and technically relevant set of specifications, standards, and best practices for all national security space programs. ➡

# Environmental Testing for Launch and Space Vehicles

Space systems must endure a physically stressful journey from the launchpad to their final destinations. Adequate testing can help ensure they survive the trip.

Erwin Perl, Thinh Do, Alan Peterson, and John Welch

The structural design of space systems is dictated by the rigors of the liftoff and ascent environments during launch as well as the extreme thermal conditions and operational requirements of spacecraft equipment and payloads on orbit. At liftoff and for the next several seconds, the intense sound generated by the propulsion system exerts significant acoustic pressure on the entire vehicle. This pressure induces vibration, externally and internally, in the space vehicle structures. In addition, the vehicle experiences intense vibrations generated by engine ignitions, steady-state operation, and engine shutdowns as well as sudden transients or “shocks” generated by solid rocket motor jettison, separation of stages and fairings, and on-orbit deployments of solar arrays and payloads. Space vehicles will also experience wide fluctuations in temperature from the time they leave the launchpad to the time they settle into orbit. Both individually and in combination, the mechanical environments of pressure, vibration, shock, and thermal gradients impose design requirements on many structural components. Ensuring the survivability of the delicate hardware poses challenges that can be met only by extensive preflight tests encompassing acoustic, shock, vibration, and thermal environments.

Environmental testing is performed at varying magnitudes and durations to verify the design of space systems and to screen flight hardware for quality of workmanship. The first step in this process is the definition of the maximum expected environments during launch and on-orbit operation. Data from previous flights and ground tests are analyzed to generate predictions for a specific mission. These environments are then flowed down from the space vehicle level to the various subsystems and components for use as design requirements and, later, as test requirements.

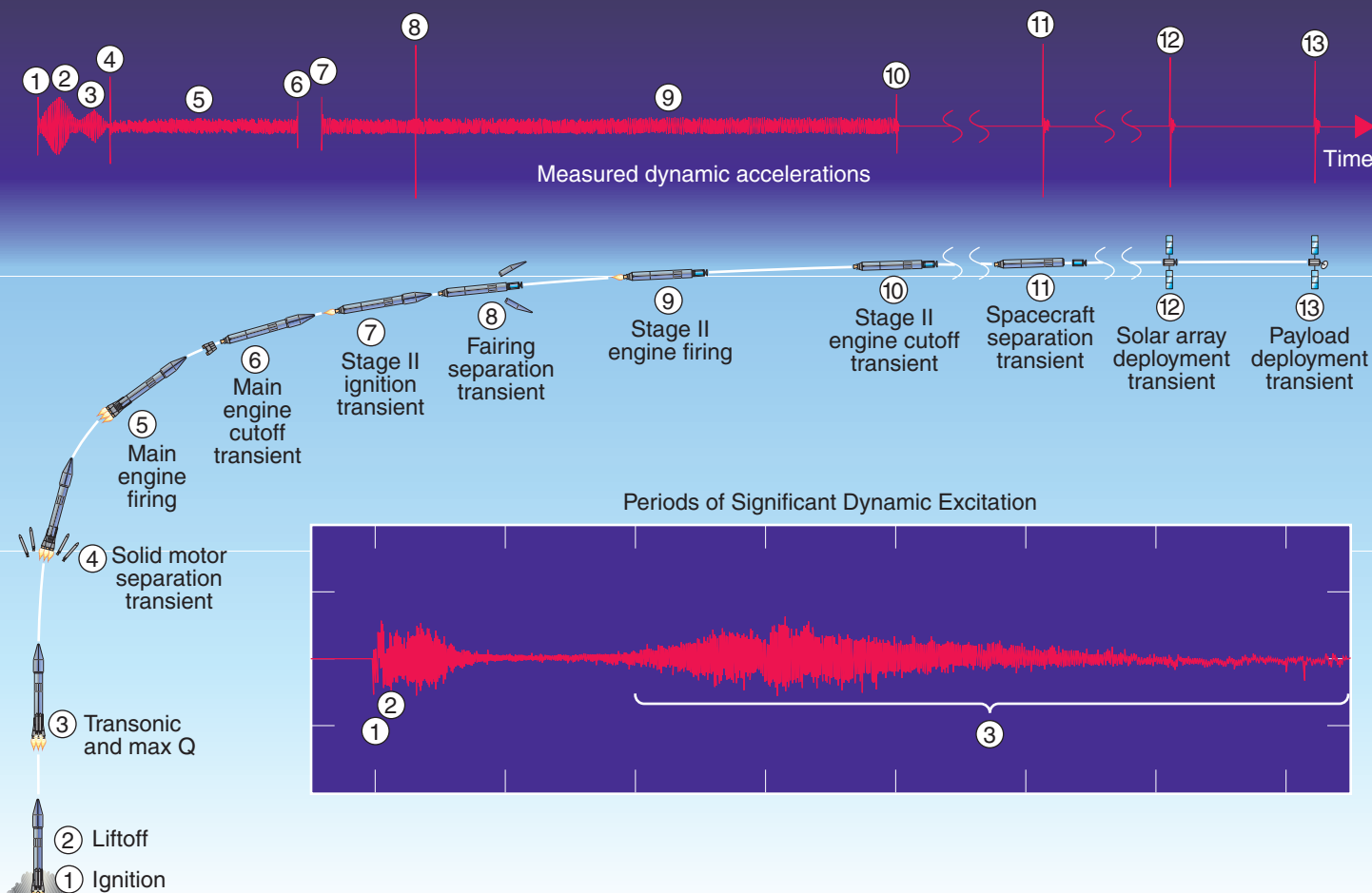
Aerospace performs a crucial role for the government in ensuring that these environments are properly defined and the design qualification tests and the hardware acceptance tests are properly planned and carried out. By reviewing test requirements and analysis methodologies, for example, Aerospace

helps verify that the results will be accurate and meaningful. Reviewing the maximum predicted environments ensures that space systems are designed to withstand the rigors of flight. Reviewing test plans helps develop perceptive test procedures. Observing the tests builds confidence that they were conducted according to specification. Reviewing the test data provides an independent validation of the results. Archiving and cataloging test data helps test planners ensure that test methods reflect the current state of the art. And of course, by observing test anomalies, Aerospace retains relevant lessons for future programs in a continuous cycle driving toward improved reliability of space systems.

## Acoustic Testing

A principal source of dynamic loading of space vehicles occurs during liftoff and during atmospheric flight at maximum dynamic pressure. It is caused by the intense acoustic pressure generated by turbulent mixing of exhaust gases from the main engines and rocket motors with the ambient atmosphere.

This acoustic excitation starts when the main engine is ignited and lasts approximately 3 to 6 seconds. Ignition produces an exhaust plume that exerts acoustic pressure on the launchpad and reflects back to the space vehicle to induce vibration. The magnitude of the exhaust plume and the amount of pressure it exerts depends on factors such as engine thrust, exit velocity, engine nozzle diameter, location of structures, and duct configuration. As the speed of the launch vehicle increases, the relative velocity between the vehicle and the ambient atmosphere generates fluctuating pressures in a turbulent boundary layer between the exterior surface and the atmosphere. As the vehicle traverses the speed of sound, the so-called region of transonic flight, and shortly thereafter, the region of maximum dynamic pressure, the airflow together with aerodynamic shock waves that attach, oscillate, and reattach cause acoustic excitations comparable to liftoff, but with different frequency characteristics. The sound pressure and its induced vibration are random in character. The spectra used to assess damage



A typical Delta II mission profile and the associated accelerations due to acoustic, vibration, and shock environments during liftoff, transonic and maximum-dynamic-pressure (max Q) flight, main engine cutoff, secondary engine cutoff, stage separation, payload fairing separation, and spacecraft separation. The acceleration time

history is processed for each significant dynamic event and transformed into frequency plots representing acoustic-pressure levels, vibration, and shock spectra that are used to establish future requirements and assess damage potential to the launch and space vehicle.

potential are expressed in terms of pressure and acceleration or converted into commonly used units of decibels and power spectral density, respectively. These spectra usually span the range of frequencies from 10 to 10,000 hertz.

Acoustic testing of space vehicles or major subsystems strives to simulate the acoustic pressure expected during liftoff and subsequent mission phases. Space vehicles also contain complex components that are susceptible to acoustic noise, and these must be tested to ensure all potential failure modes and workmanship defects have been properly screened out prior to system integration. In a typical acoustic test, the test specimen is positioned in an acoustic chamber. The chamber is a large room with thick walls and a smooth interior surface that permits high reverberation. The test article is placed on a fixture or suspended from bungee cords. In some cases, the test item may be attached to larger metal plates to simulate actual

mounting on the spacecraft structure, thereby creating a more realistic profile of the interface vibration. Loudspeakers or horns supply the acoustic energy, with four or more microphones strategically placed to control and record the sound level within the room. Numerous acceleration transducers are installed on the test item to measure the motion induced by the acoustic pressure into the item's critical components. Many of these critical components are also functionally monitored during the test. The measurements are compared with the appropriate design specifications for the components to assess their qualification for flight. Aerospace contributes to these activities by providing an independent review of the test measurements to ensure their validity and by comparing them with the design specification and the previously predicted levels to ensure the design adequacy of the components. In case of a test failure, Aerospace performs the

necessary analysis to help identify the root cause and appropriate mitigation.

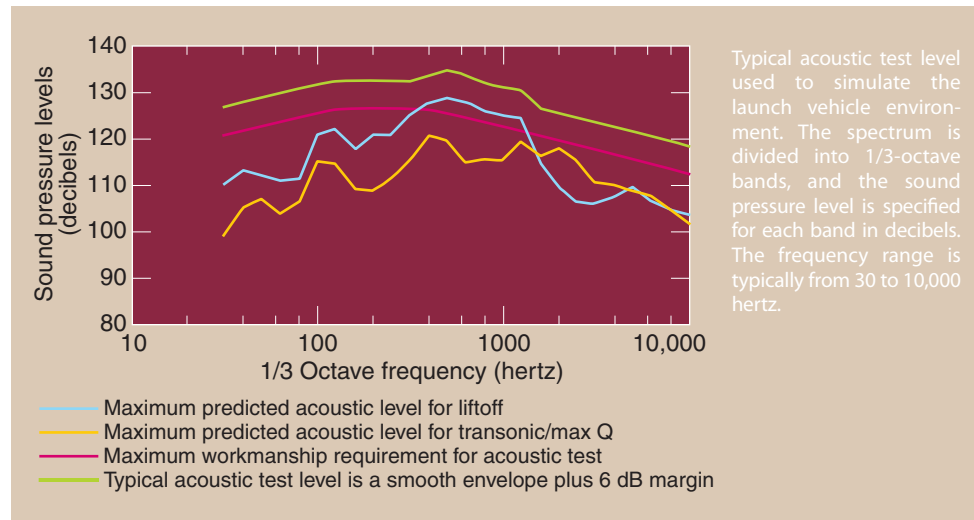
The acoustic test levels for a particular space vehicle or subsystem are usually derived from measurement of data on similar structures on past flights and ground tests. Aerospace maintains an extensive database of flight and ground-test information. This compilation is a unique resource made possible by Aerospace's access to a wide range of launch vehicle and satellite program data. Aerospace uses the database to predict the test levels in the early stages of the program and in advance of the acoustic test. This provides the program early awareness of the structural acoustic requirements for component design so that any deficiency can be addressed prior to the actual tests. If sufficient data are not available in the database, analytical tools such as statistical energy analysis for frequencies above 100 hertz and finite-element and boundary-element methods for frequencies below 100 hertz are

sometimes used to derive test levels. The predicted acoustic environment is adjusted using statistical methods to derive a maximum predicted flight environment. Margin is added to ensure that the hardware is sufficiently robust and to account for analytical uncertainties in the derivation of the environment and design of the hardware. A typical qualification margin is 6 decibels, or four times the energy of the maximum predicted environment. The test lasts at least 1 minute to establish a duration margin of four times the exposure in flight. Additional test time may be accumulated depending on the program requirements. Hardware that is susceptible to the acoustic-pressure loading are items with large surfaces and low mass density such as composite material solar arrays and antenna reflectors. These composite structures may have design or workmanship deficiencies, which result in bond or material failures.

## Vibration Testing

As the launch vehicle lifts off from the stand and throughout powered flight, the vibration caused by the operating engines excites the vehicle and spacecraft structure. Additional vibration is caused by the fluctuating acoustic pressure experienced during liftoff, transonic flight, and the maximum-dynamic-pressure phase of flight.

Vibration testing helps demonstrate that hardware can withstand these conditions. Random vibration tests are conducted on an electrodynamic vibration machine or "shaker," which consists of a mounting table for the test item rigidly attached to a drive-coil armature. A control system energizes the shaker to the desired vibration level. Feedback for the control system is provided by a series of accelerometers, which are mounted at the base of the test item at locations that correspond to where the launch vehicle adapter would be attached. Two control approaches can be used to provide realistic structural responses. Most spacecraft vibration tests use response-limiting major-appendage accelerations to reduce input at discrete frequencies so as not to cause unrealistic failures. For test structures that exhibit distinct, lightly damped resonances on a shaker, force limiting is used in conjunction with input vibration to control the shaker. In the force-limiting approach, transducers that measure the input force are mounted between the test item and the shaker. The goal is to reduce the response of the test item at its resonant frequencies on the shaker to replicate the response at the combined system at



the resonant frequencies that would exist in the flight-mounting configuration.

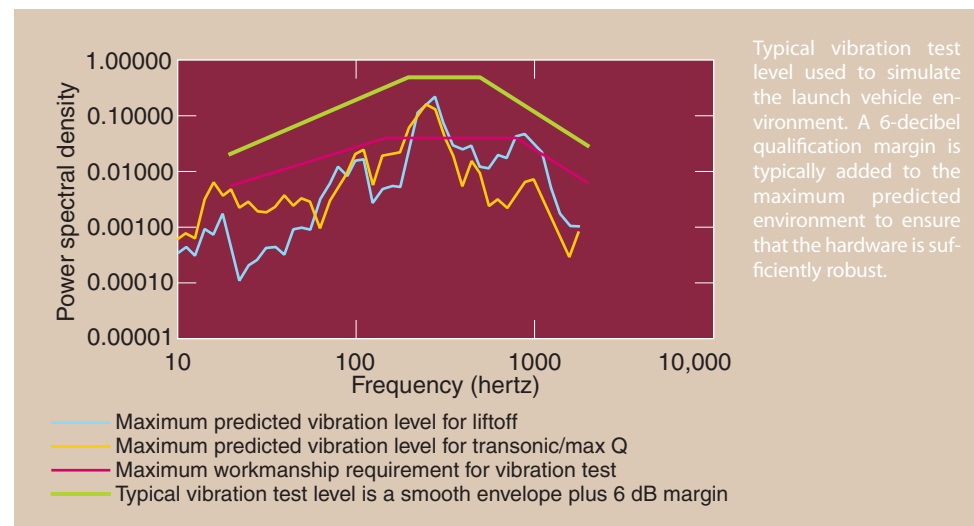
As in the case of acoustic testing, heritage flight and test data are used to predict vibration test levels, and analytical methods are sometimes used to develop transfer functions to scale heritage data to new hardware configurations. In most cases, the predicted environments are verified later with system-level acoustic tests and rocket engine static fire tests. As with acoustic testing, a 6-decibel margin is typically added to the maximum predicted environment. Structural failures of piece parts, unit assemblies, and secondary and primary space vehicle structures can and do occur from vibration-induced stress and material fatigue. Failures of inadequately designed or poorly manufactured or assembled structural interfaces are commonly revealed. Aerospace personnel, using predictive software, provide analysis confirmation for optimal instrumentation for vibration testing. Aerospace confirms hardware test perceptiveness and effectiveness with analysis,

testing experience, and consideration of interface constraints.

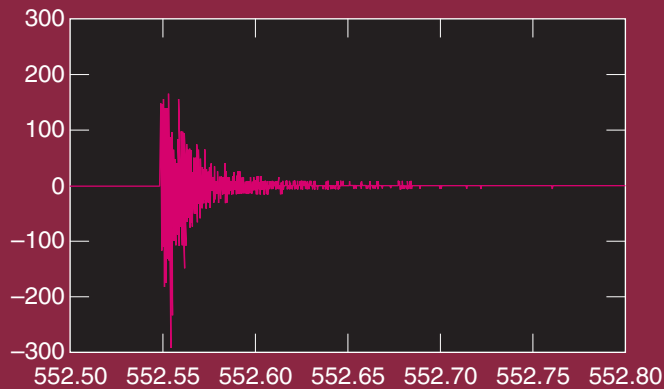
## Shock Testing

Stage, fairing, and vehicle separations are often accomplished by means of pyrotechnic devices such as explosive bolts, separation nuts, bolt cutters, expanding-tube separation systems, clamp bands, ordnance thrusters, and pressurized bellows. When activated, these devices produce powerful shocks that can damage equipment and structures. The characteristics of these shocks depend on the particular separation mechanism, but the energy spectrum is usually concentrated at or above 500 hertz and is measured in a frequency range of 100 to 10,000 hertz. A typical shock response spectrum plot is used to gauge the damage potential of a given separation event.

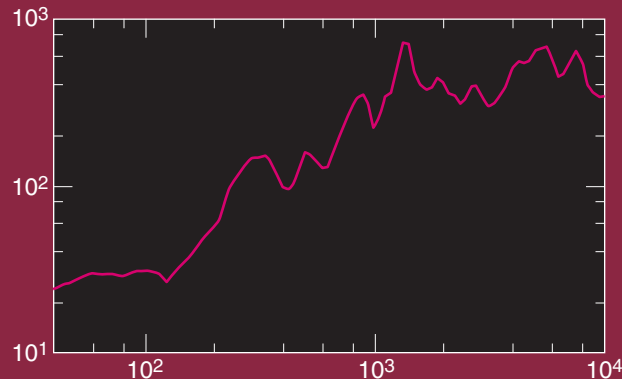
Separations or deployments generate brief impulsive loads even if no pyrotechnic devices are used. Nonexplosive initiators may produce significant shock levels simply



Measured acceleration time histories are used to derive shock test requirements.



Shock levels are specified as shock response spectra defined over a frequency range. The shock response spectra uses the response of single-degree-of-freedom oscillators, computed in 1/6 octave bands to convert the time history to the frequency domain.

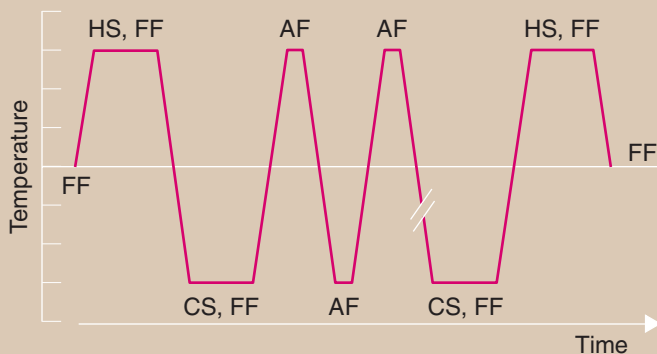


through the release of structural strain. Experience has shown that shock can induce a hard or intermittent failure or exacerbate a latent defect. Commonly encountered hardware failures include relay transfer, cracking of parts, dislodging of contaminants, and cracking of solder at circuit-board interfaces.

Unit-level shock tests are accomplished using one of several methods, which generally entail securing the component to a fixture that is then subjected to impact. This “ringing plate” approach has provided the best practicable simulation of unit exposure to shock. In addition, vibration shakers are used in some applications to impart a transient shock. Shock testing is typically not

performed as a unit workmanship screen, but is deferred to the system level for greater detection of functional defects. System-level shock tests usually activate the separation or deployment systems, providing a direct simulation of the mission event. Thus, they do not include any amplitude margin. Test fixtures are used to support hardware that has been deployed or separated to prevent subsequent contact or damage. System-level shock tests provide an excellent opportunity to measure shocks incident on components throughout the space vehicle.

Accurate prediction of high-frequency shock levels, such as those associated with explosive ordnance, remains an elusive goal.



A typical thermal cycling or thermal vacuum test profile. The profile shows temperature history and always starts and ends at room temperature. Hot starts (HS), cold starts (CS), full functional tests (FF), and abbreviated functional tests (AF) are performed at temperature plateaus.

Therefore, it is important that the shock environment be assessed during the development phase of the program through both analysis and test simulations. Shock analysis includes consideration of the source amplitudes, durations, transmission paths, path materials, and path discontinuities. Development tests employ an accurate replica of the flight structure with all significant constituents simulated. Deployed hardware is forced to physically separate at least a small amount to provide realistic shock transmission paths. When practical, a shock-producing event is repeated several times to permit meaningful statistical evaluation of the resulting data. Qualification margins at the unit level are typically 6 decibels on amplitude and twice the number of flight activations. At the system level, it is generally impractical to impose an amplitude qualification margin; however, a margin of two or three activations is imposed. Aerospace provides expertise for the prediction of test levels and the configuration of the hardware interfaces to achieve an effective test.

## Thermal Testing

Launch vehicles and spacecraft must endure a wide range of temperatures associated with liftoff and ascent through the atmosphere, direct impingement of solar radiation, and travel through the extreme temperatures of space. The thermal environment is generally considered the most stressful operating environment for hardware in terms of fatigue, and it has a direct bearing on unit reliability. For example, the use of materials with differing coefficients of thermal expansion has resulted in unsuccessful deployments of mechanical assemblies and payloads. Outgassing increases significantly with temperature, and the resulting contaminants will more readily adhere and chemically bond to colder surfaces. Electronic parts are especially sensitive to the thermal conditions and are subject to problems such as cracks, delamination, bond defects, discoloration, performance drift, coating damage, and solder-joint failure.

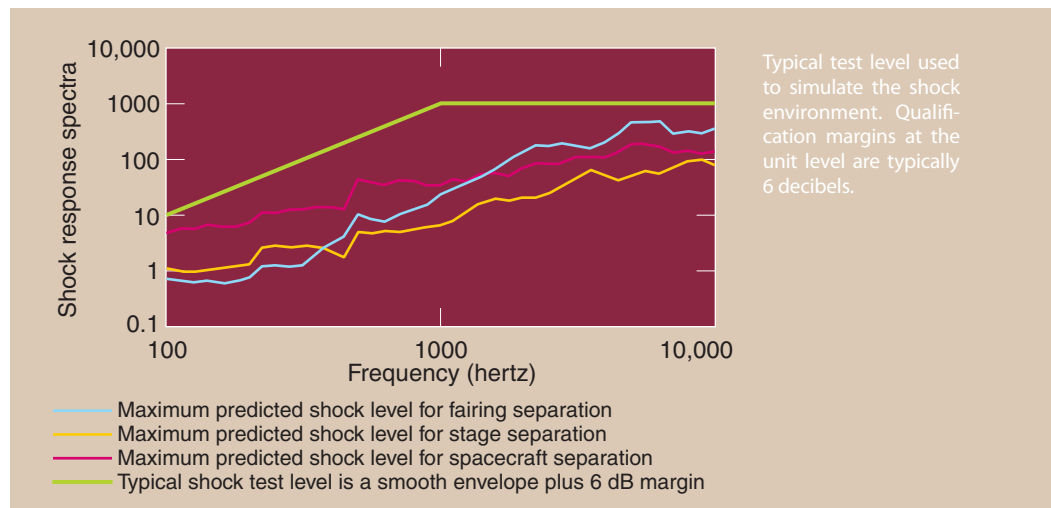
Thermal testing is used to screen out components with physical flaws and demonstrate that a device can activate and operate in extreme and changing temperatures. The four most common thermal tests are thermal cycling, thermal vacuum testing, thermal balance testing, and burn-in testing. Thermal cycling subjects the test article to a number of cycles at hot and cold temperatures in an ambient-air or gaseous-nitrogen environ-

ment; convection enables relatively rapid cycling between hot and cold levels. Thermal vacuum testing does the same thing, but in a vacuum chamber; cycles are slower, but the method provides the most realistic simulation of flight conditions. In thermal balance testing, also conducted in vacuum, dedicated test phases that simulate flight conditions are used to obtain steady-state temperature data that are then compared to model predictions. This allows verification of the thermal control subsystem and gathering of data for correlation with thermal analytic models. Burn-in tests are typically part of thermal cycle tests; additional test time is allotted, and the item is made to operate while the temperature is cycled or held at an elevated level.

For electronic units, the test temperature range and the number of test cycles have the greatest impact on test effectiveness. Other important parameters include dwell time at extreme temperatures, whether the unit is operational, and the rate of change between hot and cold plateaus. For mechanical assemblies, these same parameters are important, along with simulation of thermal spatial gradients and transient thermal conditions.

Thermal test specifications are based primarily on test objectives. At the unit level, the emphasis is on part screening, which is best achieved through thermal cycle and burn-in testing. Temperature ranges are more severe than would be encountered in flight, which allows problems to be isolated quickly. Also, individual components are easier to fix than finished assemblies.

