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SANDIA TECHNOLOGY

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Developing New Approaches to Manufacturing and Failure Analysis

ALSO:

New Approach to Process Control Revolutionizes Flame Spraying

Integrated Circuits Go Global

The LENS™ Success Story

Sandia National Laboratories

A Department of Energy National Laboratory

The American flag is raised to half-staff in front of Sandia National Laboratories' main administration building on Kirtland Air Force Base in Albuquerque in honor of those who lost their lives in the September 11 terrorist attacks. Silhouetted is Sandia security policy officer Buster Dial.

ON THE COVER:
Richard Neiser, manager of Sandia's Thermal Spray Research Lab, studies the molten high-velocity particles in a flame spray jet.
Photo by Randy J. Montoya

Sandia Technology is a quarterly journal published by Sandia National Laboratories. Sandia is a multiprogram engineering and science laboratory operated by Sandia Corporation, a Lockheed Martin company, for the Department of Energy. With main facilities in Albuquerque, New Mexico, and Livermore, California, Sandia has broad-based research and development responsibilities for nuclear weapons, arms control, energy, the environment, economic competitiveness, and other areas of importance to the needs of the nation. The Laboratories' principal mission is to support national defense policies, by ensuring that the nuclear weapon stockpile meets the highest standards of safety, reliability, security, use control, and military performance. For more information on Sandia, see our Web site at *http://www.sandia.gov.*

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FROM THE *Editor*

Dear Readers:

Sandia National Laboratories prides itself on being an engineering laboratory. Sandia scientists and engineers research, design, and develop nearly 97 percent of the 6,500 components that go into a modern nuclear weapon. That work results in many spin-off technologies that help industry and benefit Americans.

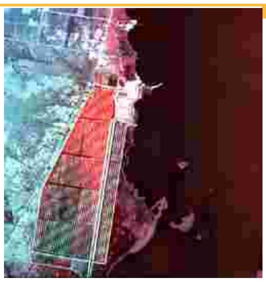
What is sometimes overlooked is Sandia's growing expertise in the manufacture of highly complex, precision components and its complementary work in failure analysis. This issue of *Sandia Technology* focuses on those capabilities and their importance to the nation's weapons complex.

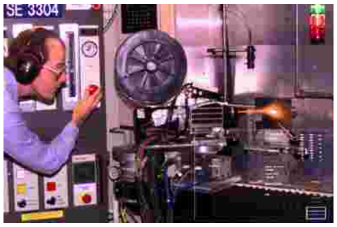
For example, Sandia's Microelectronics Development Laboratory has been designated as a supplier of integrated circuits for such strategic defense applications as the Trident missile and B-61 bomb. Sandia also is the primary supplier for the neutron tubes used in Trident missiles and other warheads. That work has driven Sandia researchers to make great advances in brazing science and technology.

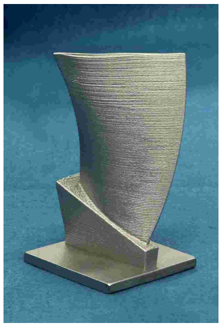
Sandia also has developed new approaches for thermally sprayed metal or ceramic coating that can greatly improve a component's performance, and a revolutionary process called laser-engineered net shaping—a rapid-prototyping system that is small enough to set up in a field location, yet capable of producing complex, one-of-a-kind components.

This issue contains information on these technologies and much more.