At the payload, subsystem, and space vehicle levels, the emphasis shifts toward performance verification. At higher levels of



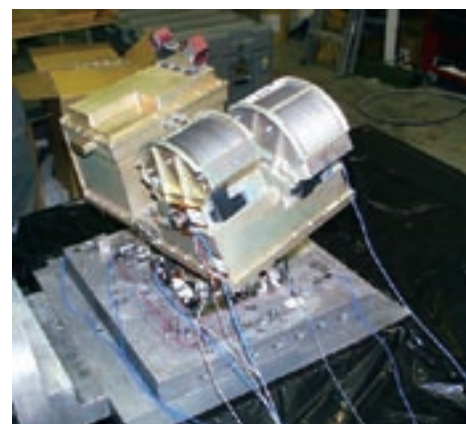
assembly in flight-like conditions, end-to-end performance capabilities can be demonstrated, subsystems and their interfaces can be verified, and flightworthiness requirements can be met. On the other hand, at the higher levels of assembly, it is difficult (if not impossible) to achieve wide test temperature ranges, so part screening is less effective.

At the unit, subsystem, and vehicle levels, Aerospace thermal engineers work with the contractor in developing test plans that prove the design, workmanship, and flightworthiness of the test article. Temperature ranges are selected that will adequately screen or accurately simulate mission conditions, and the proper number of hot and cold test plateaus are specified to adequately cycle the test equipment. Aerospace will provide expertise during the test to protect the space hardware in the test environment, resolve test issues and concerns, and investigate test article discrepancies. The reason, of course, is that

identifying and correcting problems in thermal testing significantly increases confidence in mission success.

## Conclusion

Since the first satellite launch in 1957, more than 600 space vehicles have been launched through severe and sometimes unknown environments. Even with extensive experience and a wealth of historical data to consult, mission planners face a difficult task in ensuring that critical hardware reaches space safely. Every new component, new process, and new technology introduces uncertainties that can only be resolved through rigorous and methodical testing. As an independent observer of the testing process, Aerospace helps instill confidence that environmental requirements have been adequately defined and the corresponding tests have been properly planned and executed to generate useful and reliable results. 🌌



*Left:* A spacecraft is placed in the acoustic chamber and is ready for testing. Air horns at the corners of the chamber generate a prescribed sound pressure into the confined space and onto the spacecraft. Microphones located around the spacecraft are used to monitor and control the pressure levels. *Middle:* The sudden separation of the payload fairing is used to expose spacecraft components to the shock environment expected in flight. *Right:* Space instrument placed on an electrostatically controlled slip table for vibration testing. The control accelerometers are mounted at the base of the test fixture at a location that represents the interface to the launch vehicle adapter. Accelerometers mounted on the test specimen measure the dynamic responses.

# Nanoscale Three-Dimensional Imaging: An Innovative Tool for Failure Analysis

A new method of cross sectioning and visualization provides detailed images of submicron features. Images can be rendered in movie format to show feature layers virtually melting away.

Neil A. Ives, Martin S. Leung, Gary W. Stupian, Steven C. Moss, Nathan Presser, and Terence S. Yeoh

Microelectronic devices for both terrestrial and spacecraft hardware have been growing ever smaller, with features now measured on the nanoscale—that is, less than 100 nanometers (nm) in size. In the past, for larger devices with features on the order of 10 microns, a 100-nm defect would not pose a significant problem. Today, a defect on this scale—such as a void, a misalignment, a nodule, a particle, or a dendrite—could prove catastrophic.

Visualization of device structures at the submicron and nanometer level has therefore been crucial for improving microelectronic and optoelectronic device performance and for investigating the fundamental causes of device failure. In particular, the emergence of advanced microanalytical techniques such as focused ion beam (FIB) milling has added new dimensions to the applicability of electron microscopy in semiconductor device research and development. FIB milling enables cross-sectional cuts at any location on a semiconductor component with precision and accuracy at the nanoscale. Newer FIB systems are dual-beam instruments that incorporate both an ion beam for cutting and a scanning electron microscope (SEM) beam for imaging the cross section exposed.

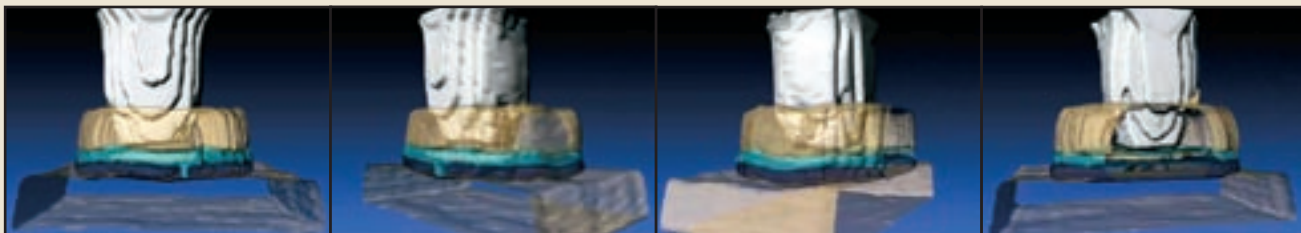
This tool has become a standard for failure analysis; however, its full potential has remained largely unexplored. The typical failure analysis involves only one FIB cut through an area of interest and one image from the electron microscope. A single slice contains some, but not all, of the structural and spatial information needed for a comprehensive analysis. Multiple

sequential cuts will of course provide more details of internal device structure. But making numerous slices of an object measuring only a few nanometers requires more precision than standard FIB systems can achieve. Moreover, the amount of data generated would require significant processing power to be useful.

In response to this challenge, Aerospace has developed a new method of cross sectioning, imaging, and visualization. The technique can be used to generate 3-D models of nanoscale features that can be examined from all angles. This technique has been dubbed nanoscale 3-D imaging, or nano-3DI. In recent device failure investigations, it's proven to be a crucial tool for determining root cause.

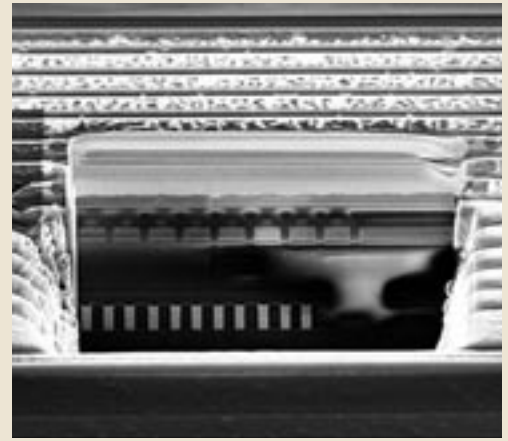
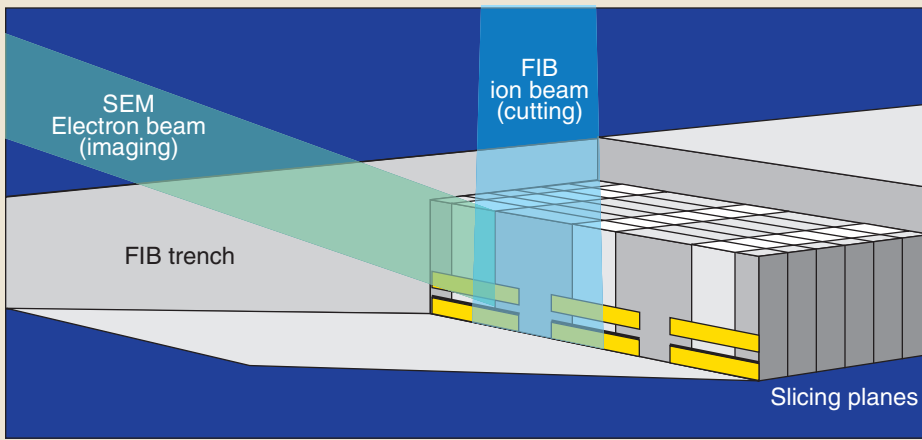
## Nano-3DI

In the nano-3DI technique, the ion beam strips away a thin layer of material from the region of interest, and the SEM images the surface of the newly exposed edge. What sets this technique apart is the extreme precision and number of the cuts and images. In fact, Aerospace has developed a special FIB milling technique that can remove material in slices less than 2 nm thick using a standard ion beam roughly 30 nm in diameter. This innovation involves using the change of SEM image contrast and brightness caused by removal of surface carbonaceous deposit as an end point. Thus, the process of cutting and imaging can be repeated at nanoscale increments until the entire structure containing the features of interest is physically



As shown here, a 3-D model, rendered as a digital movie file, can be given special views, rotated, and exploded in a scripted manner to illustrate key

points about the morphology. This animation can be found as an MPEG file on the Crosslink Web site (<http://www.aero.org/publications/crosslink>).



Deconstructing an electronic device for 3-D reconstruction is performed with a focused ion beam. The technique involves both cutting and imaging. In the diagram on the left, the focused ion beam (FIB) cuts off a slice of the electronic device to expose a new face, which is then imaged with the scanning electron

microscope (SEM). Cutting and imaging is repeated at regular intervals until the entire structure has been sliced away. The SEM image on the right shows the trench excavated by the ion beam. The internal structure of the electronic device can be seen on the back wall of the trench.

deconstructed. It can then be digitally reconstructed from the images taken after each cut.

This specialized technique allows researchers to capture a set of highly spatially correlated images of the feature of interest over the entire volume of the failure site, rather than just a few poorly correlated 2-D pictures. The grayscale information contained in the image dataset, used in combination with customized software for extracting the features of interest, enables sophisticated 3-D volumetric imaging. Given that the SEM has spatial resolution better than 1 nm and the slice thickness is less than 2 nm, the 3-D volumetric resolution is estimated to be better than 2 nm<sup>3</sup>. This resolution is at least an order of magnitude better than the current state of the art.

## Moving Pictures

While improvement in resolution is highly desirable, the voluminous data generated in the form of SEM images represent a challenge because the features of interest have to be extracted, analyzed, and presented for interpretation. For example, if a structure in a microelectronic device measures 500 nm across, a complete deconstruction would produce between 250 and 500 slices at 1–2 nm per slice. The resulting set of images represents approximately 1–5 gigabytes of data, depending upon the total number of slices and the image resolution. In principle, this set of images contains all of the details of the structure that have been captured. Viewing the images individually or in combination with others, however, does not usually allow the analyst to grasp the essential details (e.g., shape and orientation) of the features in the entire structure.

To overcome this difficulty, Aerospace made use of advanced image-processing techniques to produce movies from all the SEM images collected, making it easy to visualize shape and orientation of the features of interest. The movies render the vast amounts of visual information into a format that would be easy to analyze and interpret. (Movie samples can be found in the online version of this article at <http://www.aero.org/publications/crosslink>.) The process can be understood by imagining a deck of playing cards. The face of each card displays an image showing one slice in the complete volume data set. After making the necessary adjustments to ensure precise alignment of the image in each card, the system can display them in flip-book fashion. As one watches the succession of images, various features come and go as they are first exposed then cut away by the ion beam. This mode of data presentation allows the viewer to see the shapes of the features in detail and their spatial relationship with one another. However, even this viewing mode provides only a subjective and unquantifiable mental impression of the features being viewed.

To obtain more quantitative information, Aerospace used the advanced visualization tools of the Amira 3-D modeling program for model extraction based on voxel reconstruction and segmentation. A voxel (from “volume” and “pixel”) is the basic volumetric image element in a 3-D dataset. Voxel reconstruction is more commonly associated with noninvasive medical imaging methods such as MRI and CT scanning, which generate detailed models of internal

organs from a series of individual “slices.” Similar datasets on the nanoscale are generated through multislicing FIB deconstruction (a big difference, of course, is that medical imaging is nondestructive, whereas nano-3DI consumes the part during slicing). However, the thickness of each FIB slice is not as precisely controlled as in CT or MRI, so the process of voxel reconstruction is not entirely straightforward.

## Voxel Reconstruction

If the FIB milling machine produced a perfect and uniform 1-nm slice every time, then voxel reconstruction of the 3-D features would simply involve stacking up the images, using the grayscale data for alignment. However, in practice, the FIB cuts are not always the same thickness.

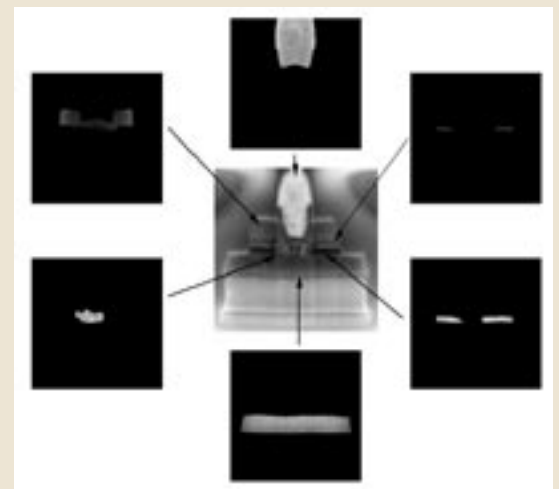


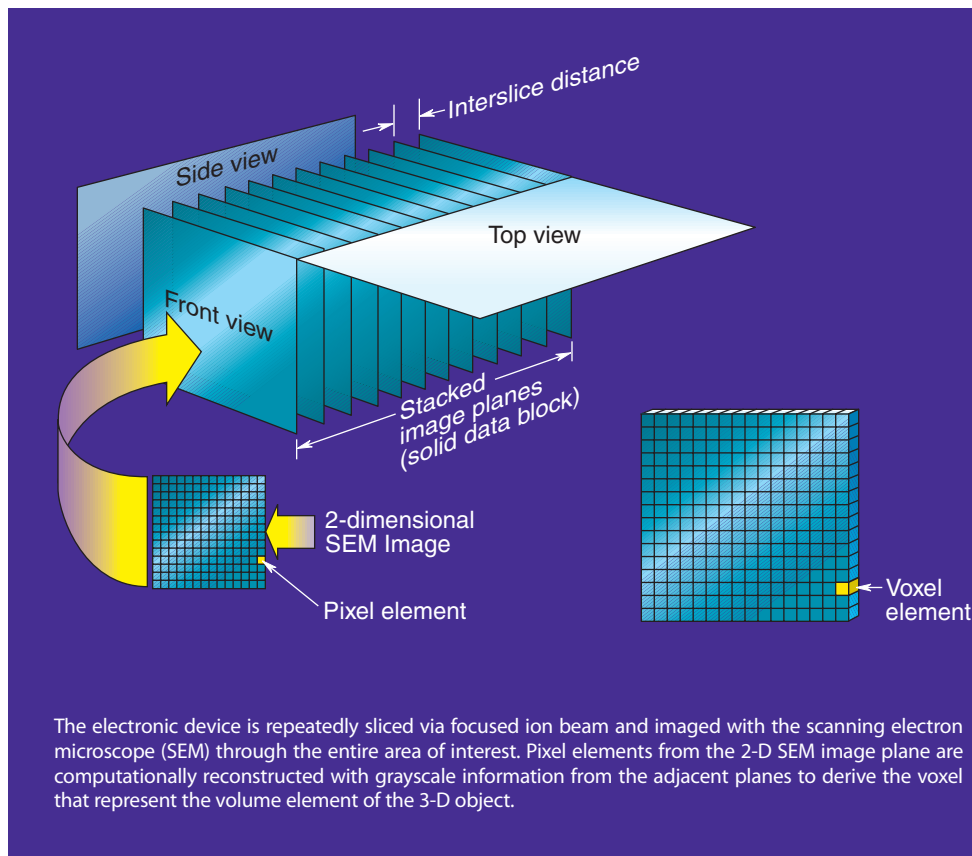
Illustration showing multiple segmented images from a field-programmable gate array (FPGA) antifuse. The six component objects are obtained from one cross-sectioned and imaged slice. Objects from all slices are extracted in a similar manner and then combined to reconstruct the 3-D object.

To compensate, Aerospace used an interpolation scheme in which *a priori* information about the larger features of the device is used to calibrate the thickness between the slices in each region of cuts through the structure. Artificial layers are inserted to keep the apparent spacing uniform and continuous. The computer processing algorithm calculates the grayscale in the artificial layers based on interpolation between regions of similar grayscale in adjacent real layers. In the worst cases, this has required insertion of one or two artificial layers between real layers at a few locations within a structure.

The complete voxel reconstruction with both real and interpolated layers now forms a uniformly spaced 3-D grid with grayscale data at each grid point, or voxel. This grid can be “virtually” sliced and viewed along any direction at any plane, creating flip-book movies along the three independent spatial axes as well as any other compound axes. These virtual cuts allow visualization of the failure site from any angle—even angles not possible with the real FIB because of limits imposed by the system geometry.

## Solid Model Reconstruction

This reconstruction technique also provides a new and more structured 3-D dataset that can be used to generate solid 3-D models. In devising the process, Aerospace researchers first made the reasonable inference that the grayscale information in the 3-D grid must correspond to real features—including the extent of structural changes, phase formation, and separation and voiding—that can be visualized with respect to specific material locations to better understand the chemical and physical mechanisms involved. So, to create a solid model, the features of a 3-D object are first identified in the 2-D voxel slices according to their grayscale image values. They are then segmented—that is, a boundary is drawn around each one. This step is repeated until all the individual features in the dataset have been segmented. They can then be stacked using a separate image-processing algorithm.



For example, dark voxels indicate a void, while bright voxels are typically associated with a metal. Semiconductors appear as voxels with an intermediate grayscale. Of course, complex material phases may confound these simple distinctions, and imaging artifacts (caused, for example, by the charging of insulators) may also complicate interpretation of the grayscale data. In practice, the investigator usually has some *a priori* knowledge of device structure and materials composition to guide the segmentation efforts. Further information can be obtained from other microscopic and spectroscopic techniques, which allow identification of not only the elemental composition of features but also chemical-bonding information with nanometer resolution.

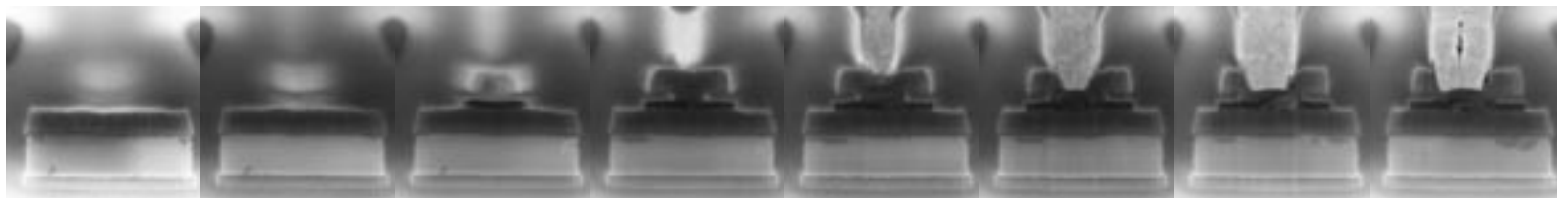
Once the features are segmented, individual 3-D models can be constructed such that each feature uniquely occupies its own space within the 3-D dataset. Each feature can be

assigned a false color to represent its chemical composition and allow viewers to easily distinguish it from other features of different composition. The computer software can display each feature as a solid, a semitransparent object, or a transparent object with a contoured surface. The presentation of the feature as a contoured surface is effective in showing the spatial relationship of one feature to another.

The solid 3-D models can also be virtually sliced, much like the virtual slicing of the voxel image. This allows investigators to obtain detailed information on the chemical composition of internal features that were present but hidden or obfuscated by adjacent features. For failure investigation, the collection of features that make up the failure site can be presented in an exploded view to show how the individual components of the device fit together. Special effects can be employed to view the individual components

Renderings such as these, from a voxel reconstruction of a field-programmable gate array (FPGA) antifuse, are compiled to form animated movies. This animation

can be found as an MPEG file on the Crosslink Web site (<http://www.aero.org/publications/crosslink>).



stereoscopically to provide perspective and detailed spatial relationships of one feature to another. Once the entire structure exists as a 3-D interconnected object, it can be imported into various simulation packages that provide an even more realistic model of failure sites. Data without interpretation is of minimal value. When data are displayed in a new and more intuitive fashion, new insights often emerge, and the physics of the root cause failure mechanisms can be more easily conceptualized. Important parameters such as resistivity, diffusivity, and reactivity of materials may also be derived quantitatively from the solid models.

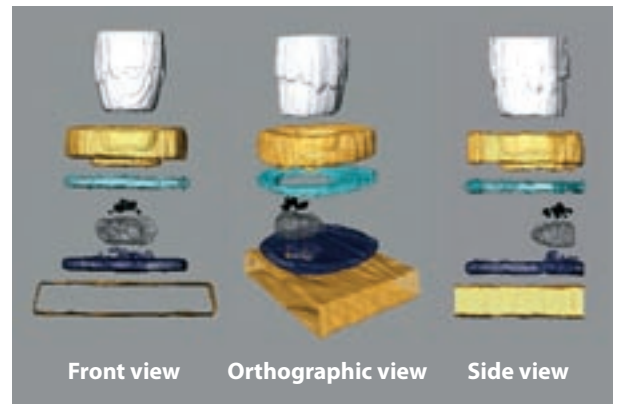
Working with solid models requires customized software, specialized hardware, and raw computer power that is available on multiprocessor workstation-class computers but not on standard desktop platforms. Exporting this new information to a common desktop platform can be accomplished using animation software. The model, rendered as a digital movie file, can then be given special views, rotated, and exploded in a scripted manner to illustrate key points about the morphology using standard media players. (Please visit the online version of this article at <http://www.aero.org/publications/crosslink> to view animations of 3-D models.)

## Conclusion

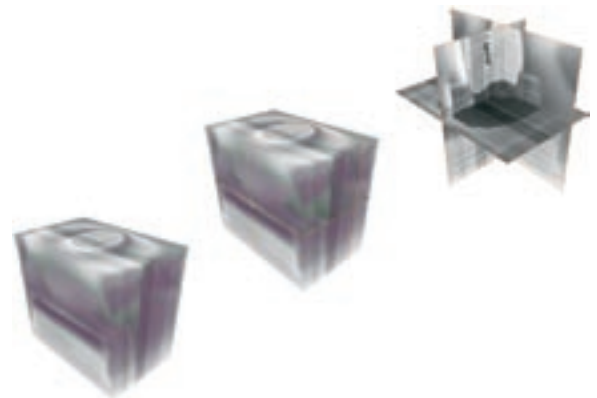
Imaging of nanoscale features in microelectronic and optoelectronic devices is essential for understanding the complex internal workings and failure modes of advanced technologies. By using state-of-the-art electron imaging and ion-beam cutting equipment, Aerospace researchers can generate 3-D models of device features with nanoscale resolution. The nano-3DI volumetric imaging method developed at Aerospace provides valuable insights, otherwise unobtainable, of the internal structure of complex nanoscale devices and could become a standard tool for future reliability investigations for both terrestrial and space hardware. ●

### "Nanoelectronics"

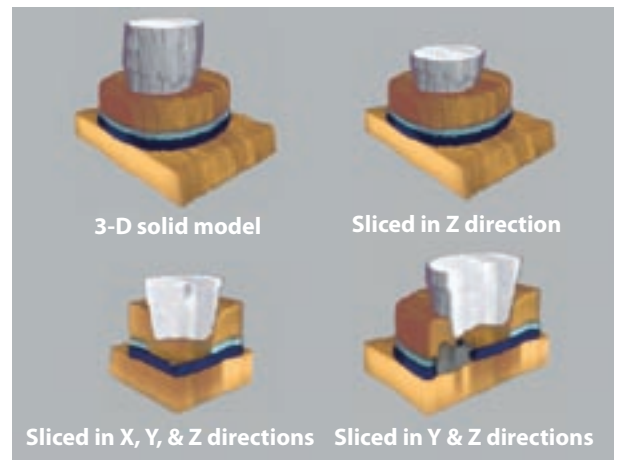
Current commercial state-of-the-art semiconductor devices range in size from 250 to 90 nm. Some fabrication facilities are rapidly moving toward 60- and 45-nm features in their device structures. As an example, the half-pitch dimensions of dynamic random-access memory (DRAM) are expected to be 45 nm by the year 2010 and 18 nm by 2018. Similarly, application-specific integrated circuit (ASIC) feature sizes are expected to be less than 25 nm by 2010 and less than 10 nm in 2018. Oxide thicknesses are expected to follow suit and shrink to less than 1 nm by 2006. Other devices such as quantum wells range in thickness from a few to a few tens of nanometers. Clearly, the impact of defects on geometries on this scale will most certainly become more critical with respect to manufacturability and reliability of these devices. New and innovative uses of advanced analytical techniques are needed that allow imaging, visualization, and detailed examination of every part of the features of interest at the nanoscale, i.e., viewing in 3-D with nanometer resolution.



An exploded view at different angles for surface-contour 3-D reconstruction of the component objects in an FPGA antifuse.



Computer-generated voxel reconstruction of an FPGA antifuse. Data volume (left) with selected planes (middle) for voxel slice viewing (right).



Multiple 3-D solid-model reconstructions of an FPGA antifuse. The model can be sliced along X, Y, and Z planes to visualize more detailed information with respect to the chemical composition of the interior geometries.



# Thermal Cycling Techniques for Solar Panels

Thermal stress testing for solar arrays is a lengthy and unavoidable part of spacecraft mission design. Aerospace has developed a method that is as fast as it is reliable.

Robert W. Francis, Charles Sve, and Timothy S. Wall

During the last 20 years, escalating launch costs have forced spacecraft engineers to design lighter and more efficient power subsystems. Constraints on solar array size, weight, and storage volume have spurred the development of efficient multijunction solar cells and lighter substrate materials. The decreased mass and size have helped reduce costs, while the higher power levels have helped increase spacecraft payload capability.

On the other hand, each new solar panel design must be tested to ensure that it can withstand the rigors of the space environment and maintain its structural integrity throughout a mission that might last 10 years in low Earth orbit. Such testing has traditionally presented a major bottleneck in the development of new solar cell arrays. Standard thermal chambers can take more than two years to complete thermal-cycle stress testing that adequately simulates mission life environments. Testing labs have sought to accelerate this testing, but have been challenged to do so in a manner that does not reduce confidence in the test results.

In response to customer need, Aerospace established space-simulated thermal cycling capabilities in the mid-1980s. These capabilities progressed through a number of evolutionary stages, each offering greater speed and fidelity. The latest approach, known as ultrafast thermal cycling, has provided timely evaluation and demonstration of advanced solar array designs for numerous space programs. The automated process controls temperature uniformity, optimizes thermal transfer, reduces cycle periods, and decreases overall test time.

These tests continue to furnish mission design and confidence data to a number of spacecraft programs and provide a valuable technical database for incorporating advanced, highly efficient solar cells into the latest spacecraft designs. Programs that have benefited from the decreased testing time and cost include present and new generation national security spacecraft, the Experimental Spacecraft System (XSS-11), the Defense Meteorological Satellite Program, as well as NASA's Messenger mission to Mercury.

As a result, the ultrafast thermal cycling facility at Aerospace is now recognized by the aerospace community as a unique capability for evaluating and demonstrating new solar cell and array design features, solar cell interconnect joint integrity, and potential early life failures with a turnaround time that is fast enough to permit a redesign, if necessary.

## Early Test Methods

The first Aerospace test chamber, built in 1985, was a conductive thermal cycling system geared toward performing life-cycle thermal stress tests on the new generation of gallium-arsenide solar cells. Temperature changes were achieved by cooling a fairly massive aluminum plate with liquid nitrogen and then heating the plate with electric rod heaters. The test articles were held under vacuum so that cycling would occur primarily by thermal conduction. Under these conditions, typical solar cell coupons required 60–90 minutes to cycle 100 degrees centigrade. The disadvantage was that the hot and cold phases worked against each other to drive the thermally conductive base plate, thereby limiting cycle rates.

In 1990, Aerospace brought its first radiant thermal cycle chamber into service. This vacuum chamber used a quartz-halogen lamp for heat generation and a cold shroud for heat absorption. Cycle periods of 30–60 minutes were now attainable for flight-like test panels. Temperature cycle rates depended solely on radiation to and from the suspended solar cell panel. The heating lamps immediately overcame the cold shroud in the hot phase; however, the shroud was warmed significantly and could recover only during the next cold phase, even though liquid nitrogen continuously flowed through it during the hot phase.

In 1996, the cooling efficiency and rate were improved. A partial pressure of nitrogen gas was introduced into the vacuum chamber, and this allowed conduction in addition to the radiation of heat to and from the panels by way of the cold shroud. Shorter cycle periods of 22–45 minutes were obtained. As with the earlier radiant design, only the hot phase worked thermally



The ultrafast thermal cycle chamber at Aerospace. Solar cells are affixed to a flight-like substrate, which is moved up and down between two thermally insulated chambers. Cycle times are relatively fast because each chamber can return

to its setpoint temperature while the other is in operation. Dwell or delay can be added to the hot or cold phases to allow for in-situ electrical characterization of the test article.

against the cold phase, and this provided some advantage in cycle period over the original conductive thermal cycle chamber.

### Ultrafast Thermal Cycle Chamber

The next innovation was the ultrafast thermal cyclers, which combines the best aspects of all previous configurations. With a cycle rate of 10 minutes, the apparatus can achieve more than 1000 thermal cycles in one week of continuous operation. This capability allows state-of-the-art performance assessments of high-performance solar cell types, interconnecting schemes, and substrate designs in much less time than commercially available thermal cyclers.

The system has two compartments—a hot compartment on top and a cold compartment on the bottom. These thermally isolated compartments are contained in an insulated chamber that is slightly pressurized with ultrapure nitrogen gas. The positive pressure of the gas mitigates moisture condensation, oxidation, and corrosion and promotes conductive heat flow. A motor, pulley, and cable system raises and lowers the test fixture from one compartment to the other.

Quartz-halogen infrared lamps in the top compartment surround the panel in the hot phase to maintain a constant high temperature. The test panel is heated rapidly and uniformly by both radiation and gas conduction. For the cold phase, the panel is lowered into the bottom compartment, which is encased in a container filled with liquid nitrogen. A marked advantage of this design is that the cold and hot phases do not work against each other. One compartment can fully recover to its designated end-point temperature while the other is in use.

This thermal chamber system provides continuous unattended temperature cycling and can easily accommodate more massive solar cell composite test panels. Thermal cycle periods of 10–12 minutes on fully populated solar cell panel substrates as large as 30 x 35 centimeters and 5 centimeters thick can be achieved, resulting in a demonstrated capability of over 50,000 thermal cycles in one year of continuous operation.

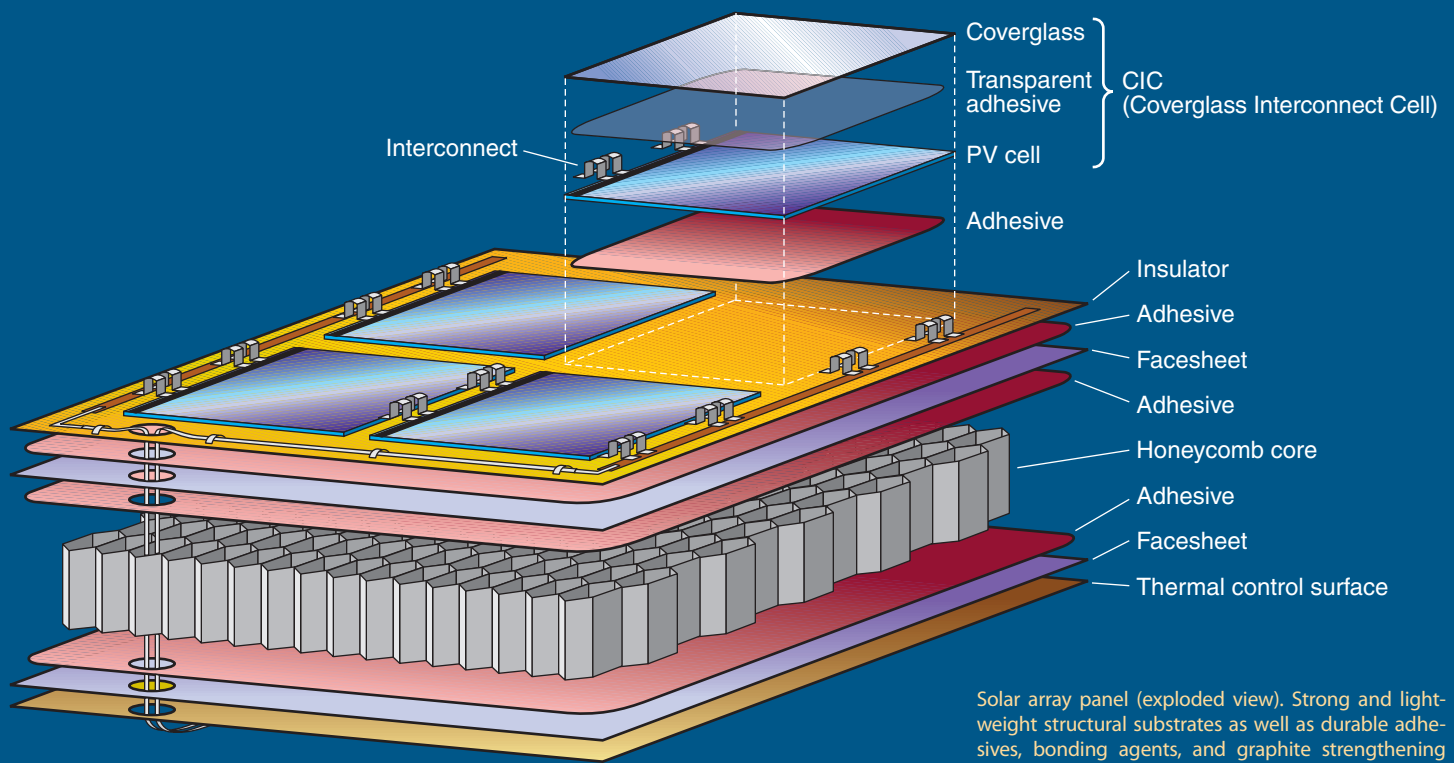
When the ultrafast thermal cycler was first introduced to perform thermo-structural stress validation and verification, contractors expressed some reservations because of the

relatively high temperature rates. However, these doubts were soon abandoned when Aerospace's fatigue analyses validated the stress failures that were replicated in the much slower traditional thermal cycle chambers.

### Measurements and Methodology

The ultrafast testing system offers additional benefits over traditional testing methods. In typical thermal stress testing, the solar panels are removed from the chamber after a certain number of cycles to allow for functional evaluation. But this interrupts (and lengthens) the process and provides only a general indication of how many cycles a panel can endure before failure. Therefore, in developing the ultrafast test method, Aerospace sought a way to verify electrical performance and circuit continuity without having to remove the solar cell panel from the testing apparatus.

Aerospace devised a fully automated method based on in-situ measurement of electrical resistance. A microprocessor-controlled power supply sends an increasing



Solar array panel (exploded view). Strong and lightweight structural substrates as well as durable adhesives, bonding agents, and graphite strengthening members are needed to construct high-power solar panels from individual photovoltaic (PV) solar cells.

current through each solar cell circuit, forward and then backward. The current is stepped up or down and held constant at specific intervals to produce a resistance-dependent voltage characteristic. The voltage-vs.-current signature is continuously monitored and compared to a baseline set of curves at both hot and cold temperatures.

Anomalous changes in resistance produce distinctive changes in the voltage-vs.-current curve. For example, problems with a device shunt, interconnect, or harness produce recognizable changes in the signature. These signature changes allow immediate detection of electrical degradation or failures. In the extreme case, an indication of an open-circuit failure would safely stop the cycling process and allow for immediate failure evaluation. This avoids continued cycling of nonfunctional or degraded solar cell circuits and facilitates the timely discovery of failure mechanisms.

In the ultrafast thermal cycler, solar cell circuits are loaded with forward-bias current during every thermal cycle. The current load is varied linearly and in proportion to the solar cell temperature. The initial and maximum allowable load currents are determined from the calculated operational photocurrent temperature coefficients of the specific solar cell device under test. The intent is to evalu-

ate a simulation of the flight-like operational electrical current produced by solar cells in sunlight while deployed in space. Traditionally, thermal cycling qualification has been performed on solar cell circuits in the passive state, i.e., with no current generation. It is believed that the forward-bias current-loading method, performed simultaneously with thermal cycling, has the potential to simulate the operational power mode of an interconnected solar cell circuit under load conditions, which is more cost effective and has less test complexity than a ground test under illumination.

### Protecting Solar Cells

The ultrafast testing apparatus also has mechanisms to protect the solar cells that are being tested. In an anomalously high or low circuit-impedance condition, the constant-current power supply can potentially exceed the load current that was initially set. This can produce an excessive voltage across the solar cell circuit and potentially damage the cells. This is an unrealistic condition, compared with solar cell circuits operating under natural solar illumination in space, where the number and type of solar cells in series inherently limit the cell-circuit voltage.

To address this situation, Aerospace implemented a software monitor and con-

trol scheme. The voltages produced while going from the maximum and minimum temperatures and throughout the current-loaded sequence are first characterized during a beginning-of-life cycle. Using these expected voltage endpoints, a reference voltage is constantly calculated by linear interpolation with respect to the instantaneous cell temperature to compare with the actual voltage being produced by the current loading process.

A deviation above or below a specified voltage will result in either an "anomaly" or "failure" response. In the case of an anomaly response, the test continues, and a voltage signature history plot is generated, characterizing the aberration. In the case of a "failure" response, the test is immediately terminated. This protects the solar cells by removing excessive voltage across the solar cell circuit that could potentially damage them.

### Case Studies

The Aerospace thermal cycling facility has benefited numerous programs, both by finding flaws and validating designs. On one national security space program, failures were observed after 8000 cycles, out of a goal of 50,000 cycles. The real-time in-situ electrical characterization measurements detected changes in the solder-joint interconnect

circuit resistance and continuity. This finding was verified at the contractor's facility six months later and required a modification to the solder-joint interconnections on the solar array.

An evaluation of an all-welded solar array being developed for another program revealed "infant mortality" or early failure of the weld joints. This discovery prompted a change of material. Similarly, for an ongoing national security space program, thermal cycling of an all-welded solar cell circuit has exposed a marginal interconnect joint in the solar cell bypass diode circuit.

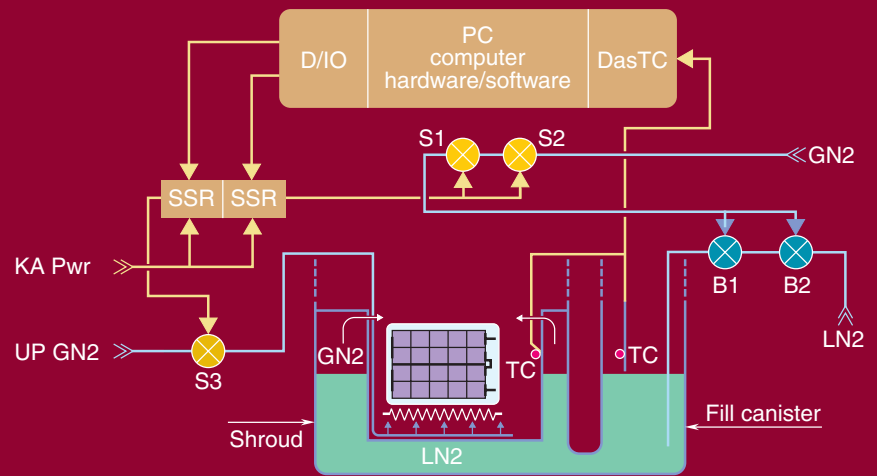
The Aerospace facility has been used to validate and verify the thermal cycle fatigue requirements for solar panels on other programs involving soldered and welded circuits with advanced multijunction solar cells bonded onto flight-like substrates. NASA's Messenger spacecraft will travel close to the sun and eventually orbit the planet Mercury. The Applied Physics Laboratory of the Johns Hopkins University contracted Aerospace's thermal cycle facility to evaluate solar array materials, processes, and design parameters proposed to satisfy this mission's thermally stressing requirements. After three phases of evaluation—which included development, prequalification, and qualification testing—the final solar panel design successfully completed the mission's thermal cycle profile sequence with no performance degradation. The Messenger spacecraft with this solar panel was launched early this year and is on its way to Mercury.

Despite initial skepticism, the aerospace community has come to recognize the ultrafast thermal cycle facility for its ability to evaluate and demonstrate new solar cell devices and interconnect joint features on solar arrays used in space. In fact, two contractors have now developed thermal cycle chambers similar to the Aerospace design.

## Conclusion

Modern communication satellites can have primary power capacity in excess of 20 kilowatts, whereas a decade ago, they typically had less than 5 kilowatts. Advances in chemical processes, solid-state technology, and materials science have enabled the creation of solar arrays capable of this performance level. While these technological advances have benefited the mission planner, they have also increased the testing burden for the validation phase.

Early verification of solar cell stability, electrical circuit continuity, joint and bond



- D/I/O: Digital input/output, used for digital logic control of external processes.
- DasTC: Thermocouple (TC) data acquisition system; reads shroud & fill canister TCs
- SSR: Solid-state relay, passes 115 Vac when triggered with DC logic level
- KA Pwr: Power present if no "failures" have occurred
- LN2: Liquid nitrogen; used for cooling
- GN2: Gaseous nitrogen, used for actuating LN2 bellows valves
- UP GN2: Ultrapure gaseous nitrogen, used for nitrogen atmosphere purge in chamber
- B1 & B2: Liquid nitrogen bellows valves, gas operated

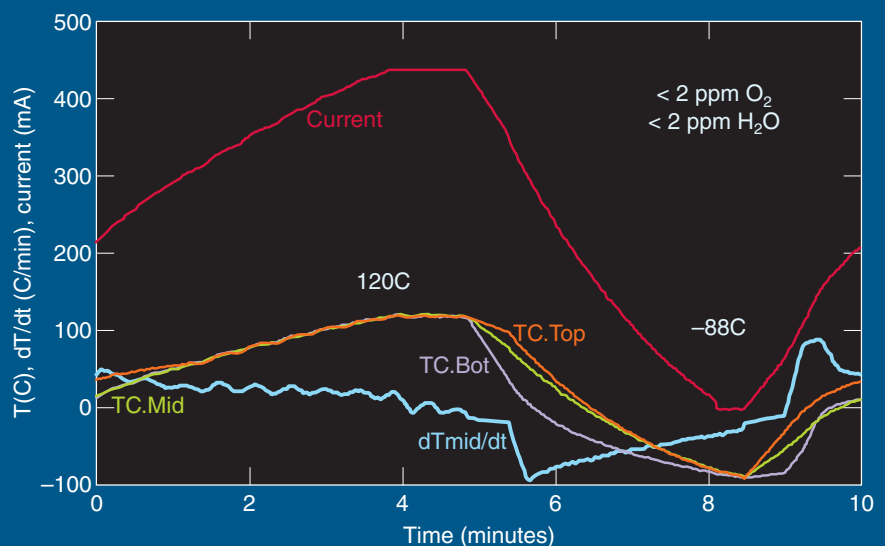
robustness, and panel substrate integrity is a critical step in minimizing mission risk and ensuring proper spacecraft design. The thermal cycle facility at Aerospace provides a unique capability for confidence-level testing, evaluation, and qualification of solar cells with a turnaround fast enough to accommodate tight launch deadlines and even permit redesign, when necessary. Thanks to innovations in chamber design and advances in electrical testing methods, the fully auto-

mated, fail-safe test facility at Aerospace has helped numerous programs save time and money and will continue to prove its benefit as newer and more efficient solar panel designs become available.

## Further Reading

T. S. Wall, P. R. Valenzuela, and C. Sve, Aerospace Report No. TR-98(8565)-7, "Ultrafast Thermal Cycling of Solar Panels," August 1998.

U.S. Patent No. 6,271,024, "Compartment Fast Thermal Cycler," August 2001. 



Temperature and forward-bias current profiles. The characteristic curve for the solar cell circuit under test is monitored and compared to a baseline set of curves at both hot and cold temperatures. Anomalous changes in either the solar cell series or shunt circuit resistance produce distinctive changes in the voltage-vs.-current signature acquired during these tests.

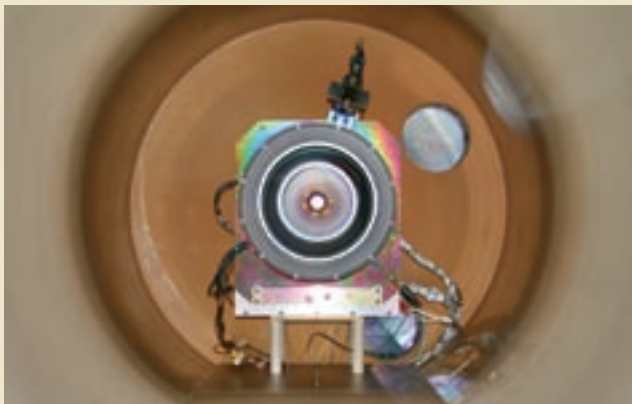
# Electric Thruster Test and Evaluation

Evaluation in ground test facilities plays a critical role in the development and qualification of new thruster systems.

Edward J. Beiting, Ronald B. Cohen, Mark W. Crofton, Kevin Diamant, James E. Pollard, and Jun Qian

Spacecraft electric thrusters are responsible for the critical functions of orbit transfer, on-orbit station keeping, and, in recent applications, interplanetary propulsion. Electric systems generate thrust by using electric and magnetic processes to heat and/or accelerate a propellant or plasma. Chemical systems create thrust through chemical reactions that generate expansive exhaust. Electric thrusters have an exhaust velocity normally 2 to 10 times higher than chemical thrusters, which means their efficiency with respect to propellant usage is greater. Payloads can therefore be augmented or launched on smaller, cheaper vehicles.

On the other hand, the testing and evaluation of electric thrusters is more challenging than for chemical systems. The amount of energy per expelled particle, the overall complexity, and the required lifetime is typically much greater. In addition, the considerable potential for sputtered particle deposition, energetic ion impingement, electromagnetic interference, and other interactions that could adversely affect the spacecraft and its subsystems must be addressed. The potential for adverse interaction tends to increase along with electrical power input and propellant flow rate, which have risen as available onboard power has increased.



A Hall-effect thruster in a fiberglass testing chamber.

In addition, ground test facilities interact with electric thrusters in ways that can skew test results. For example, facility background pressure can affect electromagnetic interference, thruster erosion, and electrical breakdown characteristics. Wall surfaces near the thruster produce contamination, thermal interactions, artificial plume neutralization, and perturbations on electric fields and plasma migration. Contamination from walls is one of the most insidious effects: The deposition of a conductive layer on thruster surfaces can cause the loss of insulator functions, upset emission characteristics, and modify the apparent contamination potential of the thruster.

In view of all these considerations, electric propulsion test and evaluation techniques and facilities have been forced to grow in sophistication and scope.

Aerospace has a lengthy history of testing and evaluating thruster technologies for diverse space programs and has played an important role in the development and qualification of new thruster designs. The recent emphasis on high-power electric propulsion is pushing the envelope on system performance and service life. Through its Advanced Propulsion Diagnostic Facility, Aerospace is working to ensure that the next generation of electric thruster systems will achieve the envisioned power and efficiency without sacrificing reliability.

## History of Electric Propulsion

Development of electric propulsion systems has already spanned more than four decades. After the invention of the gridded ion engine in 1960, many inside and outside the space community believed that the benefits of this technology would soon be realized. With ion propulsion, charged particles are accelerated by passing them through highly charged electrode grids. In theory, a relatively high specific impulse can be achieved, but at the expense of high energy requirements. The early years of frenzied activity included space tests—one even used electricity derived from a nuclear reactor. These tests were not entirely successful, and research continued in the 1970s and

1980s at a slower pace. At the same time, several forms of electric propulsion were developed.

The first among these was the resistojet, a relatively simple form of electric thruster. It operates by passing gaseous propellant, usually hydrazine, over a resistive heater and expanding it through a conventional nozzle.

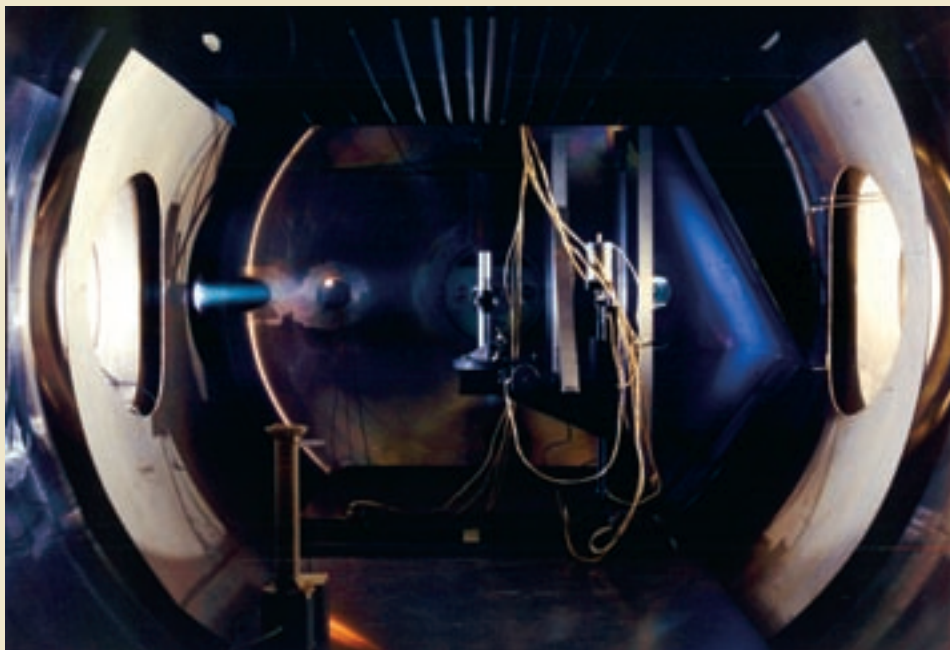
The resistojet was followed by the arcjet, which passes the hydrazine through an electric arc that heats it before it expands through a nozzle. Developed for flight applications in the 1990s, the hydrazine arcjet offers a more substantial specific impulse boost compared with standard chemical thrusters.

The pulsed-plasma thruster, despite its modest efficiency, found niche applications on spacecraft, thanks to its flexibility and simplicity. In a pulsed-plasma thruster, a capacitor discharge creates a pulsed arc across the face of a block of solid propellant. A small amount of the material is ablated and ionized to form a plasma that is accelerated in a magnetic field.

Additional research focused on magnetoplasmadynamic thrusters, which function by passing a large current through a neutral plasma from a central cathode to an annular anode. The radial current induces a circular magnetic field that accelerates the plasma along the axis of the electrode structure. Operational efficiency is poor if input power is below 50 kilowatts, but nuclear-powered spacecraft may make attractive platforms if other design issues can be resolved.

In the 1990s, work on ion devices such as the Hall-effect thruster intensified. In a Hall-effect thruster, neutral atoms from a heavy gas such as xenon are ionized by collision with high-energy electrons whose movement is confined by a radial magnetic field. The ions are largely unaffected by the magnetic field but are accelerated by the electric field between the anode and cathode. Development of the Hall-effect thruster had come to a stop in the United States, but the former Soviet Union spearheaded an intensive development program that led to extensive flight application.

Ion engines became operational as commercial devices in 1997, with the launch of the Galaxy 11 communications satellite. The success of NASA's Deep Space 1 mission, the first beyond Earth orbit to use an ion engine, further established the viability of this technology. Ion propulsion will be used on the Wideband Gapfiller and Advanced EHF military communication satellites. The first



The T5 (UK-10) ion engine operating in the Aerospace facility, revealing the fluorescent ion beam and focusing effect of the extraction grids. The ion beam is reexpanding as it strikes the beam stop on the right.

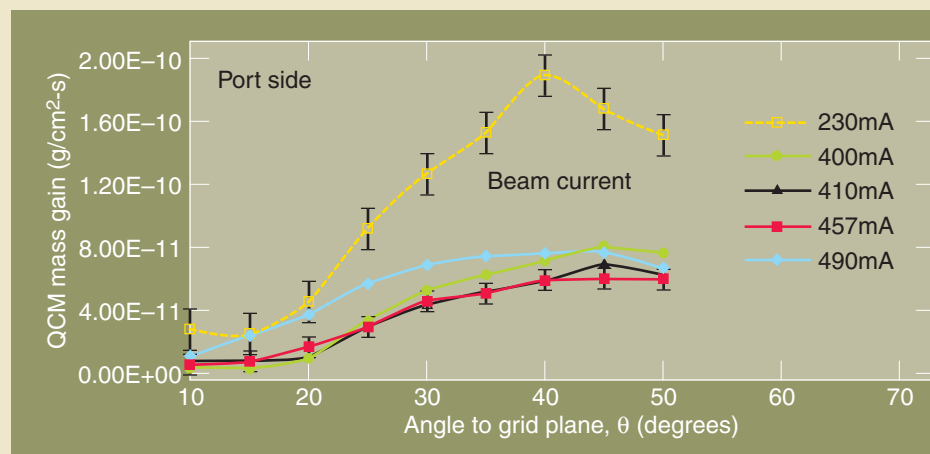
will carry a type of gridded ion engine, and the latter will use Hall-effect thrusters.

## Aerospace Role

Aerospace has been a central force in electric thruster test and evaluation since 1989, when the company's Advanced Propulsion Diagnostic Facility became operational. The cylindrical test chamber, 2.4 meters in diameter by 4.8 meters long, was intended to handle gases such as hydrogen and nitrogen (principal products of hydrazine decomposition) that would be exhausted by a resistojet or arcjet. The chamber was equipped with an integrated molecular-velocity analyzer that could quickly obtain the velocity distributions of individual plume species. It was a unique instrument in the electric propulsion community.

Important projects in the early years included a 1-kilowatt simulated hydrazine arcjet designed by NASA. Detailed measurements were made of thrust, plume dissociation fraction, rotational and vibrational temperatures, molecular velocity, and emission characteristics. These measurements were made with various propellants and for multiple operating points. The NASA arcjet development program led to the successful operational use of arcjets, beginning in 1993.

During a three-year period starting in 1992, Aerospace conducted an intensive test and evaluation of a British ion engine, eventually flown on the Artemis communications satellite. The project entailed a minor upgrade of the facility, along with the introduction of various diagnostic techniques, including several that were developed specifically



Contaminant deposition rate measured by a quartz-crystal microbalance in the T5 (UK-10) ion engine plume.

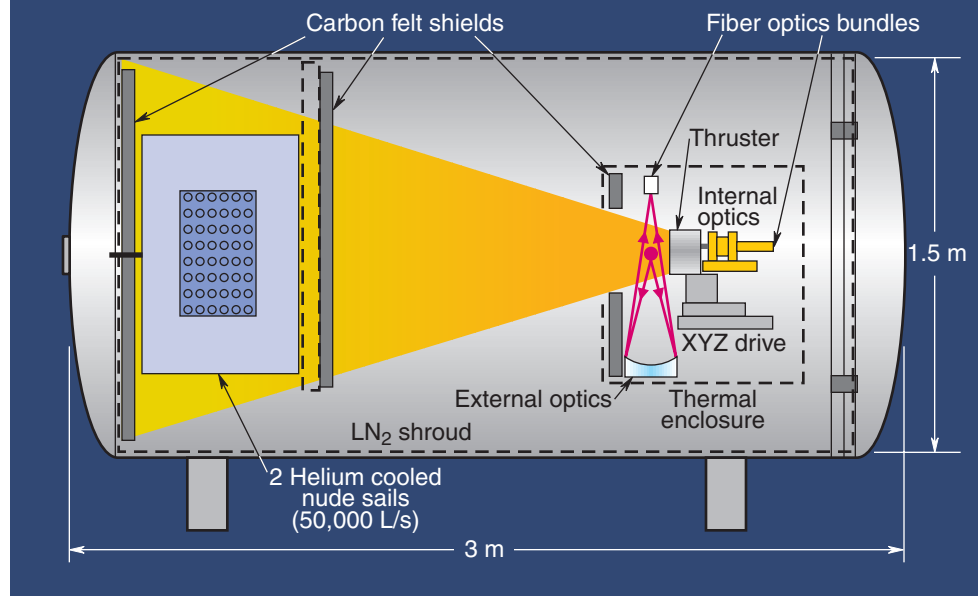
	Diagnostic	Measured	Sensitivity	Method	Remarks
1	Continuous thrust stand, pulsed thrust stand*	Continuous and pulsed thrust	0.5 mN cont.; 5 $\mu$ N-s pulsed	Inverted pendulum continuous; Pendulum pulsed	Range: 1 – 300 mN, $10^{-2}$ s resolution cont.; 5 $\mu$ N-s – 1.0 mN-s
2	Telemicroscopy	Grid deflection, thruster erosion	17 $\mu$ m	Telemicroscope/CCD camera	All instruments outside vacuum chamber
3	Grid erosion	Grid hole enlargement	5 $\mu$ m	Mechanical/optical	Grid diameters $\leq$ 30 cm
4	Faraday probe	Fast ion flux	1 nA/cm <sup>2</sup>	Reject low energy ions	Far-field angular distribution
5	Ion energy probe	Energy and charge-state distributions	< 20 eV	Time-of-flight parallel-plate electrostatic deflector	Far-field angular distribution
6	Langmuir probe	Plasma potential, electron density & temperature, ion flux	$10^7$ /cm <sup>3</sup>	Internally heated wire probe	Minimize probe surface contaminants
7	Calorimeter*	Total heat flux	20 W/sr	Instrumented copper disk	Far-field angular distribution
8	Beam profiler	Ion flux contour maps	1 mm resolution	Ion current collected by long wire	Near-field ion current map
9	Quartz microbalance	Erosion/deposition rate	$2 \times 10^{-9}$ g/cm <sup>2</sup> -s	Mass accumulation	Positioned 360° around thruster
10	Ion-beam surface effects	Composition of deposits, deposit/erosion rates	Submonolayer	Material coupons arrayed in the far-field plume	Destructive testing technique
11	Thrust vector tracking*	Ion-beam centroid	0.01° resolution, 0.1° accuracy	Cruciform wire probe, thruster positioning system	< 1 second time response
12	Single photon near-infrared LIF	Xe and Xe <sup>+</sup> velocity vector	50 m/s	Doppler profile of infrared absorption/visible fluorescence	Near-field map of axial, radial, azimuthal velocity; 0.5 mm spatial resolution
13	Two photon UV LIF*	Xe density; H and H <sub>2</sub> density, velocity, temperature (kinetic, rotational, vibrational)	$10^{10}$ – $10^{12}$ cm <sup>-3</sup>	UV absorption/ visible fluorescence, Doppler profile	Near-field map; 0.5 mm spatial resolution, rotational & vibrational temperature also measurable
14	Single photon visible/UV LIF	Velocity, temp, density: Xe, Xe <sup>+</sup> NH, Mo, Ti, W, B, Ba, etc.	$10^5$ cm <sup>-3</sup> in favorable cases	Doppler profile of visible or UV absorption/ visible fluorescence	Near-field map; 0.5 mm spatial resolution
15	Extreme UV absorption*	H <sub>2</sub> density, dissociation fraction, rotational and vibrational temperature	$8 \times 10^{12}$ cm <sup>-3</sup> ; 250 K	Line-integrated extreme UV laser absorption	Configured for centerline traversal only
16	Visible absorption*	Absolute Ba, Ba <sup>+</sup> , Xe <sup>+</sup> density	$10^6$ cm <sup>-3</sup> in favorable cases	FM spectroscopy, Doppler profile	Near-field map, submillimeter spatial resolution
17	Magnetic field	Map of magnetic induction	0.1 Gauss	Hall probe	Measured on stagnant thruster
18	Optical emission	Plume signature, erosion species identification	Varies with species	Spectrograph/CCD	Single point and line imaging
19	Mass/velocity analyzer*	Velocity distribution for 6 masses simultaneously	2%/5%	Time-of-flight mass spectrometer with position sensitive detection	Far-field angular distribution for pulsed thrusters
20	CARS*	H <sub>2</sub> velocity and translational temperature	200 m/s; 20%	Doppler shift/linewidth using single frequency CARS	35 x 350 $\mu$ m spatial resolution; minimum density of $5 \times 10^{15}$ cm <sup>-3</sup>
21	EMC*	Electromagnetic emissions	Near thermal noise	HP 8572A receiver; fiberglass vacuum tank; semi-anechoic room	MIL-STD 461/462D 100 MHz to 18 GHz
22	Microwave interferometer	Electron density	$10^8$ – $10^9$ cm <sup>-3</sup>	Microwave absorption and interferometry	Near-field nonintrusive measurement, 2–4 cm spatial resolution
23	Infrared imager	Thermal flux and temperature maps	300–900 K $\pm$ 10 K	Infrared camera	128 x 128 pixel resolution; 2–4 $\mu$ m spectral band
24	Quadrupole mass spectrometry*	Mass-selected velocity distributions of neutral species	Down to single ion counting	Differentially pumped mass spectrometer with chopper wheel	Far-field angular distributions of mass flux, momentum flux, and energy flux
*Aerospace Corporation unique application or approach					

A comprehensive list of diagnostic capabilities developed at aerospace for electric thruster test and evaluation.

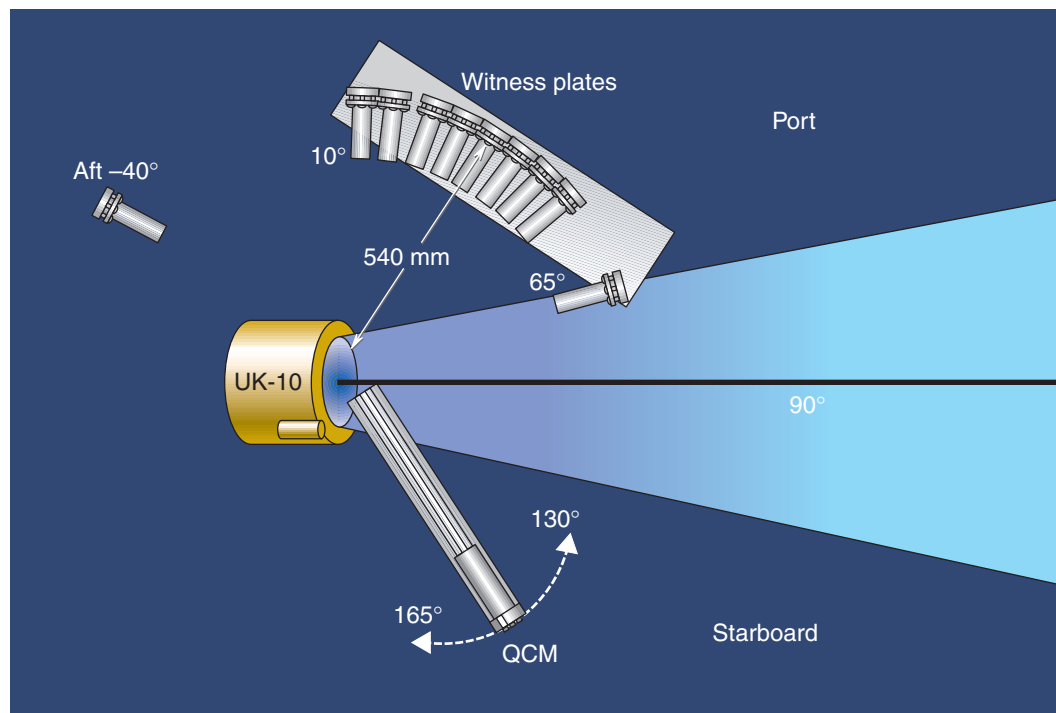
for the project. In addition to quantifying basic electrical and flow parameters, Aerospace was able to evaluate the thrust-vector direction and magnitude, grid deformation during operation, beam divergence, plasma density, plasma potential, electron temperature, ion charge distribution, ion velocity distribution, xenon neutral density, metal erosion rates, ultraviolet and visible emission, radio-frequency and microwave emission, infrared emission, component temperature, microwave phase shift, and surface modification of spacecraft materials. This effort resulted in the most comprehensive set of evaluation tools for an ion engine anywhere in the world and was a vital factor in establishing a baseline for ion propulsion in military communications satellites. These tools were directly applicable to the testing of small ion engines and Hall-effect thrusters for military and commercial programs. During the next few years, Aerospace performed detailed evaluations for various programs and also designed, constructed, and employed a low-power laboratory-model Hall-effect thruster to evaluate engineering trades and to assist in diagnostic development.

During the same period, Aerospace began component-level evaluations and established small supporting facilities for component work and one-off specialized measurements. In the mid 1990s, for example, coherent anti-Stokes Raman scattering was used in a small vacuum chamber to measure the velocity and kinetic temperature of molecular hydrogen both inside and outside the nozzle of an operating resistojet. Since then, Aerospace has installed several smaller test chambers for component work, small thruster efforts, and thruster and diagnostic development. A near-field facility, for example, is applied to the performance testing of small ion thrusters and development of new diagnostics. Aerospace has also devoted considerable effort to thruster hollow-cathode and extraction-grid components and to the study of alternative propellants and novel thruster designs.

A major upgrade of the diagnostic facility in 1999—which doubled the length of the test chamber—enabled Aerospace to perform high-fidelity measurements on medium-power thrusters. Since then, Aerospace has evaluated most of the advanced electric thruster systems in the world. Much of this work has been proprietary to individual customers. In some cases, evaluations have been quite comprehensive, and in the other extreme, limited to one specific measurement result.



The 1.5 meter diameter by 3.0 meter long test chamber used for near-field and performance studies. The facility is applied to the performance testing of small ion thrusters and development of new diagnostics.



Measurement configuration used for contamination and grid-life assessment of T5 (UK-10) ion engine.

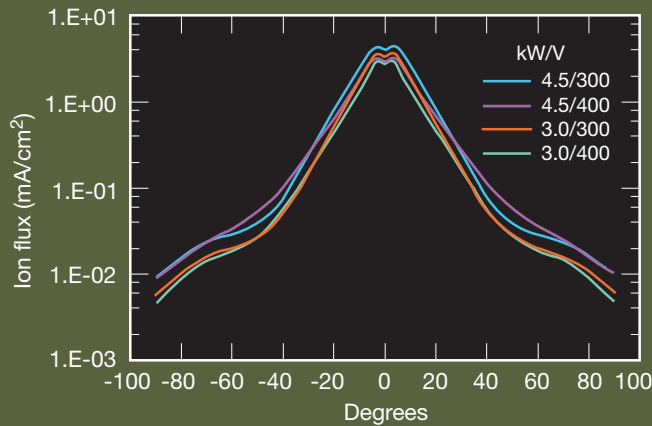
## Diagnostic Capabilities

Thruster performance, life-limiting characteristics, and interactions between spacecraft and exhaust plumes are best understood through a combination of measurements and modeling. In the case of arcjets in particular, the combination of measurement and modeling has resulted in an unusually complete understanding of many aspects of the device physics and performance.

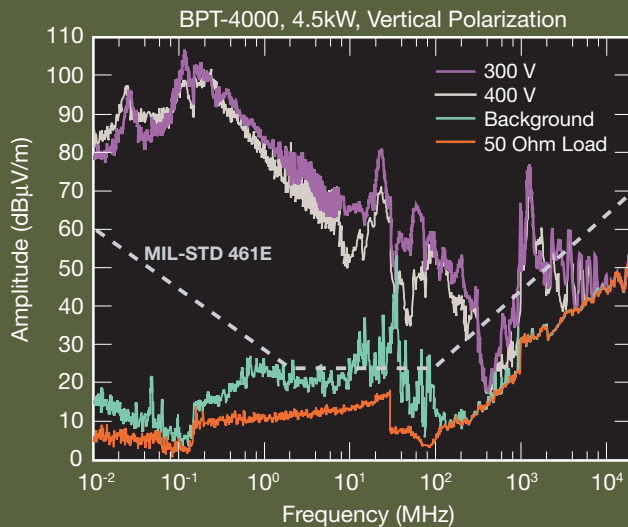
Modeling can help place measurement data in a framework that lends better predictability for changes in parameters or system design. These models are complex,

and typically, the accuracy of one model can have direct bearing on the accuracy of another. For example, numerical plume-propagation models need as inputs the flow properties at the exit plane, which are predicted by a separate model of the propellant acceleration zone. Measurements of near-field plume properties are essential for validating the acceleration-zone model and for controlling the erosion rate of thruster components. Far-field measurements are required for validating the plume-propagation model and assessing interactions with spacecraft materials and sensor payloads.

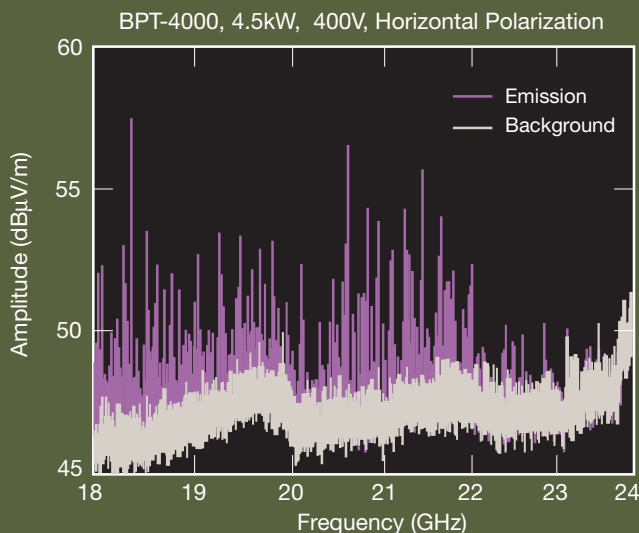
Ion flux vs. angle for the BPT-4000 Hall current thruster at steady-state conditions. Flux scans at 100-centimeter radius were measured with a retarding potential analyzer. A high degree of symmetry is evident about the thruster's physical centerline at 0 degrees. Within 35 degrees from centerline, the flux is predominantly fast ions. Beyond 35 degrees, the contributions from ion-neutral elastic scattering and from charge-exchange production of slow ions become more important, yielding the wings on the flux curves.



Emission from a BPT-4000 Hall-effect thruster operating at 4.5 kilowatts with discharge voltages of 300 and 400 volts. The frequency span shown (10 kilohertz to 18 gigahertz) was measured using four broadband antennas and a spectrum-analyzer-based receiver controlled by Aerospace-developed software. An increase of 20 decibels is equivalent to a 10X increase in measured electric field. Spacecraft EMC limits are payload specific and generally proprietary; the MIL-SPEC limit is shown for comparison.



Electron plasma frequency emission from a BPT-4000 Hall-effect thruster.



These measurements can be obtained through various methods, depending on the nature of the thruster and plume. Each thruster type has sets of particles with intrinsic velocity, density, and temperature distributions that are determined by complex physical processes. Gas kinetic behavior produces a more diffuse density distribution of lighter particles, as opposed to more massive ones, with a pronounced difference in many cases. Plasma devices generate ions, which are normally fast, and neutral particles, which are normally slow; however, scattering effects produce a degree of homogenization, such that a small percentage of fast ions become slow and slow neutrals become fast (as a result of charge exchange). Scattering also produces ions and neutrals having moderate velocities, and these are directed away from the plume centerline; these need to be considered in spacecraft erosion and contamination models. Slow ions can find themselves in the thruster backflow region, where they can impinge on spacecraft surfaces. Charge transfer can occur between ions and neutral particles of the propellant, and between propellant ions and contaminant particles that were sputtered from thruster components. Densities are always low in backflow regions, where detectability is usually an overriding consideration. The detectability of various species in any region and the measurement of more general properties, as a function of the thruster and the diagnostic employed, is an important consideration.

To address these concerns, Aerospace has developed a comprehensive array of diagnostic capabilities, representing a large investment in equipment and expertise. Within the testing chamber, a wide range of test configurations have been implemented, including movable diagnostic devices and rake-mounted sample holders. Small movable probes are suspended on a rotating arm that samples the plume over a 360-degree range at a distance of up to 1.1 meters, extending to a larger radius if the angular range is reduced. View ports allow access for laser-induced fluorescence and video cameras. Beam profiling, thrust-vector tracking, and spatially resolved laser-induced fluorescence are performed by mounting the thruster on a multiple-axis microstepper positioning system, which is temperature controlled to counteract the radiative cooling effect of nearby cryopanels.

Near-field plume measurements are performed with a fast intrusive probe near the exit plane. The ion current is collected

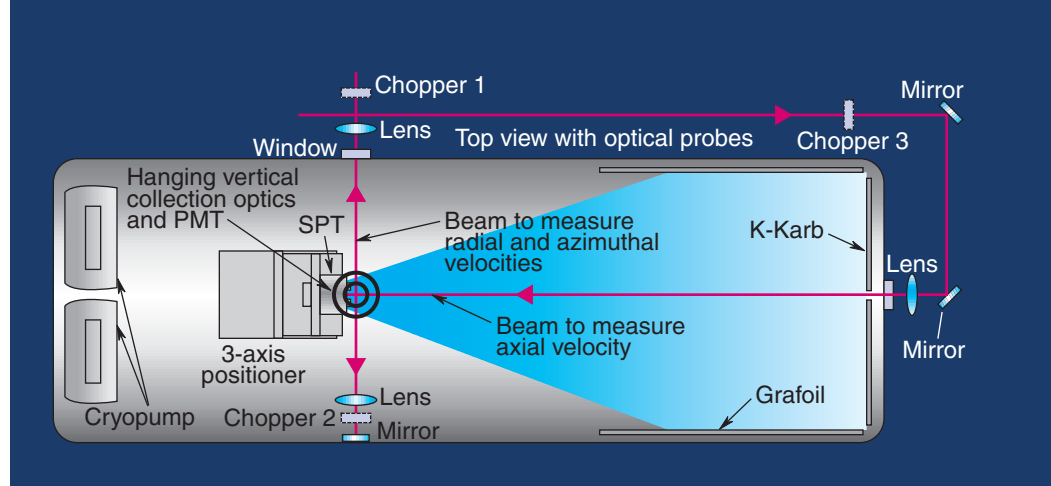
with a long, electrically biased wire that crosses through the plume. The collected data are converted into flux contour maps. Angle-resolved laser-induced fluorescence is used to measure the longitudinal and azimuthal velocity of neutral particles and ions. Fluorescence of single-charge xenon ions or other suitable species allows a determination of the translational temperature and the most probable velocity vector over a grid of measurement points close to the exit plane. Fluorescence of plume metals, such as low-density grid-sputtered molybdenum, generates contaminant density and velocity maps. Laser absorption determines absolute column-averaged density for suitable species of sufficient abundance. Two-photon laser-induced fluorescence measurement using a 225-nanometer excitation wavelength is used to map density of neutral xenon and hydrogen atoms and, with modeling, determine propellant utilization efficiency.

Far-field measurements have been made using a Faraday probe to determine the flux-versus-angle and a time-of-flight parallel-plate electrostatic deflector to determine energy and xenon charge distributions. Electron density measurements in the far field are performed using Langmuir probes and radio-frequency resonator probes. Measurements of plume optical radiation and electromagnetic compatibility can be tailored to support specific requirements.

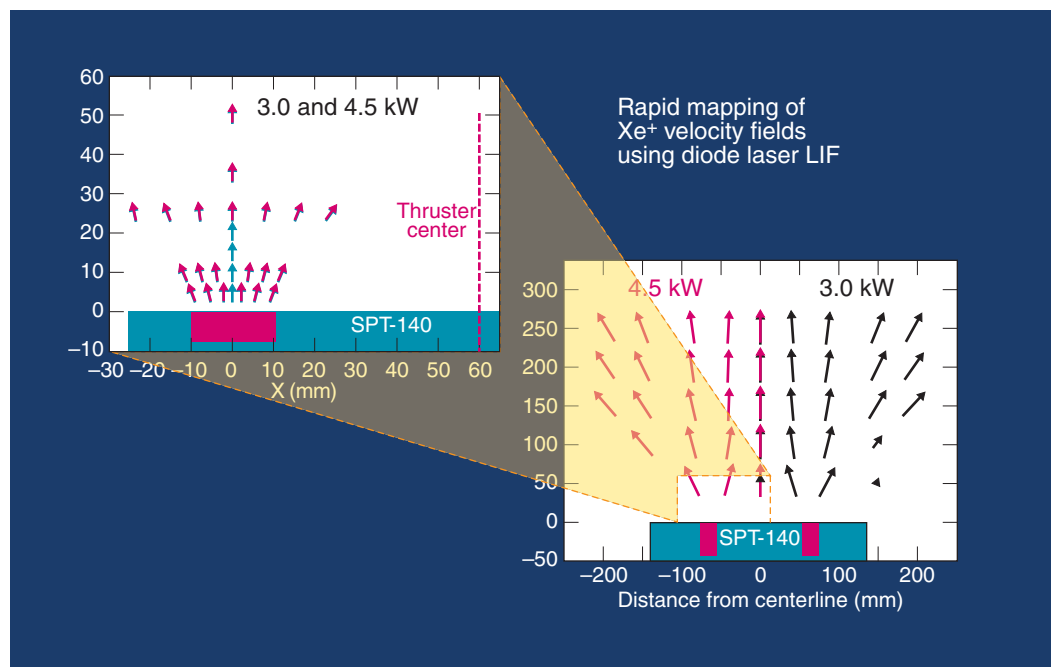
To supplement conventional surface-effect tests that use spacecraft material coupons arrayed in the far-field plume, Aerospace researchers determine the sample deposition or erosion rate as a function of angle using several temperature-controlled collimated quartz-crystal microbalances at set distances. Another bulk property of interest is the accommodated heat flux caused by plume impingement, which is measured using an instrumented copper disk coated with a reference material. Plume heat flux can be evaluated as a function of the angle of incidence on the probe surface and as a function of the probe position relative to thruster centerline.

## A Case Study

The Aerojet BPT-4000 is a 4.5-kilowatt xenon Hall-effect thruster that will be used for orbit insertion, orbit maintenance, and repositioning of geosynchronous satellites such as Advanced EHF. A requirement of the BPT-4000 flight-qualification program is to demonstrate that the thruster will survive repeated cycles from the minimum on-orbit temperature to the maximum steady-state



The typical configuration for laser-based diagnostics. Beam profiling, thrust-vector tracking, and spatially resolved laser-induced fluorescence are performed by mounting the thruster on a multiple-axis microstepper positioning system, which is temperature-controlled to counteract the radiative cooling effect of nearby cryopanel.



Angle-resolved laser-induced fluorescence (LIF) is used to measure the longitudinal and azimuthal velocity of neutral particles and ions. Fluorescence of single-charge xenon ions or other suitable species allows a determination of the translational temperature and the most probable velocity vector over a grid of measurement points close to the exit plane.

temperature. Another requirement is to measure the thrust-vector angle from the physical centerline during startup and at steady state.

Aerospace performed thermal cycling and thrust-vector alignment tests. The thruster was placed in a copper shroud cooled by liquid nitrogen to simulate the orbital environment. The shroud door was closed for thruster cooling and opened just before the start of each firing cycle. An aluminum mounting bracket fitted with cartridge heaters maintained the desired interface temperature. The thruster operated nominally through 10 thermal cycles starting at the minimum expected on-orbit temperature and finishing in 3.5–4 hours at the hot steady-state condition. The shroud returned

the thruster to the cold steady state in 9–10 hours. Temperature variability between cycles was minimal.

Angle-dependent ion flux scans at 100-centimeter radius were measured with a retarding potential analyzer. All scans displayed a high degree of symmetry about the thruster's physical centerline at 0 degrees. Within 35 degrees from centerline, the flux was predominantly fast ions. Beyond 35 degrees, the contributions from ion-neutral elastic scattering and from charge-exchange production of slow ions became more important, as evident in the flux curves. A high degree of symmetry about the centerline was observed at all operating points, and none of the measured thrust vector angles

exceeded 0.7 degrees. Steady-state angles varied by no more than 0.2 degrees between operating points, with no clear dependence on discharge power or voltage. Thrust vector motion was typically 0.25 degrees during the first two hours of operation and 0.05 degrees during the second two hours. Based on the reproducibility between cycles, the random error in the thruster vector measurements was plus or minus 0.05 degrees.

## EMC Test and Evaluation

Aerospace also tested the BPT-4000 thruster for electromagnetic compatibility—a particular area of expertise. Electromagnetic compatibility measurements consider four general categories: radiated emission through space, conducted emission onto the bus, susceptibility to radiation fields, and susceptibility to injected currents. Extensive measurements are carried out in all four areas, following military standard MIL-STD-461.

Hall-effect thrusters and gridded ion engines support complex plasma oscillations that can emit electromagnetic radiation from dc to frequencies above 20 gigahertz. These emissions can be quite strong, often exceeding MIL-STD-461 specifications for frequencies below 4 gigahertz. The low-frequency emissions may induce currents in satellite structures or cause problems directly with electronic components, while high-frequency emissions may interfere with communication channels. Additionally, dc and ac magnetic fields may affect operation of sensitive instruments that are part of the satellite payload. Selective shielding, repositioning of antennas, and modifications of operational procedures may be required to successfully integrate thruster and spacecraft.

The Aerospace approach to radiative emission measurements involves a closed cylinder of dielectric material—largely transparent to electromagnetic radiation—that houses the thruster and mates to the large vacuum chamber. This cylinder is surrounded by a semi-anechoic room, which shields the measurement space from the ambient electromagnetic fields and reduces the reflections of the thruster radiation from the metallic walls of the room. The plume of the thruster exhausts through a carbon-fiber grid into the main vacuum tank, terminating on a beam dump comprising a series of carbon-covered pyramids. The grid reduces the background radiation that leaks from the main chamber, and the pyramids reduce sputtering by the high-energy xenon ions and

scattering of electromagnetic radiation by the metal walls of the vacuum tank.

This arrangement allows antennas to be placed 1 meter from the thruster, as required by MIL-STD-461, and remain unexposed to plasma or metallic surface reflections. Residual facility effects are measured from antenna response at various positions, with calibrated-emission transmitters at the location of the thruster.

Radiative Hall-effect thruster emissions at frequencies below a few hundred megahertz are largely understood, and many of the associated oscillations are required for the proper operation of the thruster. Emissions above 18 gigahertz are primarily caused by electron plasma oscillations. The strong emission seen in the 1–8-gigahertz range (the L, S, and C communication bands) exhibits complex temporal and spatial characteristics and is not currently understood. Thruster-to-thruster variations in the L, S, and C band and dependence on thruster age are also unknown, and are subjects of active research.

## Looking to the Future

The ability to operate medium-power thrusters and apply a comprehensive suite of precision diagnostics has made Aerospace an important independent test and evaluation resource. Given the direction of development toward high-powered spacecraft, including those with nuclear electric power sources, Aerospace will soon need to perform high-fidelity characterizations of much more powerful thrusters. Continued facility upgrades will therefore be necessary.

While some of the more sophisticated forms of electric propulsion have finally entered service, refinement of current designs and progress toward higher power devices continues at a rapid pace. Ion propulsion use by NASA and the military is still in the initial phase. Many issues requiring detailed test and evaluation are being addressed for a variety of thruster systems and flight programs, and Aerospace will continue to play a central role in this work.

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# Software Testing in Space Programs

As space-system software grows in size and complexity, adequate testing becomes more difficult—and more critical.

Myron Hecht and Douglas Buettner

Failures attributed to software defects are becoming increasingly visible in space systems. Recent newsworthy examples include the failure of the Mars rover Spirit to execute any task that requested memory from the flight computer; the unanticipated descent of the Mars Climate Orbiter into the Martian atmosphere, ultimately traced to a unit conversion defect in a navigation system; and the crash of the Mars Polar Lander onto the Martian surface after a premature shutdown of its descent engines. In 1996, the first launch of the Ariane 5 booster ended with a spectacular crash off the coast of French Guiana. The cause was traced to a variable overflow that affected software running in both channels of its dual redundant inertial reference system. Earlier this year, the European Space Agency's Huygens probe successfully beamed back only half of its image data. The other half was lost because of a single missing line of code.

In the period from 1998 to 2000, nearly half of all observed spacecraft anomalies were related to software. Anomalies, less severe than failures, have been occurring with increasing frequency on U.S. national security space vehicles. One reason is that space-system software has been growing more complex to meet greater functional demands. Another reason is that software quality is inherently difficult to determine. The challenge in developing the next generation of national security space vehicles will be to ensure reliability despite increasing software size and complexity. Software testing is an important factor in meeting this challenge.

## Types of Software Testing

Software testing methods generally fall into two categories: “black box” and “white box” (while some authors also identify a third category, the “ticking box,” which involves not doing any testing).

Black-box methods disregard the software's internal structure and implementation. The test data, completion criteria, and procedures are developed solely to test whether the system meets requirements, without consideration of how the software is coded. Black-box testing is used at all levels of testing and is particularly applicable at higher levels of integration, where the underlying components are no longer visible.

White-box testing, on the other hand, does account for the internal software structure in the formulation of test cases and completion criteria. The most common types of white-box testing include branch testing,

```
...
declare
  vertical_veloc_sensor: float;
  horizontal_veloc_sensor: float;
  vertical_veloc_bias: integer;
  horizontal_veloc_bias: integer;
...
begin
  declare
    pragma suppress(numeric_error, horizontal_veloc_bias);
  begin
    sensor_get(vertical_veloc_sensor);
    sensor_get(horizontal_veloc_sensor);
    vertical_veloc_bias := integer(vertical_veloc_sensor);
    horizontal_veloc_bias := integer(horizontal_veloc_sensor);
  ...
exception
  when numeric_error => calculate_vertical_veloc();
  when others => use_irs1();
end;
end irs2;
```

Photo courtesy of European Space Agency; Ada code from <http://www.aix.gsi.de/~glese/swr/ariane5.html>

The Ariane 5 launch vehicle failed on its maiden flight in June 1996. About 40 seconds after liftoff, a software bug in the flight controller made the rocket veer off course, leading to its destruction via ground command. Ariane 5 reused software from Ariane 4 without proper testing. Contributing to the mishap, run-time range checking had been turned off because of processor limitations. Also, the backup channel had failed milliseconds earlier because of the same coding defect.

which runs through every instruction in each conditional statement in a program, and path testing, which runs through every set of conditional statements or branches. White-box testing is typically conducted at the unit level (i.e., the smallest testable component of software) and at the unit integration level.

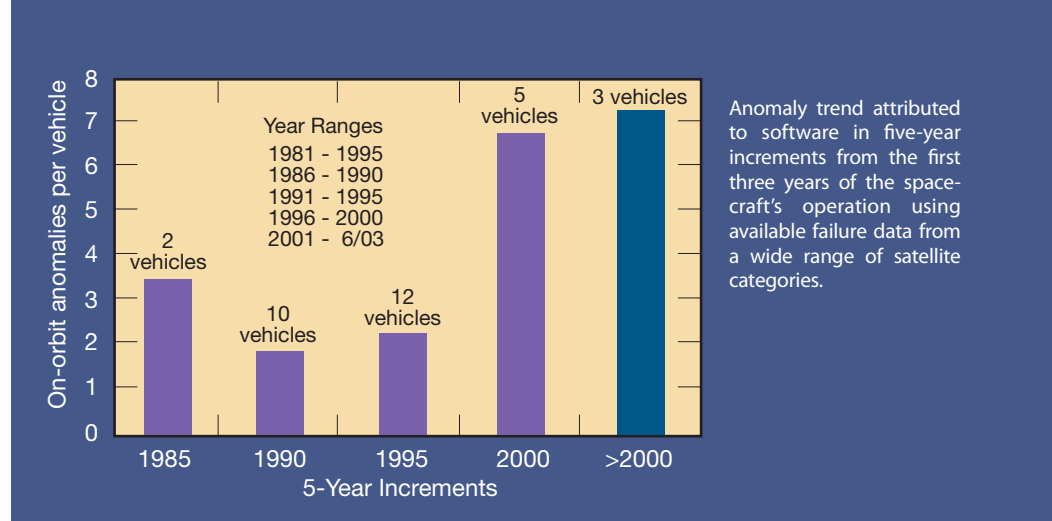
Both methods would typically include some sort of nominal testing, in which test cases are designed to mimic normal operation, and negative testing, in which test cases are selected to try and “break” the program. For example, the software might be run using input values of the correct type and within the expected range to verify conformance with nominal requirements. It might also be run using input values and data rates beyond expected ranges to check failsafe and recovery capabilities.

## The Testing Program

White-box and black-box testing is performed within the context of an overall software test program that starts during the requirements phase and continues through product release and maintenance. Software development standards provide a basis for defining the activities of the overall test program. Although the use of such standards declined in the 1990s, they are now increasingly recognized as an important way to help ensure software quality despite rising complexity.

For example, the National Reconnaissance Office (NRO) and the Air Force Space and Missile Systems Center (SMC) recently asked Aerospace to recommend a set of software development standards to be used as compliance documents on NRO and SMC contracts. Aerospace assisted with a detailed survey of existing life-cycle standards and recommended the use of MIL-STD-498 or its commercial equivalent, J-STD-016-1995. However, MIL-STD-498 was canceled in the mid-1990s, and J-STD-016 is no longer being maintained by the technical organizations that produced it. Therefore, SMC and NRO felt that a new software standard should be developed.

Aerospace helped analyze MIL-STD-498 in greater detail and identified ways to modernize J-STD-016. Based on this effort, Aerospace prepared a new standard, published as Aerospace Report No. TOR-2004(3909)-3537, “Software Development Standard for Space Systems.” It uses MIL-STD-498 as a foundation, but incorporates additional requirements from J-STD-016. It also adds exit criteria for various levels



of software testing and requirements that bring the standard up to date with modern terminology and best practices in software development.

Many software development standards, including MIL-STD-498 and the Aerospace revision, set forth requirements for three major activities of software testing: planning, definition, and execution.

Software test planning addresses all levels of coding and integration, from the highest-level software package down to the lowest-level software units. The results are documented in a software test plan. Lower-level test plans are independently created if the software’s size and complexity warrants it. The software test plan enables the program manager to assess the adequacy of test planning for each of the software items and for the software system qualification testing. In addition, the software test plan lists the issues that should be considered in the development of the software test definition.

In the test definition stage, the test preparations, test cases, and test procedures are all described and documented. This may involve a significant design and development effort—in some cases, equal to or exceeding that of the software itself. This is particularly true for software item qualification testing, in which individual software components are accepted for integration into the system. Software item qualification testing is critically dependent on the accuracy of the software test definition.

Once the test definition has been completed, it is possible to actually run the tests and record the results in the software test report. As part of this process, the test organization should emphasize findings and observations of anomalies. The software test report can also include suggestions for further testing based on the limitations of the test equipment or limitations arising from budget or time constraints. The software test report

documents the test results and includes accumulated test analyses, results, summaries, deviations from dry runs, and metrics.

## Limitations of Software Testing

Despite its obvious importance, software testing is only a partial solution to creating reliable software. In a sense, the purpose of testing is to show that a program has bugs. Thus, while it can provide a means to find and fix defects, it cannot by itself provide an assurance of failure-free operations. Software testing must be pursued in conjunction with other appropriate practices in systems engineering, requirements definition, and software development (such as inspection, the use of automated development aids, static source code and design analysis, and peer review).

A significant limitation is that software testing cannot occur until after the code is written—about halfway or more through project development. The cost of fixing errors rises dramatically as the project progresses because more deliverables are affected. For example, requirements errors cost 10 times more to fix in the code phase than in the requirements phase. Methods of software verification other than testing (under the broad categories of inspection, analysis, or demonstration) must be used to catch errors in the earlier phases of design.

A related limitation is that the effectiveness of a testing program is no better than the requirements on which it is based. Aerospace analysis has shown that the generation of software requirements is a major source of errors in system development. Specific challenges include poorly stated requirements, changing or “creeping” requirements, and nonfunctional requirements. A study of requirements-originated software failures showed that roughly half resulted from poorly written, ambiguous, unclear, and incorrect requirements. The rest came from

Method and Description	Objective	Test Type	Applicable Level
Scenario-based (also called thread) testing: Testing using data based on usage scenarios, e.g., simulation of the mission.	Assess overall conformance and dependability in nominal usage.	Black box.	Integrated software and system.
Requirements-based testing: Testing to assess the conformance of the software with requirements.	Determine whether the software meets specific requirements.	Black box.	All levels at which requirements are defined.
Nominal testing: Testing using input values within the expected range and of the correct type.	Verify conformance with nominal requirements.	Black box.	All.
Stress testing (a type of negative testing): Testing with simulated levels beyond normal workloads, or starving the software of the computational resources needed for the workload; also called workload testing (usually run concurrently with endurance tests).	Measure capacity and throughput; evaluate system behavior under heavy loads and anomalous conditions to determine workload levels at which system degrades or fails.	Black box.	Integrated software and system.
Robustness testing (a type of negative testing): Testing with values, data rates, operator inputs, and workloads outside expected ranges.	Challenge or “break” the system with the objective of testing fail safe and recovery capabilities.	Black and white box.	All.
Boundary-value testing (a type of negative testing): Testing the software with data at and immediately outside expected value ranges.	Test error detection and exception handling behavior of software with anticipated exception conditions.	Black and white box.	Unit, software subsystem.
Extreme-value testing (a type of negative testing): Testing for large values, small values, and the value zero.	Same as boundary-value testing.	Black and white box.	Unit, software subsystem.
Random testing: Testing the software using input data randomly selected from the operational profile probability distribution.	Assess overall stability, reliability, and conformance with requirements.	Black box.	Integrated system.
Fault-injection testing: Testing on the nominal baseline source code and randomly altered versions of the source (white box) or object code (black box).	Assess failure behavior, ensure that system properly responds to component failures.	Black and white box.	Integrated software.
Branch testing: Testing using test cases selected to test each branch at least once.	Test correctness of code to the level of branches.	White box.	Software unit.
Path testing: Testing using test cases selected to test each path (i.e., feasible set of branches) at least once. Also called flow-graph testing.	Test correctness of code to the level of paths.	White box.	Software unit.
Modified-condition decision coverage: Every point of entry and exit in the program has been invoked at least once, every condition in a decision in the program has taken all possible outcomes at least once, every decision in the program has taken all possible outcomes at least once, and each condition in a decision has been shown to independently affect that decision’s outcome.	Test for safety-critical software where a failure would probably or almost inevitably result in a loss of life.	White box.	Software unit (assembly code created by compiler under some circumstances).

Typical black-box and white-box test methods.

requirements that were completely omitted. Most problems introduced into software can be traced directly to requirements flaws.

An additional limitation is the difficulty—and hence the time, cost, and effort—of software testing. Ideally, a software system could be exhaustively tested and thereby proven correct. However, this is impossible for all but the simplest systems. Many space-system software applications are so complex, and run in such an interdependent environment, that complete testing can never be achieved. Instead, program managers must prioritize their testing objectives and optimize their testing procedures to ensure that the most important tests are completed. Skill in risk analysis is therefore essential for establishing an appropriate test coverage objective—usually stated as a proportion of the requirements, input data, instructions, or program paths tested (e.g., testing is com-

plete when the tests addressing 100 percent functional coverage of the system have all executed successfully).

Proper selection of input data can increase the testing efficiency by either increasing the error-detection effectiveness or reducing the number of test cases needed to achieve a given test coverage objective. For example, tests can be partitioned to exercise the same code using only one representative case. The number of test cases for each class of failure behavior can be limited. If software inspection is used in the development process, the distribution of defects (by category) detected by inspection can be used to drive the distribution of test data. The amount of coupling (intermodule referencing of variables or subroutines) can be used to focus test cases—particularly if a significant amount of software changes have been made. Test cases can also be concentrated on areas exhibiting

an abnormally high number of failures. Test case input data can also be selected using a “design of experiments” approach.

## How Much Testing is Enough?

Considering that complete test coverage is generally not possible, project managers face a difficult question in deciding when to stop testing. In practice, this decision is often based not on specific and quantifiable goals but on deadlines, budgets, or completion of an arbitrary number of test runs.

For national security space systems, a better criterion would be the point at which the software reaches an acceptable level of reliability, as measured in time between failures. This method, often referred to as software reliability engineering, is a recommended practice by the American Institute of Aeronautics and Astronautics (AIAA).

The fundamental premise of software reliability engineering is that the rate at which software defects are found and removed can be described mathematically and therefore predicted. These discovery and removal rates can be constant or variable, depending on the models used. If the testing environment simulates the operational environment, then failure rates observed at any point in the test would be similar to the operational failure rates, and the model would enable a prediction of the future failure rate as the testing program proceeded. They would therefore provide an ability to predict the software's future reliability.

Software reliability engineering originated in the 1970s and has been the subject of extensive research since that time. Tools have been developed to fit various models to test data to enable determination of the best fit and subsequent extrapolation to enable prediction. Software reliability engineering provides a cost-effective method to determine when to stop testing. Cost typically ranges from 0.1 to 3.0 percent of project development costs.

To help improve the accuracy and value of these prediction models, Aerospace has been working to develop a database schema for software reliability data. The project, Space Systems Mission Assurance via Software Reliability Monitoring, will correlate software life-cycle engineering practices (including test) with the reliability measured from deployed space-systems software. An eventual goal is to provide a risk-assessment tool for program managers that will allow them to compare key software life-cycle metrics and test practices from their program to historical data from other programs. The database is being designed to support three types of analyses: exploratory, quantitative, and qualitative. Exploratory analysis would allow users to investigate relationships that could be used to predict software and system reliability based on project, structural, and test program attributes. Quantitative analysis would allow users to extract event data to predict software reliability. Qualitative analysis would allow users to address questions such as what are the major failure causes, effects, or developmental problems.

## Safety-Critical Software

Although software reliability engineering can benefit many types of software, special considerations must be made for safety-critical software—the failure of which can lead to death, major injury, or extensive

Activities	Key Issues
Software Test Planning	<p>Test organization, including personnel, responsibilities, discrepancy reporting requirements, and release processes.</p> <p>Budget and schedule requirements, test schedule estimates, milestones, and deliverables.</p> <p>Plans for maintaining and updating test plans, test cases, test environment, and automated tools through the life cycle.</p> <p>Strategy for changes in the requirements and software items (in particular, regression testing).</p> <p>Testing of commercial or nondevelopmental item software.</p> <p>Particular equipment, procedures, methods, or data necessary to address the requirements of the specific program for which the plans are developed.</p> <p>Completion criteria.</p>
Software Test Description	<p>Software requirements addressed by the test.</p> <p>Test driver environment (interfacing hardware, software, communications, etc.).</p> <p>Automated testing tools (record/playback tools, coverage analyzers, test tracking, etc.).</p> <p>Test completion criteria.</p> <p>Means of evaluating correctness of results (test method).</p> <p>Test tracking, logging, and archiving processes.</p> <p>Test setup steps.</p> <p>Metrics for the reporting of results.</p> <p>Retest criteria.</p> <p>Test input data requirements.</p> <p>Evaluation of test case data to assess success or failure.</p> <p>Procedures to undertake when an anomaly occurs to capture the circumstances surrounding the failure.</p>
Software Test Execution and Reporting	<p>Overall assessment of software tested.</p> <p>Identification of deficiencies.</p> <p>Problem reports filed.</p> <p>Test environment version, constraints, etc.</p> <p>Recommendations for improvement.</p> <p>Deviations from procedures for each test case.</p> <p>Details for analysis required to document the pass/fail conclusion.</p> <p>Who executed the tests.</p> <p>Who witnessed the tests.</p> <p>Where the test results are archived.</p> <p>When were the test cases executed.</p>

Key software test issues.

property damage. A good example is the software supporting the Global Positioning System (GPS). An undetected failure in the navigation signal from any of the GPS satellites might result in an aircraft receiving misleading information on its position or altitude, thereby exposing its occupants to a high risk of a crash landing. Thus, the software components involved in integrity monitoring, which would detect and announce a navigation signal failure, must receive special scrutiny.

Aerospace is supporting the GPS program office in producing high-integrity software for the next-generation GPS constellation. For safety-critical software, testing is part of a process of analysis, documentation, and traceability that starts at the beginning of the project and continues throughout the system lifetime. For example, when requirements are being formulated, a preliminary or functional hazard analysis is performed to identify major hazards and develop mitigation strategies. At the design phase, two more

system-safety analyses are performed to determine the safety impact of the software components in their normal and failed states. For critical software components, verification, testing, and documentation must be performed intensively. For example, in aviation applications, the RTCA DO 178B standard provides for testing of all combinations of conditions in branches in such software.

Even intensive testing has the same limitation discussed earlier: it can only prove the presence of defects in software, not their absence. Thus, Aerospace and other organizations are researching methods that use mathematical techniques to prove the correctness of the specification, the verification test suite, and the automatic code generators that create the software. The goal is to use formal methods and testing together to significantly decrease development time while producing dependable software.

## Conclusion

With the addition of progressively more software functionality in both space and ground segments, program managers will face tougher challenges in ensuring software reliability. Software testing efforts will require better analytical methods and oversight approaches to meet the greater demand without adversely affecting budgets and schedules.

By participating in software test planning and data analysis, reviewing software development standards and practices, and by performing research on software reliability, Aerospace is helping to make the software testing process more efficient and effective. The results of this research should augment software-intensive system acquisition practices with tools to help program managers ensure mission success.

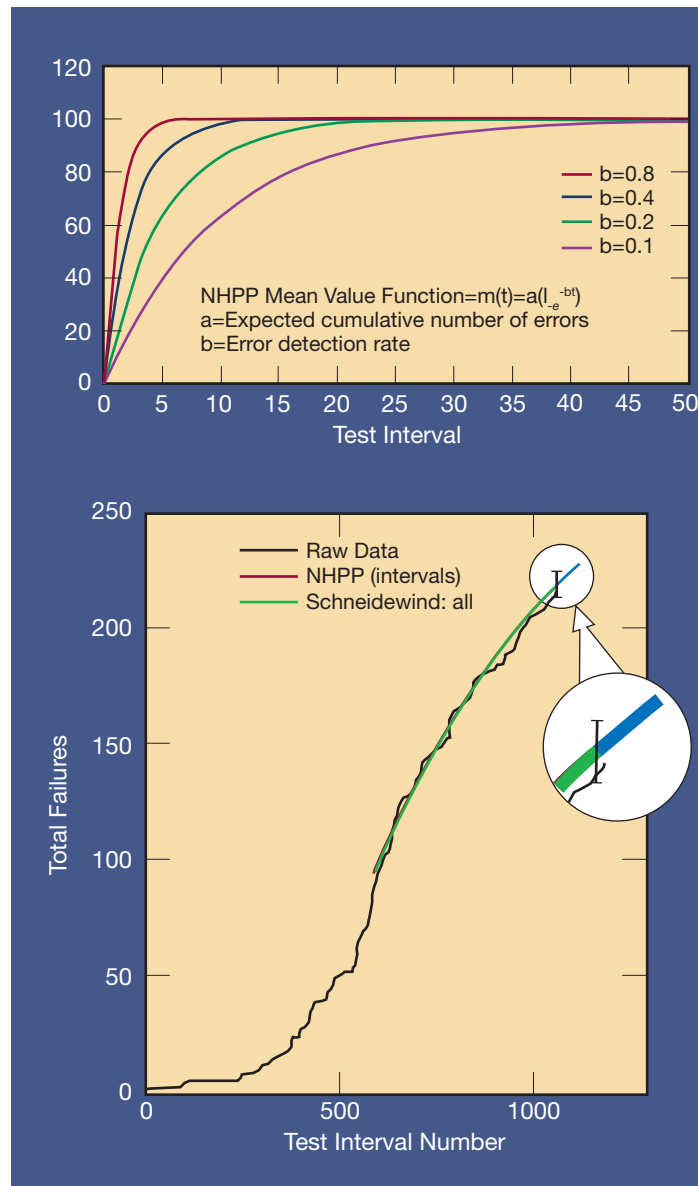
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This graph shows the benefit of error-detection effectiveness under the assumption that the defect detection can be modeled as a nonhomogenous Poisson process (NHPP). As the proportion of defects removed per test case or interval moves from 0.2 to 0.8, the number of test intervals needed to remove 80 percent of the defects goes from 8.03 down to 2.01.

This figure shows the output of a software reliability modeling tool called CASRE (Computer Aided Software Reliability Estimation) developed at CalTech/JPL. Two of the models, the nonhomogenous Poisson process (NHPP) model and the Schneidewind model, closely fit the cumulative defect history curve from system testing for a flight software project. The blue part of the curve displays the end of data bar and the failure prediction results two weeks into the future.

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# Ground Systems Testing

Testing procedures are seldom fully foolproof, but an independent review can help identify and correct potential sources of trouble.

**Norm Strang**

Ground systems testing covers many different aspects of the total ground operations, including areas such as launch facilities, power supplies and generators, fire protection, fluid storage and transfer, air conditioning, payload facilities, fixed and mobile tracking stations, communications, and vehicle transport. These testing operations begin with component testing and end with integration and testing of the complete space system. The goal is to ensure not only that systems function properly, but that they pose no safety hazard for workers in the vicinity.

An important function that Aerospace performs for the government is the review of ground facility test plans and procedures. These documents, generated by the contractors, must be composed with rigorous attention to detail. The independent review helps verify that the tests will be performed as intended and will not damage equipment or present a safety risk. In the past, these reviews have revealed major problems that could be corrected before they caused a mission failure. It has also happened that test plans, implemented without adequate review, contained problems that were only revealed by a subsequent mission anomaly or failure.

## Problems Caught in Time

Human error is a major source of problems in ground systems testing. Errors can arise when procedures are not detailed enough, not interpreted properly, or not performed correctly. An incomplete set of instructions, when followed literally, can lead to serious consequences. For example, Aerospace reviewed a procedure for proof testing booster propellant tanks. The procedure entailed filling the tanks with water, pressurizing them, and subsequently draining them. The procedure was written so that the drainage valve could be opened before the tank's pressurizing gas valve was opened. This would have caused a negative pressure in the tank as the water drained out, which would have damaged the tank and could have caused a failure in flight. The procedure had to be rewritten

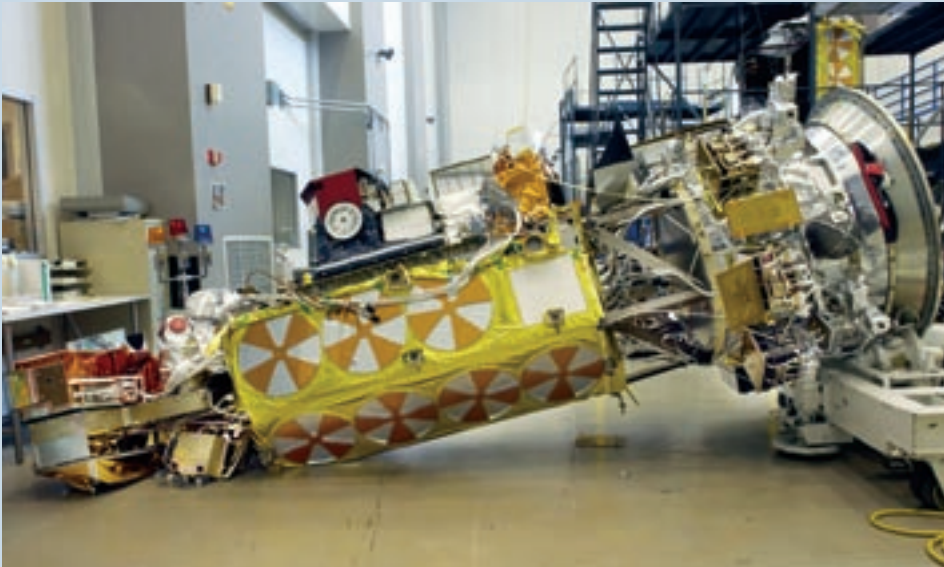
to incorporate more detailed operations, warnings, and a final quality-assurance check.

Similarly, a procedure for testing a solid rocket motor was written in such a way that the equipment used to lift the motor could be lowered onto the motor case at a speed and inclination that would have caused an impact severe enough to damage it. If that had happened, the motor probably would have failed after ignition.

A functional test procedure for a space booster was written so that the engine propellant valves would be cycled at the same time, with the cover on the rocket engine nozzle. Because of the difference in size of the booster propellant tanks, this allowed the smaller fuel tank to have a higher air pressure than the liquid-oxygen tank, as a result of the ambient temperature. Therefore, when the valves were opened, air from the fuel tank flowed through the engine injector, carrying hydrocarbon residue from previous static firing operations back into the liquid-oxygen tank. This could have caused a liquid-oxygen/hydrocarbon explosion during flight had it not been found—accidentally—during some special checkout operations. This problem illustrates the importance of considering the total system during test procedure development. In this case, the nozzle cover should have been removed.

Sometimes, problems arise through a lack of realism in the testing process, or through an incomplete assessment of the working environment. For example, the acceptance test procedure for a new ground station in Thule, Greenland, was written such that the hydraulic fluid lines to the antenna were not tested at actual working pressures and temperatures. During a walk-through inspection later in the certification process, Aerospace noted this deficiency. It turned out that these lines had to be reworked to add additional expansion joints. This could have caused a mission delay, had the Aerospace engineers not been involved.

Similarly, during the review of an acceptance test procedure for a new ground station, Aerospace noted that the radome



This is an example of what can happen when test procedures are not followed properly or were not written correctly. This payload accident probably cost millions of dollars in equipment replacement and program schedule slips. The accident was caused by improper support of the payload during handling operations.

foundation and the antenna foundation were joined together, without an isolation joint. A review of the antenna mission requirements showed a clear specification for high signal resolution. Without an isolation joint, the wind-induced vibration from the radome would be transmitted through the foundations, allowing the antenna to vibrate. This would adversely affect signal resolution. As a result, the foundations had to be redesigned to incorporate an isolation joint.

Even ancillary safety systems must be tested for safety. While reviewing another ground station acceptance test plan, Aerospace determined that the fire suppression system in the computer areas could be inadvertently activated by a wastebasket fire or by minor events such as a sprinkler-head malfunction or a spurious activation signal. This would dump water onto the computers, causing major damage and potential loss of mission. The problem was solved by installing an emergency shutoff switch to be manually activated when these or any similar problems occurred.

### Problems Discovered Too Late

Over the years, missions have failed because of major problems that were overlooked because of inadequate testing. A general lack of testing rigor, complacency in part qualification, and failure to consider important systems as a whole have all contributed to past mission failures. For example, cascading relays shut down a ground station during a high-priority mission. The problem was triggered when a short circuit caused

the electronic relays in one system to open and dump their electrical load onto the next system, causing that system's relays to open, and so on. An analysis of the complete electrical power system would have revealed the possibility for this type of failure to occur. This would have triggered a system requirement to test for this type of failure. Proper testing would have required that the relays be subjected to the highest power level possible. The system could then be modified to protect against any problems observed. Had proper testing been performed during this system's development and acceptance testing, this design problem would have been found long before it caused the loss of a mission.

In another instance, a hydraulic system failure caused a booster to go out of control, leading to its destruction. Aerospace helped conduct the failure investigation, which traced the problem to the hydraulic pump pistons, which got stuck in the cylinders because they were too large. These pumps had been used successfully on many other missions. The failure investigation determined that new personnel in the machining facility introduced a drawing error into the machining operation, and as a result, the pistons were made too large. If the acceptance test procedure for the pump had been written to require testing at maximum operating conditions, instead of at much lower time and cycle rates, the problem would most likely have been found, and the launch would have been saved.

Ground systems are highly complex, and modifications to any one component,

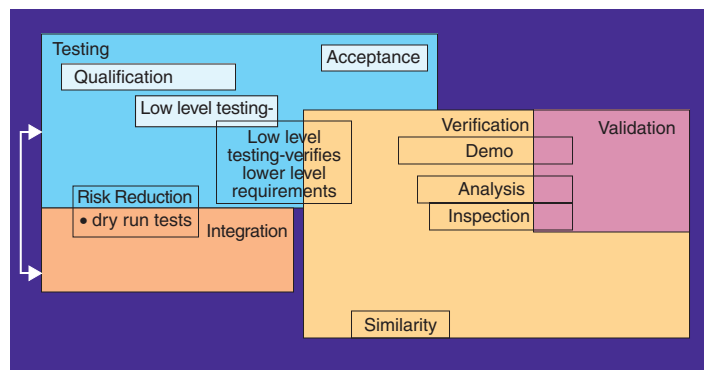
no matter how simple, can have a profound impact on all the others. Testing procedures must therefore be sufficiently thorough to account for any component changes—but this is not always the case. For example, the ground systems fuel loading line to a booster vehicle was not tested after it had been modified. As a result, an area in the line that trapped air was not discovered. Had the test procedure included checking the volume of fuel in the fuel line, it would have shown that an air bubble was displacing fuel. This caused the vehicle to be loaded 135 kilograms light, which caused a premature shut-down of the booster during flight and loss of the mission.

Problems with rocket boosters can arise during integration or final preparations at the launch site, and ground checks provide the last opportunity to find and correct them. Skimping on these final checks can have disastrous consequences. For example, in an effort to reduce cost and weight of a booster vehicle, a transducer was removed from the booster system used for monitoring pressurization of the liquid-oxygen tank. The transducer was originally located downstream from the heat exchanger, which generated gaseous oxygen, in a bend in the line with a flex hose connected to it. The transducer was removed, and an elbow was installed in its place. No testing was performed. During the first launch with this configuration, the mission was lost because the flex hose failed after experiencing resonance, which allowed the pressure in the liquid-oxygen tank to decay. Had this change been properly tested, the problem would have been found, and the mission saved.

During a commercial launch, the first and second stages of a space booster failed to separate. The failure was traced to the vehicle separation slide mechanism, which had evidently seized up. An investigation revealed that during testing of the vehicle integration, a problem was noted in this separation system. The quality-assurance engineer and the test engineer reviewed the problem at the time, going back through the checkout procedure step by step. The test engineer determined that per the procedure, the separation system was acceptable. The quality-assurance representative disagreed, but was overruled. This example clearly illustrates the need for a formal system that requires agreement between the test engineer and the quality-assurance inspector and prohibits one from overriding the other. During the flight failure investigation, Aerospace determined



Image courtesy of Lockheed Martin



This diagram provides an overview of a test and integration master plan, showing the relationship among testing, integration, verification, and validation. Qualification testing provides proof that the delivered item can meet the specified environments with margin for uncertainties. Low-level testing verifies lower level requirements and provides confidence for going to the next level of integration. Acceptance testing provides confidence that there are no workmanship issues.



Image courtesy of The Boeing Company

The mobile launch platform is a major part of the “clean launchpad” concept for the EELV. It contains all of the systems needed to launch the booster. All systems are checked out and tested off the pad, and then moved to the pad, where propellants and gases are loaded. All systems must be tested to ensure they work properly the first time or the mission will, at the very least, be delayed. The major ground systems involved are the umbilical systems, vehicle hold-down system, air conditioning, electrical power, electronic sequencing, trains, and tracks.

Space Launch Complex 6 in Vandenberg, California, was built to launch the space shuttle but was never used for that purpose. It has since been modified to launch the Delta IV EELV. Testing of this launch pad is complicated by the many systems that were modified from the original design or were abandoned in place. This increases the chance that the checkout procedures and testing operations will be misinterpreted or incorrectly performed. Special precautions must therefore be taken, which increases the testing burden.

that the test procedure used to check the slide mechanism did not have enough detail, and as a result, it was interpreted incorrectly.

## Overtesting

It's easy to conclude that ground systems can never be tested enough—but in fact, overtesting can be as big a problem as undertesting. Testing is an invasion of the system, and provides new opportunities for injecting human error. The more a system is tested, the more likely it is that new errors will be introduced. There's an old saying, “If it ain't broke, don't fix it,” and taking apart a good system to do more testing ignores this simple wisdom. Overtesting also adds cost to the program by funneling time and resources into activities that may no longer be providing benefit. Therefore, only needed testing should be performed based on a detailed understanding of how the system functions. The amount of

testing required should be based on past experience with similar designs, materials, and levels of complexity. In this case, the years of experience that Aerospace has gained through involvement with diverse space programs can help determine the proper amount and the proper type of testing.

## Conclusion

Ground systems operations depend on total systems engineering to ensure proper design and development. This includes knowing that the design is correct, proper materials were used, proper manufacturing was performed, proper assembly operations were conducted, and proper testing was applied. Each of these steps requires successful testing before proceeding to the next step. If not, system failure is all but inevitable.

Ground systems represent the largest overall cost for most space programs.

However, testing of ground systems does not always get the same visibility as vehicle testing, for example. This is a major concern because problems with ground systems are just as likely to cause a mission failure as are vehicle problems. Also, ground systems tests are more prone to human error, ranging from a lack of detail in writing the test plan to a failure to understand and implement the testing protocols. Test plans must be meticulously written to prevent errors, to protect personnel, and to ensure a high level of confidence in the results. This is best achieved through a formal system designed to ensure that the technicians are well trained, the procedures are well written and approved by qualified reviewers, and the testing operations and results are accepted in a formal approval process. An independent review, such as that performed by Aerospace, is an important part of this process. ●

## Evaluating Lithium Batteries

Lithium-ion batteries tend to be smaller and lighter than the nickel-hydrogen batteries commonly used in satellite power systems. They also offer a significantly lower rate of self-discharge—a phenomenon that affects all batteries, causing them to lose power over time. For these and other reasons, lithium-ion is expected to be the next dominant type of space vehicle battery. Still, not much is known about the long-term performance of these batteries. Real-time life tests would require 10 years or more, and no validated accelerated test methods have yet been designed.

To learn more about the performance of these batteries, a group of Aerospace researchers led by Albert Zimmerman, Distinguished Scientist in the Electronics Technology Center, has developed a variety of new diagnostic techniques. The group has also mapped out a meta-analysis approach that can digest industry-wide life-test data (from ground tests) for statistical analysis. The goal is to develop and validate a life model based on wear rates, degradation processes, and cell statistics.

“Lithium ion cells degrade steadily during life by a combination of capacity loss and resistance growth,” Zimmerman said. “If we can predict the amount of capacity loss and the amount of resistance growth during cycling, we can determine cell lifetime.”

Some current research is directed at assessing the stress factors that affect degradation. For example, Zimmerman’s group devised a new method for measuring self-discharge. The method involves measuring the amount of charge required to periodically restore cell voltage to a fixed level, along with the rate of voltage decay between periodic voltage restorations. Using this technique, researchers determined that lithium-ion cells, like most types of cells, will develop capacity imbalance over time. This is a significant concern for power system designers. “If one cell in a battery becomes much lower in state of charge than the others, it will fail prematurely during discharge,” Zimmerman explained. “If one cell becomes higher in state of charge than the others, it can be overcharged during recharge, and potentially ignite or explode.” No mechanisms exist to prevent the imbalance, except for cell-balancing electronics, which add cost and complexity to the power system.

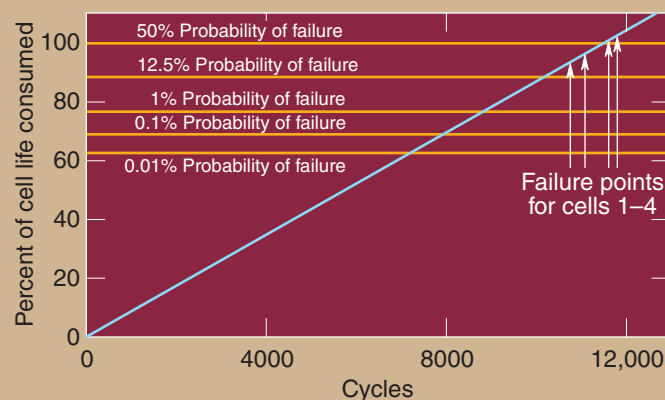
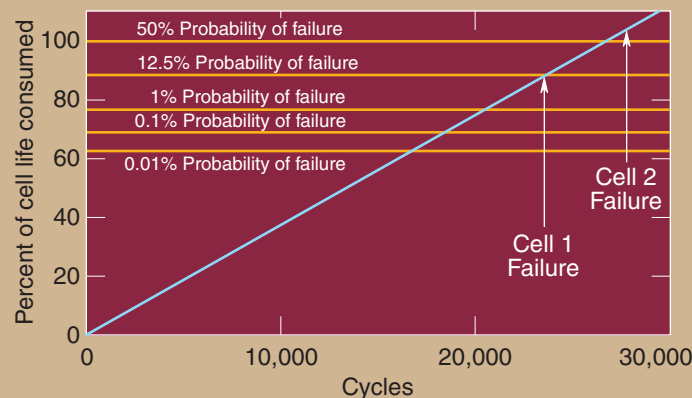
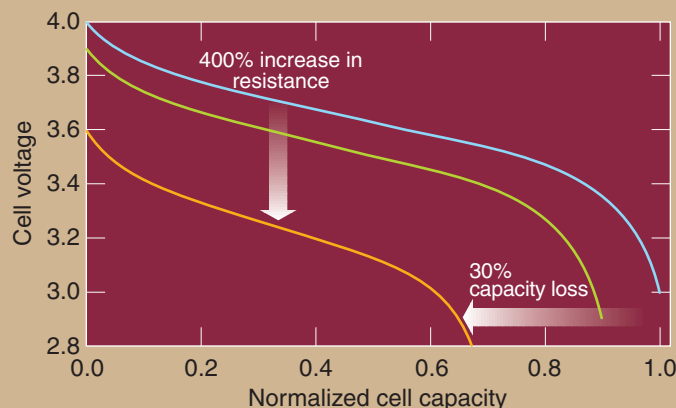
Zimmerman’s research further suggested that external losses through insulation resistance could contribute to cell imbalance. “If one cell in a series has inadequate insulation resistance,” he explained, “that cell connection point will provide a current leakage path that will bleed capacity from some of the cells in the battery, thus causing them to become imbalanced.”

Other diagnostic methods based on impedance, residual capacity, entropy, and thermal measurements were developed to characterize the electrical and thermal performance of the electrodes. “A parasitic lithium-metal plating process can be significant in some electrodes at high charge rates or low temperatures and cause them to degrade faster than normally expected,” Zimmerman said. Some materials are better, he noted, primarily because they offer improved lithium ion transport rates.

Complete validation of a lithium-battery life model would require that both real-time and accelerated tests have been completed to cell failure, but few such cases are available. Nonetheless, Zimmerman’s

group has developed a capacity-loss and resistance-growth model based on observed life-test behavior and cell-failure statistics. Validation efforts have shown that the model correctly predicts the observed cycle life within 10 percent.

The ultimate service life that can be expected from lithium-ion batteries is so far unknown, but Zimmerman predicts it will be about half of that possible from the best nickel-hydrogen batteries (which can last more than 20 years in some applications). That “may be adequate for many future space missions,” he said.



## Thermal Properties of Ball Bearings

In terrestrial applications, ball bearings and their attached rotational components are often cooled by convection, either by the atmosphere or by a flood of lubricant. But neither method of cooling exists in space. Bearings, for instance, cannot be flooded with lubricant because of the potential for spacecraft contamination, and the lack of air eliminates convection altogether. Thus, the dominant mode of cooling is conductance through the bearing itself. As such, temperature predictions for rotating mechanisms in space require knowledge of a bearing's thermal conductance; however, such information is generally not known, and little has been published on the subject.

To address these concerns, an interdisciplinary group of researchers led by Yoshimi Takeuchi of the Mechanical Systems Department devised experiments to assess the thermal conductance of bearings in vacuum. The studies were designed to allow control of parameters such as axial load, thermal environment, and speed. The investigation identified variables of importance for bearings in dry, lubricated, static, and dynamic states.

A static bearing is one that remains nearly stationary. A pointing mechanism, for example, might require a finely tuned bearing that moves in extremely small increments, and may remain motionless for some periods of time. "Although the bearing is not generating heat in these applications, knowledge of bearing thermal conductance is still important because heat is being transferred between the housing and the sensor bed through the bearings," Takeuchi explained. At the other extreme are dynamic bearings—for example, the bearings in momentum wheels, which typically run between 6000 and 9000 rpm. "This may not seem like much compared with terrestrial applications," Takeuchi said, "but keep in mind that on Earth, the atmosphere cools the bearings. In space, there is no convection cooling, so heat generated by the bearings creates an upper limit to component speeds."

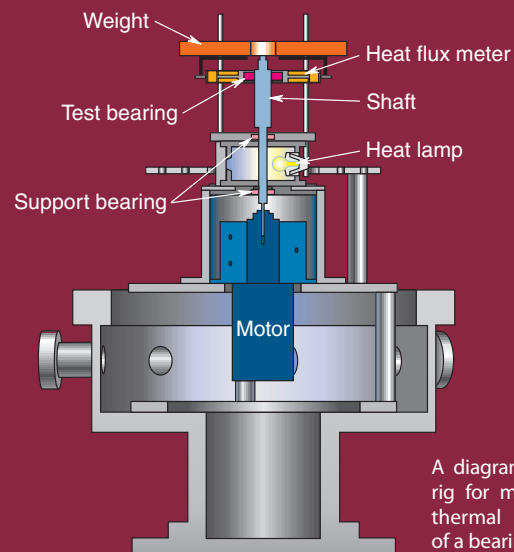
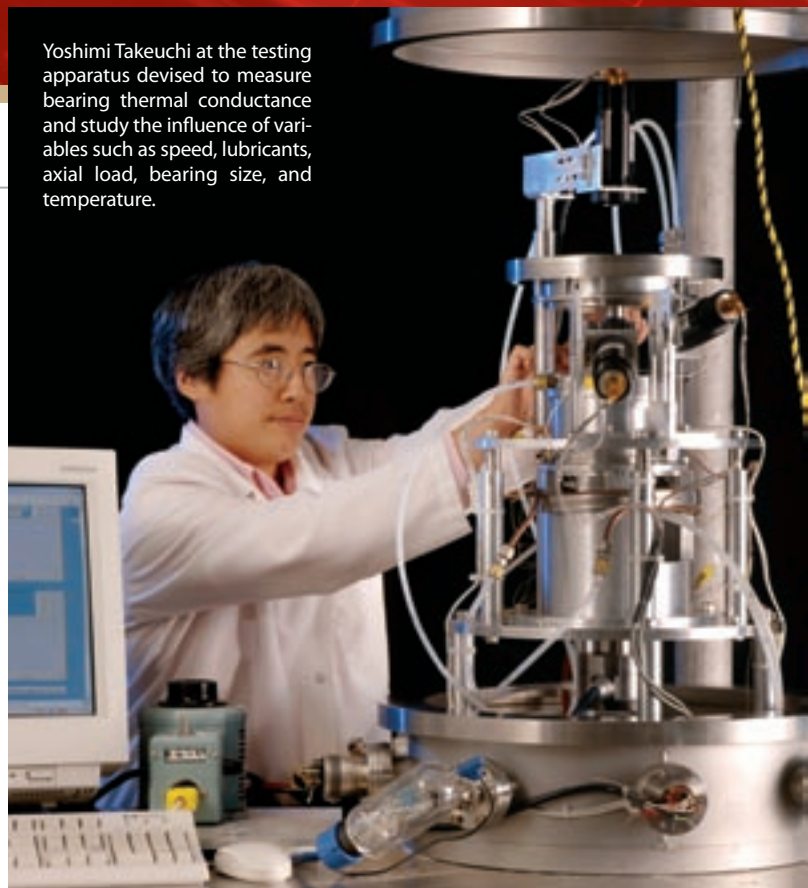
Takeuchi's team developed a testing apparatus in which the outer race of a single ball bearing remains stationary while the inner race rotates at speeds ranging from 0 to 20,000 rpm. The test bearing supports the balance of its outer fixture and a dead weight, creating a constant axial load. A heat lamp and a cooling channel provide temperature control, and pyrometers and thermocouples take measurements for calculating thermal conductance.

The tests yielded some useful information, Takeuchi said, and showed how operational conditions affect thermal conductance differently depending on whether a bearing is static, dynamic, lubricated, or dry.

For example, the thermal conductance of a static dry bearing appeared insensitive to temperature, but increased to the 1/3 power of axial load. For a static and oil-lubricated bearing, thermal conductance did not change with axial load, but did change with temperature. For a dynamic and oil-lubricated bearing, thermal conductance increased linearly with axial load and linearly with temperature; the degree of temperature sensitivity depended on the axial load.

"Of all variables, lubrication and lubricant quantity could potentially dominate the thermal conductance properties of a bearing," Takeuchi said. "The presence of oil, for instance, could increase bearing conductance by an order of magnitude."

Yoshimi Takeuchi at the testing apparatus devised to measure bearing thermal conductance and study the influence of variables such as speed, lubricants, axial load, bearing size, and temperature.



A diagram of the test rig for measuring the thermal conductance of a bearing.

The research could give engineers a new tool in designing mechanisms. Typically, engineers use heritage information from similar bearings when designing a rotational component. Where no heritage information is available, they sometimes rely on a closed-form solution known as the Yovanovich model; however, this model is only applicable to a dry static bearing. "This may be a good approximation for some applications, such as a bearing for a pointing mechanism with solid lubrication," Takeuchi explained. "But our experiments show that with oil or grease lubrication or significant motion, these assumptions no longer hold, and predicted conductance values could be drastically different. Our research gives a thermal analyst an idea of what bearing thermal conductance values would more likely be."

## Contamination Detection and Resistance

Hardware cleanliness is a major issue for spacecraft. For example, polymeric materials, such as conformal coatings, thermal blankets, or the epoxy used in composite structures, contain molecular species that can outgas and collect on sensitive spacecraft hardware, such as optics or solar cells. Identifying and controlling such contaminants can help ensure that space instruments will meet their required service life. In general, however, the space industry suffers from a lack of advanced laboratory tools to detect and examine contamination and techniques to address contamination on the ground or on orbit.

In response to this problem, Aerospace has been conducting research geared toward detecting ultrathin contaminant films and developing space materials that resist contamination. "The goal is to replace standard spacecraft materials with smarter, multifunction materials that not only serve the originally intended purpose, but also impart the ability to reduce contamination exposure and thus protect hardware," explained Randy Villahermosa, lab manager for the Contamination Control Section of the Materials Processing and Evaluation department. Villahermosa's group used surfaced-enhanced Raman scattering (SERS) to characterize the molecular vibrations of ultrathin contaminant films. In Raman scattering, a laser pulse directed at a sample is deflected at a different wavelength based on the vibrational frequency of the sample's constituent elements. This data can be used to identify and characterize contaminants, both in the lab and out in the field. "In essence, a surface that is microrough, with feature sizes on the order of nanometers, will act like an amplifier of the Raman-scattered light," said Villahermosa. "With SERS, we can boost a standard Raman signal by a factor of 1,000,000 or more."

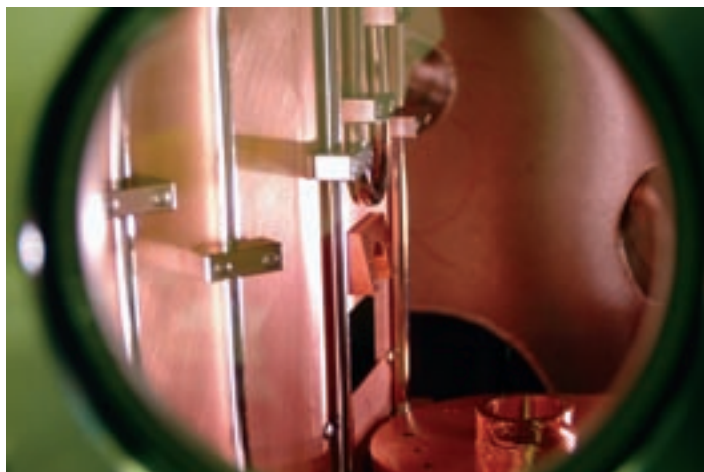
Recent work has involved the detection and characterization of submonolayer films on SERS-active surfaces. The analysis so far has also yielded some curious insights. "For the most part, the vibrational characteristics of the contaminants looked the same whether they were in bulk solution or cast as an ultrathin film," Villahermosa explained. "In essence, the contaminant doesn't really care if the surface is there or not—which is good from the standpoint of understanding how to treat surface effects in our contamination modeling analyses." Still, this finding was somewhat unexpected. "Surface-bound contaminants have been shown in numerous studies to act differently than their bulk counterparts, which makes this result interesting and something worth exploring further," he said.

Raman scattering has been used successfully in other industries, such as semiconductor manufacturing, but the use of SERS to address spacecraft anomalies is rare, if not unique to Aerospace. But based on recent advances, Villahermosa expects to see the technique used much more widely. "Just recently, we had very good success analyzing samples containing hard-particle contamination," he said. "These particles are believed to play a role in reducing the life of certain spacecraft mechanisms." Working with the contractors, Aerospace analyzed the samples via scanning electron microscope and Fourier-transform infrared—the usual techniques for samples of this type. "But it was Raman that gave us the definitive identification," Villahermosa said.

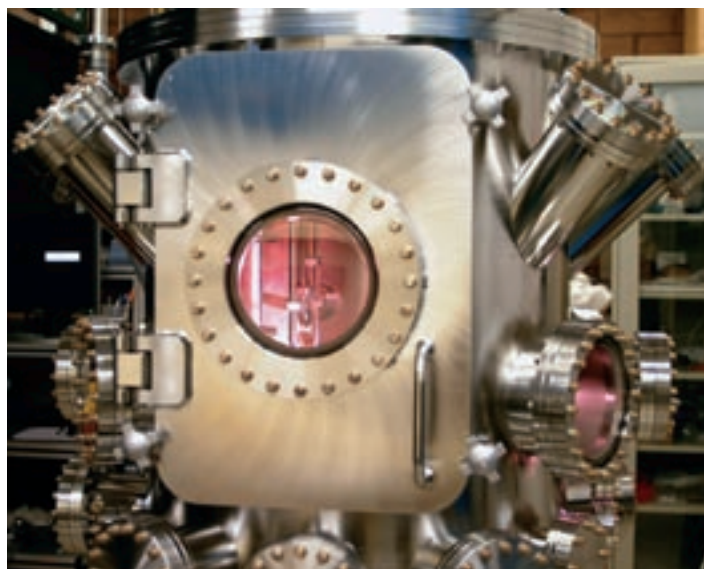
Aerospace has been synthesizing nanofibers of polyaniline, a conducting polymer, using a variety of techniques that are capable of

forming fiber diameters from 100 to 500 nm (about 100 times thinner than a human hair). "Bruce Weiller and his team have developed a new class of highly sensitive chemical sensors using these nanofibers," Villahermosa said. "Weiller's work spawned other research efforts, including one led by Alan Hopkins, who is developing new spacecraft materials that take advantage of the electrical conductivity properties of the nanofibers." In the case of contamination detection, researchers are trying to exploit the chemical mechanisms that give rise to conductivity in the nanofibers so as to make them respond to otherwise inert analytes. "Many outgassed contaminants are fairly benign from a chemistry standpoint, so we need a new way to detect and measure their presence," Villahermosa said. One important goal is to create a sensor that can not only detect certain contaminants, but filter and identify them based on chemical class or structure.

Looking at the bigger picture, Villahermosa one day expects to incorporate contamination sensors directly into spacecraft materials



A look inside the contamination chamber, where surfaced-enhanced Raman scattering is used to characterize the molecular vibrations of contaminant films.



Outside view of the contamination chamber. The use of surfaced-enhanced Raman scattering to address spacecraft anomalies is rare, but highly useful.

and structures. Unlike other on-orbit contamination-control technologies, which typically involve separate hardware, this approach would have little affect mass or installation. Other projects are also in the works to mitigate contamination on orbit, including materials that will absorb contamination before it ever reaches a detector or other sensitive surface.

"I'd like to think that someday, we'll launch spacecraft with multifunction materials that will provide thermal, radiation, and contamination resistance and protection all in one package," Villahermosa said. "Moreover, the materials will be smart because they will sense when the space environment is becoming dangerous and respond accordingly."

## Characterization of Defects in Advanced Solar Cells

Modern solar cells are far more complicated than their early counterparts, containing many more materials, interconnects, and metalization layers. Defects introduced in the chemical-vapor deposition process are believed to contribute to failure mechanisms in multi-junction photovoltaic cells, but no study has attempted to correlate defect centers to cell degradation or to develop a set of failure modes for calculating mean time between failure.

To address this need, Aerospace has developed a set of nondestructive, noncontact techniques to inspect multilayered photovoltaic semiconductors for crystalline defects. The first technique, optical-beam-induced current (OBIC), can be used to identify millimeter-sized areas of high defect concentration in solar cells. The second technique, microwave-detected photo-induced-current transient spectroscopy (MD-PICTS), can then be used to map the concentration of defects in those areas to 1-micron resolution as well as determine their cross section and activation energy.

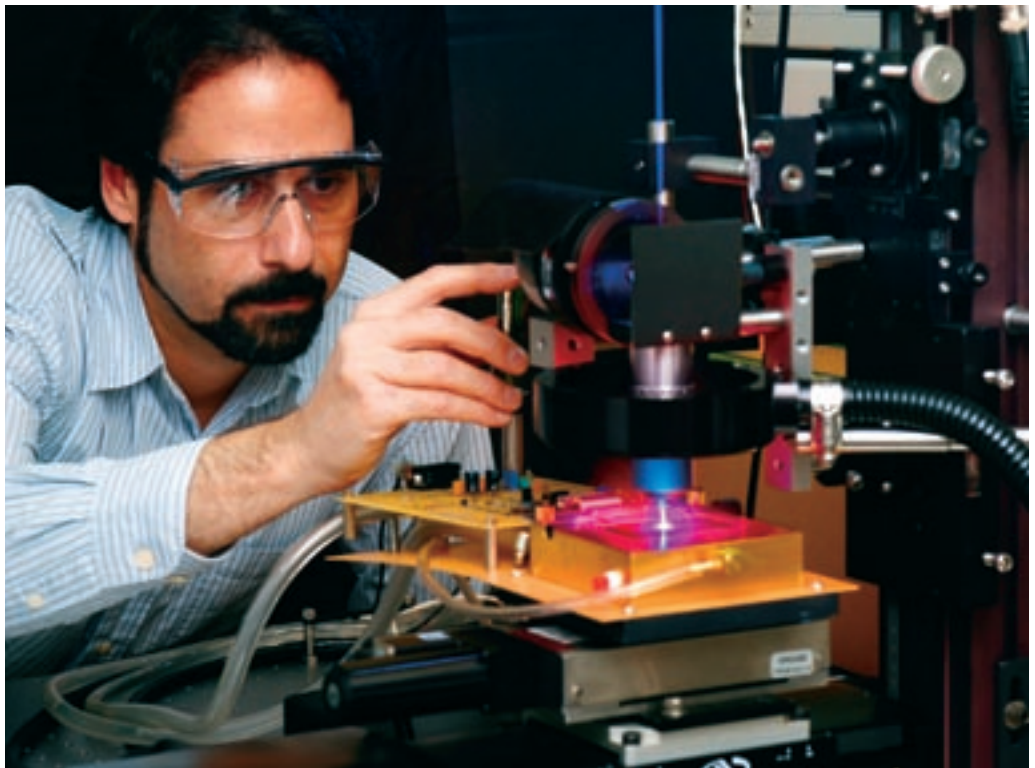
As explained by Brad Reed, engineering specialist in the Electrical and Electronic Systems department, the OBIC system counts the number of 5- to 50-micron features and correlates them to a semiconductor defect frequency per unit area to define the scope of the problem. The system performs a laser scan of a region of interest, mapping both electrically defective features and electrically functional features. Researchers have theorized that some of these electrically functional features, which appear to operate nominally at the beginning of life, may change to become localized shunt sites, or electrical defects, as the cell ages.

MD-PICTS is part of a family of spectroscopic techniques that use transient measurements at various temperatures to determine the relative concentration and activation energy of deep-level defects in semiconductor materials, explained Maribeth Mason of the Microelectronics Technology department. While most of these techniques use capacitance transients to find this information, MD-PICTS uses photoconductivity transients. "Because carriers can be locally excited with a laser beam, this allows measurement of the spatial

distribution of defects as well," Mason said. "The photocurrents can be detected from changes in the quality of a microwave resonant cavity near the sample, making MD-PICTS a contactless and non-destructive defect characterization method."

The greatest challenge, said Mason, has been to design a microwave bridge sensitive enough to detect the small change in photoconductivity induced by laser illumination of the solar cell. The 20-gigahertz bridge is still being optimized, although the MD-PICTS equipment has not yet been fully assembled. "We are in the process of constructing an improved prototype system" in conjunction with specialized software for modeling microwave transmission through small apertures, Mason said.

The researchers have been using the OBIC and MD-PICTS techniques to test solar cells from major manufacturers. Analysis of the data will indicate failure modes and frequencies and support development of the first statistical model to predict solar-array failure. The data will also help refine Aerospace models of solar-cell semiconductors and arrays, particularly in regard to how temperature, applied electrical bias, optical illumination, and defect density affect solar-cell response.



John Nocerino with the OBIC system, developed to help understand the nature of latent defects in solar cells.

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- J. L. Roeder, J. F. Fennell, and Y. Dotan, "Polar Observations of Isotropic Angular Distributions of Energetic Ions During Geomagnetic Storms," 2005 Joint Assembly American Geophysical Union (New Orleans, LA, May 23–27, 2005).
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- R. W. Russell, D. K. Lynch, D. L. Kim, et al., "Very Early 3–13 Micron Spectral Development of V1187 Scorpii (Nova Scorpii 2004 #2)," 205th Meeting of the American Astronomical Society Winter Meeting (San Diego, CA, Jan. 9–13, 2005).
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- P. Schmidt, J. Milstein, and S. Alvarado, "Architectural Assessment of Embedded Systems Using Aspect-Oriented Programming Principles," Eighth IEEE International Symposium on Object-Oriented Real-Time Distributed Computing, ISORC 2005 (May 18–20, 2005), pp. 90–93.
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- C. P. Silva and A. M. Young, "High-Frequency Implementation Approaches and Circuit Issues for PWL Chaotic Oscillators," SIAM Conference on Applications of Dynamical Systems, Minisymposium MS42: Dynamics of Chaotic RF/Microwave Devices (Snowbird, UT, May 22–26, 2005).
- E. J. Simburger et al., "Fabrication and Testing of a PowerSphere Engineering Development Unit," 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference (Austin, TX, Apr. 18–21, 2005), AIAA Paper 2005-1878.
- E. J. Simburger and S. H. Liu, "Distributed Power System for Microsatellites," Proceedings of the 31st IEEE Photovoltaics Specialists Conference (Orlando, FL, Jan. 5, 2005).
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- M. E. Sklar and S. M. Dawson, "Space Nuclear Power Public and Stakeholder Risk Communication," Aerospace Nuclear Science and Technology/Space Nuclear Conference (San Diego, CA, June 5–9, 2005).
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- R. T. Sugiyama, "Mass Properties Control Standard for Space Vehicles," Society of Allied Weight Engineers/64th Annual International Conference on Mass Properties Engineering (Annapolis, MD, May 15–10, 2005).
- D. P. Taylor and H. Helvajian, "Curious Behavior in Pulsed UV Laser Irradiation of an Al(III) Surface," Brandt-Ritchie Workshop 2005, 25th on Penetration Phenomena (Gainesville, FL, Apr. 10–13, 2005).
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- C. C. Venturini, R. Rudy, D. K. Lynch, S. Mazuk, et al., "0.47–2.5 Micron Reflectance Spectroscopy of Pluto" 205th American Astronomical Society Winter Meeting (San Diego, CA, Jan. 9–13, 2005).
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- R. Walterscheid, G. Schubert, and M. P. Hickey, "Gravity Wave Heating and Cooling in Saturn's Thermosphere," 2005 Joint Assembly American Geophysical Union (New Orleans, LA, May 23–27, 2005).
- H. Wang and G. H. Iyanu, "Formation of Ultracold Ground-State RbCs Molecules via Photoassociated 11P State," American Physical Society (APS) March Meeting, *Bulletin of the American Physical Society* (Los Angeles, CA, Mar. 21–25, 2005).
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- C-P. Wang, L. R. Lyons, M. W. Chen, et al., "Modeling the Transition of the Inner Plasma Sheet from Weak to Enhanced Convection," *Journal of Geophysical Research*, Vol. 109, No. A12 (Dec. 1, 2004).
- B. H. Weiller, S. Virji, J. Huang, et al., "Polyaniline Nanofiber Composites with Metal Salts: Chemical Sensors for Hydrogen Sulfide," *Nano Letters*, Vol. 4, No. 3, pp. 491–496 (2004).
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- T. S. Yeoh, "Open-Source 3-D Modeling and Rendering: An Interactive Tutorial," IEEE Coastal LA Section General Meeting (Long Beach, CA, May 17, 2005).
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- A. H. Zimmerman, "Life Testing of Nickel Hydrogen Batteries at 60%—Depth of Discharge for Low Earth Orbit Satellite Applications," 2004 Space Power Workshop (Manhattan Beach, CA, Apr. 19–22, 2004).
- A. H. Zimmerman and M. V. Quinzio, "Demonstration of Extended Nickel Hydrogen Battery Life at High Depth of Discharge Using an Optimized Charge Control System," 2004 Space Power Workshop (Manhattan Beach, CA, Apr. 19–22, 2004).

## Patents

- L. Gurevich, "Adjustable Multipoint Docking System," U.S. Patent No. 6,840,481, Jan. 2005.

An adjustable multipoint docking mechanism can be used by a space vehicle to grasp orbiting satellites by the adapter rings that originally joined them to their launch vehicles. The capture vehicle would include a circular mounting plate with a number of docking mechanisms, each comprising a set of radially adjustable jaws mounted on sliding blocks that are moved by ball screws to the required position. After the jaws have grasped the flanged adapter ring, compression pads secure it against the rescue vehicle. Because it can adjust to accommodate rings of different diameters and positions, the mechanism can be used to capture a variety of target vehicles, including those not originally designed for docking. Typical missions would include boosting a satellite from an incorrect orbit, removing a dead satellite from a valuable orbital slot, or rescuing personnel from a deorbiting space station.

- P. A. Herman, "Method of Controlling Pointing for a Flexible Structure," U.S. Patent No. 6,845,951, Jan. 2005.

Lighter satellites can be cheaper to deploy than their heavier counterparts, but tend to be more flexible and therefore harder to control. This technique, known as "Universal Bang-Bang Control," makes it easier to point flexible satellites from one target to another accurately and quickly. A command generator is configured to generate a scaled "bang-bang" input based on system capabilities and input magnitude. The input is first directed through low-pass filters that attenuate the energy spectra that would excite the undesirable modes associated with structural flexibility of the system. Pole locations are derived directly from the lowest frequency mode present in the structural dynamics. After filtering, the bang-bang command is used for the reference path and the feedforward path.

- E. J. Simburger, H. Helvajian, "Inflatable Ablation Gas Cell Structure System," U.S. Patent No. 6,851,259, Feb. 2005.

This patent describes a method and system for sequentially inflating the cells in an inflatable structure by means of electronic control and power lines integrated into the walls of each cell. A microelectromechanical system (MEMS) capable of generating inflation gas via laser ablation is placed inside each cell. The MEMS contains all of the associated electronics for controlling the release of gas in small increments and determining the resultant pressure change in the inflatable structure. The control electronics can execute a preprogrammed inflation sequence and communicate status along with any measured parameters to a central processor. The MEMS devices would operate using direct current and control lines supplied from a spacecraft bus.

- K. W. Baker, "Capillary Two-Phase Thermodynamic Power Conversion Cycle System," U.S. Patent No. 6,857,269, Feb. 2005.

A two-phase thermodynamic system converts heat energy into mechanical energy that can be used to power spacecraft electronics. A capillary device such as a heat loop pipe or a capillary pumped loop draws liquid from a reservoir. Heat directed toward the capillary turns the liquid into a high-pressure vapor that can be used to drive a turbine, generating electrical power. The vapor then passes through a condenser, which transfers the waste heat out into the environment. The cooled vapor once again becomes liquid and can be conducted back to the capillary to repeat the process. In space, the system can use direct heat from the sun or a radioisotope or waste heat from a power system or spacecraft electronics. The use of a capillary solves the problem of two-phase fluid management in microgravity; evaporation drives the capillary action, effectively creating a passive pump.

- J. V. Osborn, "Microelectromechanical system Optical Sensor Providing Bit Image Data of a Viewed Image," U.S. Patent No. 6,861,633, Mar. 2005.

This integrated microelectromechanical system (MEMS) sun sensor can be used for attitude determination on spinning spacecraft. The device

includes a microlens, a folded optical element, and an active pixel sensor array. Using the motion of the spinning spacecraft, the sensor scans the sky to sweep out a two-dimensional intensity bit map image that is divided into pixels in azimuth and elevation over the sensor field-of-view. A data processor can use information from the bit map to accurately interpolate the position of the sun. The sensor can be integrated as an ultralow-power semiconductor device in a radiation-tolerant hermetic package. The imaging pixels can be formed in the integrated readout circuit via silicon micromachining techniques, and the folded optics can be combined with the analog and digital readout circuitry in the substrate. An integrated microcontroller provides the data processing and control. The MEMS sun sensor features low power usage, small size, high performance, and compatibility with planar semiconductor fabrication techniques.

- G. L. Lui, K. Tsai, "Data-aided Symbol Timing System for Precoded Continuous Phase Modulated Signals," U.S. Patent No. 6,862,324, Mar. 2005.

Developed for digital communication systems, these data-aided synchronizers can track the symbol timing or carrier phase of a continuous phase modulation (CPM) signal. The synchronizers can be simply implemented to provide reliable data demodulation of noisy signals having dynamic carrier phase and symbol timing errors, as found in CPM systems employing Gaussian minimum shift keying (GMSK) signals with small bandwidth-time-product values. The symbol-time tracking synchronizer includes a data-aided discriminator that extracts the timing error of the received CPM signal from the principal Laurent amplitude modulation component by an early and late gating operation, followed by a multiplication of the data decision to remove the data modulation. The carrier-phase tracking synchronizer includes a data-aided discriminator that extracts the phase error of the received CPM signal via cross-correlation with the data decision produced by a serial data demodulator. In either case, the error signal is then tracked by a second-order digital loop operating at the symbol rate.

- I. Bekey, "Adaptive Reflector Antenna and Method for Implementing the Same," U.S. Patent No. 6,888,515, May 2005.

An adaptive reflector antenna includes an adaptive reflector and a mechanism for simultaneously affecting its feed rotation and shape so as to maintain performance with large scan angles. The system overcomes the limitations of current space-based radar and communications system designs, which are generally limited by the power-aperture product for transmission and by the antenna aperture for reception. The wide scan angle, light weight, essentially unlimited size, and simple and light feed can greatly simplify associated electronics hardware and information processing systems. Thus, the design can decrease total system weight and cost and increase system performance. Fine sidelobe control through large scan angles helps achieve the signal-to-noise ratio and clutter rejection needed for demanding applications, such as identifying and tracking moving targets near the ground.

- W. H. Ailor et al., "Spacecraft Reentry Breakup Recorder," U.S. Patent No. 6,895,314, May 2005.

This invention relates to onboard equipment used to monitor the breakup of a spacecraft during reentry through the atmosphere. One or more small recorders equipped with a sensor suite would be disposed within a spacecraft to collect and record data before and during breakup. A communication system would broadcast the data before impact with Earth. An internal GPS receiver would provide data of the reentry and breakup positions. Such collected data will aid analysis and modeling of critical events leading up to breakup—when and where breakup occurs, how a spacecraft disintegrates during breakup, and possible trajectories of breakup debris. The data may also be used to prevent damage to property or injury to people.

## Patents (continued)

- R. L. Wong, J. H. Q. Ly, P. R. Dahl, A. C. Or, "Spacecraft Off-Gimbal IRU Precision Payload Pointing and Disturbance Rejection System," U.S. Patent No. 6,897,821, May 2005.

For inertially stabilized spaceborne gimballed pointing systems, a common system architecture uses relative angle sensors (resolvers, inductosyns, encoders, differential proximeters) as feedback control sensors and an inertial reference unit (IRU or gyroscopes) as the base motion compensation sensor. The disturbance rejection performance of this system configuration (off-gimbal IRU) is generally degraded with respect to an on-gimbal IRU design. Due to weight (inertia), size, thermal loading, and power considerations, an on-gimbal design may be too costly for space-based systems. A methodology to improve the disturbance rejection performance of the off-gimbal design has been developed. The methodology involves the development of an easily implementable (digital or analog) filter which bandwidth limits the outputs of the feedback and base-motion sensors. By bandwidth shaping of the sensor response, the resulting off-gimbal disturbance rejection performance can be tuned to better than that of the on-gimbal performance. This can be achieved without the need for enhanced performance requirements on the sensors.

- G.-T. Tseng et al., "Method and System Using a GPS-Based Phased-Array Scheme for Three-Axis Attitude Determination," U.S. Patent No. 6,906,664, June 2005.

A sensor system enables three-axis attitude determination by means of null-cone patterns and line-of-sight vectors to two or more GPS satellites. The system includes an antenna, a GPS receiver, a processor, and a digital input/output controller. Attitude determination is achieved by exploiting electronic scans of antenna pattern nulls using closely spaced antennas. An active planar phased-array scheme is employed to electronically slew two pattern nulls created by four antennas to obtain three-axis attitude information. In addition to attitude data, navigation information could also be made available from the GPS receiver. The sensor system can be made as a small stand-alone unit or integrated into mobile systems for three-axis/spin-axis/heading/leveling determination and navigation. Multiple configurations are possible using varying numbers of antenna patches, GPS receivers, etc.

- D. A. Kozlowski, J. P. Hurrell, "Tunable Optical Local Oscillator," U.S. Patent No. 6,907,052, June 2005.

A tunable optical local oscillator uses an electro-optic Mach-Zehnder modulator driven by an RF local oscillator to provide an accurate, rapidly tunable signal for heterodyne detection. The signal is generated by passing an unmodulated optical carrier through the Mach-Zehnder modulator, which is voltage-biased and tuned by an RF generator to provide a suppressed carrier double sideband signal. The oscillator suppresses unwanted optical signals, up to 50 dB, throughout the bandwidth of the Mach-Zehnder modulator. This results in high spectral purity of the oscillator waveform. The oscillator can be used for spectral analysis of incoming signals, either as part of a communication receiver or as a spectrum analyzer. It can also be used in transmitters, such as in optical radar systems and optical communication systems. The device can provide chirped signals for radar and multiple carrier signals for frequency-hopping in densely populated communication channels. It can be configured using tunable lasers to provide differing optical carriers.

- A. H. Quintero et al., "Surveillance Monitoring and Automated Reporting Method for Detecting Data Changes," U.S. Patent No. 6,910,071, June 2005.

An automated monitoring and reporting method is used for detecting changes in data sources accessible via network. Based on user-defined search criteria, the method can look for changed data on a regular schedule and notify the user when changes are found. The method extracts content from specified data sources and updates a master database, then tracks changes in data constrained by the search parameters. The user can be notified of changes via graphical interface, email, pager, or personal

data assistant. As a stand-alone process executed on a networked computer, the method monitors other networked computers. For Web-based services, users may be given an account that allows them to specify a list of information sources, such as Web pages identified by the URL, and a set of keywords or other search criteria.

- R. K. Douglas, A. S. Abbott, "Spread Spectrum Receiver Kalman Filter Residual Estimator Method," U.S. Patent No. 6,914,931, July 2005.

This processing method improves interference robustness and navigation accuracy in GPS and other spread-spectrum communication systems. A Kalman filter with a Riccati-matrix computation process tracks code and carrier phases. Early and late in-phase and quadrature inputs to the Kalman filter are used to estimate carrier-phase tracking error and rate and acceleration, as well as code-phase tracking error and signal amplitude. Because these inputs do not need to be processed in real time, more advanced algorithms in low signal-to-noise conditions can be applied. The filter state is a tracking residual applicable to navigation correction in ultratight GPS coupling with inertial measurement units. In this case, the residual estimation drives the code and carrier replica oscillators in tightly coupled correlation loops, providing adjusted early and late code replicas and adjusted demodulation carriers for closed-loop code and carrier tracking. This tracking can also be applied to a weak-lock navigation system also using the tracking residual estimation to the code and carrier replica oscillators.

- K. W. Baker, "Superheater Capillary Two-Phase Thermodynamic Power Conversion Cycle System," U.S. Patent No. 6,918,254, July 2005.

A new heat engine concept operates on a two-phase thermodynamic power conversion cycle. This engine would be useful as part of a space dynamic power system. It exploits the spaceflight-proven technique of using a porous capillary structure to separate liquid from vapor through heat addition. This engine is different from the existing Rankine because liquid and vapor are at different pressures and are separated during the phase change heat addition process (in the Rankine cycle, liquid and vapor are at the same pressure and mixed during phase change heat addition). It is advantageous to apply this engine to space applications because management of the two-phase working fluid in microgravity can be accomplished using proven loop heat pipe and capillary pumped loop technology. The power system is well suited for space applications using a radioisotope, active nuclear, or solar heat source. It can also use waste heat from various sources such as spacecraft electronics for input energy. The system offers relatively high thermal efficiency while operating at low maximum cycle temperatures.

- H. Helvajian, P. D. Fuqua, W. W. Hansen, "Ultraviolet Method of Embedding Structures in Photocerams," U.S. Patent No. 6,932,933, Aug. 2005.

A direct laser processing method creates integral 3-D structures in photostructurable glass-ceramic materials (photocerams). It also enables the patterned undercutting of unexposed structures, resulting in the fabrication of suspended or supported microstructures. The process involves a computer-controlled micromachining station with a pulsed UV laser that can be moved relative to a workpiece holding the photoceram. A critical dose of UV light selectively exposes embedded volumes of the material for subsequent selective etching. Laser depth is determined by wavelength and focusing optics. As the laser wavelength is tuned to the weak end of the UV absorption band of the photoceram, the absorption decreases in the collateral volume and the penetration depth increases into the focal volume, causing material crystallization. Thus, structures can be created that will retain the shape of the laser beam. For example, a collimated beam can produce a cylindrical hole, while a focused beam can produce a conic section or hyperboloid structure. The process is amenable to rapid batch fabrication.

## A Successful Strategy for Satellite Development and Testing

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**Steve Pavlica** was Principal Engineer in the National Systems Group until his untimely death from cancer in May. He managed a variety of the NRO Director's special projects, including the joint NRO/SMC Mission Assurance Improvement Task Force, and served as colead for the NRO Testing Study. From 1996 to 2004, he served as Spacecraft Systems Director for Directorate H. He joined Aerospace in 1995 as a Project Engineer after a career in the U.S. Army. In addition to winning the Aerospace President's Award in 2004, he received an NRO Medal for Distinguished Service and several NRO Director Team Awards. A graduate of the U.S. Military Academy, he received his M.S. in electrical engineering from the University of Virginia.



## Environmental Testing

**Erwin Perl**, Director of the Environmental Test and Ordnance Department, Structural Mechanics Subdivision, is responsible for management and technical guidance in all aspects of testing environments for vibration, acoustics, and shock for satellite and launch vehicle systems, subsystems, and components, as well as explosive ordnance behavior and device actuations. He coordinated the development of MIL-STD-1540E and is its principal editor. He is also the cochair of the Aerospace Testing Seminar and sponsor of the Spacecraft and Launch Vehicles Environments Workshop. He joined Aerospace in 1977 to work in the Structural Dynamics Department and subsequently managed the Launch Vehicle Dynamics Section. He provided direct technical support to numerous launch vehicle and spacecraft programs. In 2003, he received the NRO Director's Team Award for contributions to a study on test practices on national programs before and after acquisition reform. He has a Ph.D. in mechanical engineering from Northeastern University ([erwin.perl@aero.org](mailto:erwin.perl@aero.org)).



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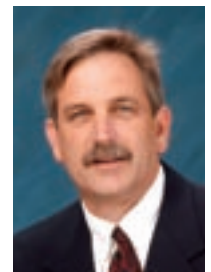


**John Welch**, Associate Director of the Spacecraft Thermal Department, provides thermal control expertise to spacecraft program offices. He wrote the thermal testing chapters in the *Satellite Thermal Control Handbook* and the *Spacecraft Thermal Control Handbook* (both published by The Aerospace Press) and helped specify thermal testing requirements for MIL-STD-1540E. He has taught courses on thermal control subsystem requirements and thermal testing through the Aerospace Institute, AIAA, the Aerospace Testing Seminar, and UCLA. He joined Aerospace in 1987 after receiving an M.S. in mechanical engineering from the University of Washington ([john.w.welch@aero.org](mailto:john.w.welch@aero.org)).



## Nanoscale 3-D Imaging

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## Thermal Cycling for Solar Panels

**Robert W. Francis**, Distinguished Engineer in the Electronics Engineering Subdivision, provides power sources and systems technology and evaluation support to many national security space programs. He has also supported a number of NASA and commercial programs and has provided systems engineering support for various solar array designs and power systems. He joined Aerospace in 1983 to work in the Power Sources and Technology Section of the Electronics and Optics Division. He received The Aerospace Corporation's President's Award in 2000 for discovering and fixing a serious failure mechanism in a new solar cell array design (robert.w.francis@aero.org).



**Charles Sve**, Senior Scientist, Propulsion Sciences and Experimental Mechanics Department, Space Materials Laboratory, joined Aerospace in 1968. He has been involved in the development of thermal cyclers for solar cells for 20 years in support of more than 20 programs and received The Aerospace Corporation's President's Award in 2000. He holds an M.S. in civil engineering from MIT and a Ph.D. in theoretical and applied mechanics from Northwestern University (charles.sve@aero.org).



**Timothy S. Wall** is an Associate Member of the Technical Staff in the Experimental Mechanics Section of the Space Materials Laboratory. Since joining Aerospace in 1982, he has been primarily engaged in developing fully automated facilities tailored to long-term life testing of flight hardware. As a coinventor of the ultrafast thermal cycler, he designed its electronics-control and data-acquisition systems, wrote the control code, and serves as the primary operator. He holds A.S. degrees in electrical engineering and math from El Camino College and is completing a B.S. in computer science at California State University, Long Beach (timothy.s.wall@aero.org).



## Electric Thruster Testing

**Edward Beiting**, Senior Scientist in the Propulsion Sciences and Experimental Mechanics Department, develops optical diagnostics to study atmospheric phenomena, reactive flows, and plasmas. During the past decade, his work in the field of electric propulsion has included fundamental studies of rarefied flows in resistojets using coherent anti-Stokes Raman spectroscopy; an investigation of the effects of certain propellant contaminants on resistojets and arc jets; the creation of diagnostic techniques to investigate grid erosion in ion engines; and the invention of a sensitive impulse thrust stand for micropropulsion. He is now using optical techniques to measure plasma properties inside Hall-effect thrusters and is using an EMC facility he developed to characterize electromagnetic



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**Kevin Diamant** has been a Senior Member of the Technical Staff in the Propulsion Sciences and Experimental Mechanics Department since 2000. He has 15 years of experience working in electric propulsion, including research and development in magnetoplasmadynamic thrusters, ion thrusters, Hall-effect thrusters, and microwave electrothermal thrusters as well as microwave hollow cathodes. He received his Ph.D. in mechanical engineering in 1996 from Princeton University (kevin.d.diamant@aero.org).



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## Software Testing

**Myron Hecht**, Senior Engineering Specialist, works in the areas of systems engineering, software architecture, reliability, and system safety. He supports the next generation Global Positioning System and other national security space programs and has previously worked in the areas of nuclear energy and air traffic control. Research interests include software dependability, fault tolerance, and products liability. He is an author of more than 75 peer-reviewed publications and has served on standards committees of the IEEE, AIAA, and American Nuclear Society. He holds an M.S. in engineering, an M.B.A., and a J.D., all from UCLA (myron.j.hecht@aero.org).



**Douglas J. Buettner**, Engineering Specialist, provides software and test engineering expertise to various space systems under development at the Los Angeles Air Force Base. He conceived and leads an Aerospace initiative to accumulate software life-cycle process data from software-intensive space system acquisitions and correlate these processes with deployed failure data. He has held both quality-assurance management and software test lead positions in the software industry. He is working on a Ph.D. in astronautics at the University Of Southern California and holds an M.S. in physics from Oregon State University (douglas.j.buettner@aero.org).



## Ground Systems Testing

**Norman L. Strang**, Director of the Ground Systems Development and Operations Department, is responsible for engineering management of the Ground Systems Engineering Office and the Ground Systems Support Office. Since joining Aerospace in 1977, he has worked for many different programs and organizations, including the shuttle, Titan, Atlas, EELV, NRO, SBIRD, and civil and commercial projects. Prior to joining Aerospace, he worked for McDonnell Douglas Astronautics as a propulsion engineer. He earned an M.S. in engineering management from the University of Southern California (norman.l.strang@aero.org).



## The Aerospace Testing Seminar

During the 1960s, national security space programs suffered repeated failures, with some programs having more than others. The disparity among different programs prompted the Air Force to institute a critical examination of satellite design, development, and manufacturing processes. The goal was to identify improvements that could reduce the orbital failure rate of Air Force satellites.

The study revealed a wide diversity of philosophies, methods, and requirements. Each program developed its own test protocols based upon the experience of the contractor, Aerospace, and Air Force personnel working on the project. In some cases, the absence of a centralized "lessons learned" feedback mechanism resulted in the same failures and failure modes repeated on different programs. Aerospace began to document failures and the associated lessons learned in an effort to avoid repetition of failures. One clear lesson that emerged was the importance of perceptive testing, applied in a consistent and reproducible manner.

The Air Force asked Aerospace to conduct a forum for discussing test practices across the industry. The meeting, the first Aerospace Testing Seminar, took place in Palo Alto, California, in 1973 and was supported by an advisory board composed of Air Force and Aerospace personnel. In hindsight, the striking feature of this event was the level of disclosure about design, testing, and manufacturing processes among organizations that were essentially competitors.

The testing practices used by the various contractors in attendance were considered, and a first step was taken toward establishing a standard set of test requirements for use in the acquisition of Air Force space systems. A testing document was selected as a baseline for the development of a comprehensive environmental test standard. Another outcome of this symposium was a request that Aerospace develop a military standard to establish a testing baseline for all Air Force space systems. The result of that effort was MIL-STD-1540 "Test Requirements for Space Vehicles," issued in 1974. The second Aerospace Testing Seminar was held in 1975 to present details of the newly developed military standard and to continue the dialog fostered by the first seminar.

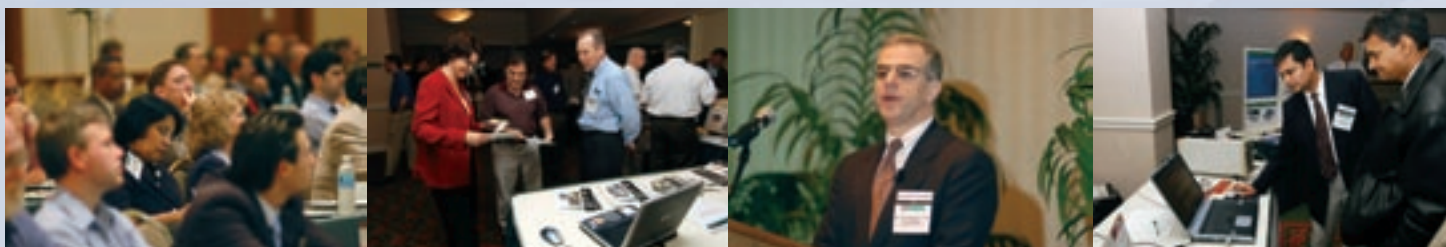
Since that time, the Aerospace Testing Seminar has become a regular event held every 18 months. The planning board has grown to 50 members, representing a wide spectrum of the aerospace industry, including major contractors, Air Force, NASA, JPL, Naval Research Laboratories, Sandia National Laboratories, and The Aerospace Corporation. The European Space Agency and several European contractors are also



represented. The 22nd seminar took place in March 2005, jointly sponsored by Aerospace, the Air Force Space and Missile Systems Center, and the Institute of Environmental Sciences and Technology. The only event of its kind in the United States, the seminar now attracts participants from all across the world.

The 22nd seminar provided four days of conferences under the general theme of "testing relevance into the next generation." A review of the session and paper titles provides a quick snapshot of the most pressing issues facing the aerospace testing field. The event included a full day of tutorials in areas such as force-limited vibration testing, satellite structural testing, thermal testing, and high-frequency structural dynamics. Many aerospace organizations, including Air Force program offices, rely on these tutorials as a means of expanding the education of their staff on testing practices. Conference sessions were divided into six general topics. A session on testing philosophies and standards discussed vibroacoustic test specifications, a new verification standard, and an environmental test thoroughness index. A session on testing strategies and management included presentations on the use of thermal vacuum chambers and testing of an advanced synthetic-aperture radar satellite. New thermal cyclers designs, test fixtures in arc-jet facilities, and options for replacing base shake tests were among the topics covered in a session on innovations in test facilities and equipment. The test perceptiveness and effectiveness presentations covered lessons learned from EMC testing of the Mars Rovers, mechanical qualification tests, and suitable satellite complexity indicators for evaluating flight failures. A session on instrumentation, data acquisition, and evaluation considered topics ranging from a comparison of pyroshock test-prediction methods to videogrammetry based on microcameras to techniques for deriving a motor current drive waveform. The modeling, analysis, and simulation session explored analytical impact models and experimental test validation, the use of air bearing simulator for attitude control systems, and static qualification logic for launch vehicle structures.

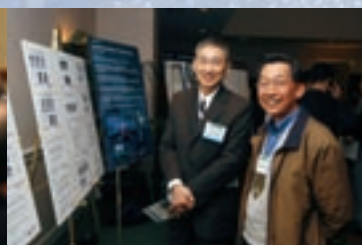
Papers presented by Aerospace researchers covered topics such as burst testing of graphite-epoxy composite tubes, attenuation of transient vibrations using a tuned vibration absorber, application of new and



revised national security space development test standards, evaluating the effect of protoqualification acoustic test duration on mission reliability, development of an advanced environmental test thoroughness index, and improved vibroacoustic test specification and practice.

In an interesting replay of history, the Air Force recently asked Aerospace to help develop a series of updated environmental test standards. In response, Aerospace published a Technical Operating Report that will soon be released as MIL-STD-1540E—the latest version of the standard that evolved from the first testing seminar 30 years ago. In fact, Aerospace researchers at the 22nd seminar delivered papers discussing the vibration, acoustics, shock, thermal, and electromagnetic compatibility requirements in MIL-STD-1540E. And again, members of the planning board reviewed the draft MIL-STD and provided extensive comments to help make this baseline industry document more relevant in the drive to make future space systems more reliable than ever.

The 23rd Aerospace Testing Seminar will take place October 10–12, 2006. The theme will be “New Dimensions.” For details, visit <http://www.aero.org/conferences/ats/>.



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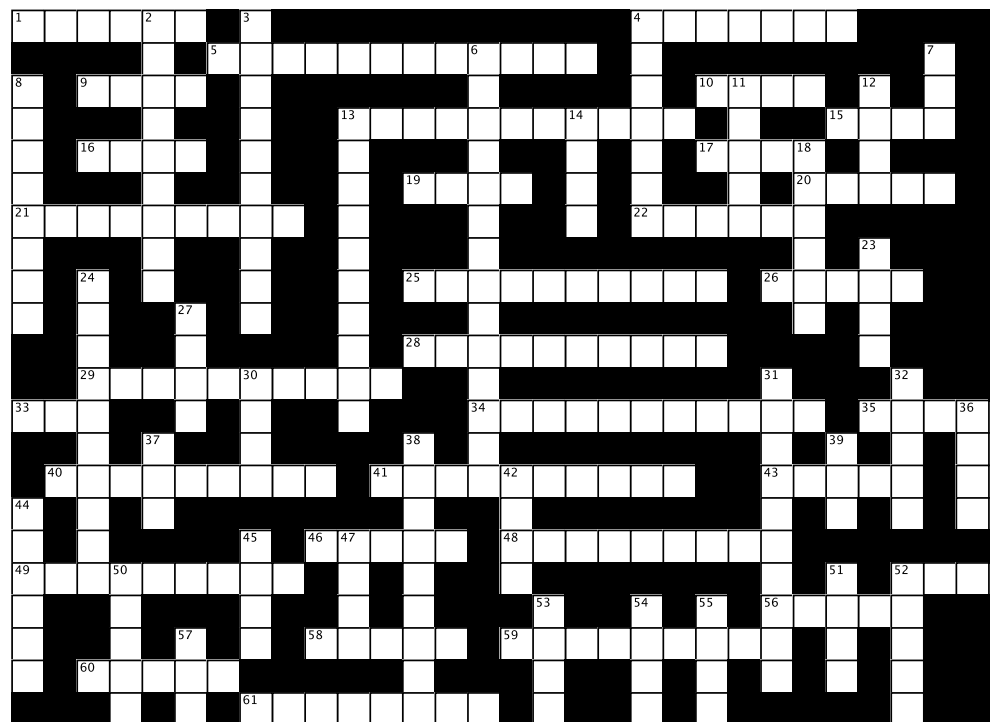
## The Crosslink Crossword

### Across

1. Low-level system?
4. Irregularity
5. Proof
9. Container for liquid oxygen
10. It may have millions of transistors
13. Big picture
15. Software glitches
16. Chance of mishap
17. Concern for space shuttle
19. Fluid mover
20. First astronaut's vehicle
21. The buzz
22. Machine with good vibe
25. Untested software package?
26. Don't, if it ain't broke
28. Looking at little things
29. It's taken for granted
33. Propulsion type on AEHF comsats
34. Getting it together
35. Nothingness
40. Region near speed of sound
41. Realistic, in spacecraft testing
43. Thruster exhaust shape
46. Circuit problem, briefly
48. Ultimate reason
49. Stand-in
52. High-temp
56. Picture
58. Destroy (a program, as a test would)
59. Piece of the action
60. Kind of cell
61. Sound-related

### Down

2. Ion beam resolution level
3. Simple electric thruster
4. Comsat in thruster test
6. Blowing hot and cold



7. Shuttle abbrev.
8. Return to normal
11. Intense impulse
12. Air bubbles displace it
13. System aping a system
14. Give off, as radiation
18. Allowance for error
23. Loads fuel to vehicle
24. People factor
27. A fluid state
30. Way to go
31. Intricacy
32. Volumetric unit
36. Kind of matter
37. End-to-\_\_\_ testing
38. Newest kind of thermal cycling
39. Dry \_\_\_
42. Acoustic source or band instrument
44. Blueprint
45. Thing being tested
47. Has 75-micron diameter
50. Thoroughness
51. Earth's neighbor
52. Frequency unit
53. Expense
54. Join to a surface
55. It has 4 main stable isotopes
57. Hydrogen or nitrogen, for example