Chris Miller
Editor







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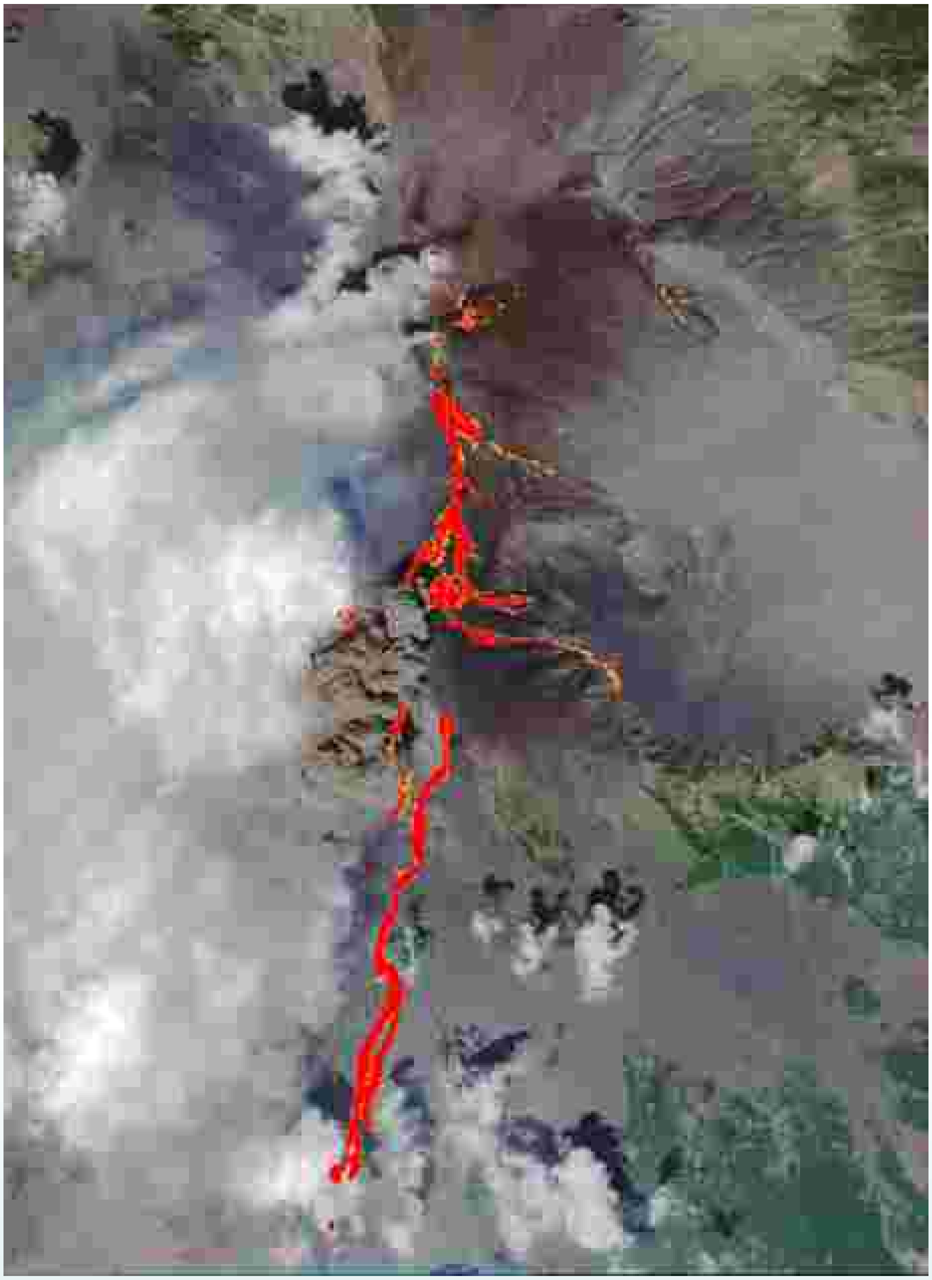
INSIGHTS

Custom silicon integrated circuits drive a sophisticated imaging system

When Sandia launched its multispectral thermal imager (MTI) satellite into polar orbit in March 2000, researchers gained the capability to record light and heat patterns on Earth that are invisible to the human eye. Since then, the satellite's imaging system has conveyed information on agriculture, climatic and ocean temperature, and topographic features.

MTI liftoff on March 12, 2000, aboard an Orbital Sciences Corporation Taurus rocket.

The data have applications in many branches of scientific research and technological development, including nonproliferation treaty monitoring systems, military operations, hazardous waste site characterization and cleanup, environmental and climate research, resource exploration, and crop health and yield assessments.



MTI infrared image of Mount Etna, Sicily, showing hot lava in red.

The radiation-hardened PTM ASIC was one of the key components that Sandia Microelectronics Development Laboratory designed, fabricated, tested and qualified.

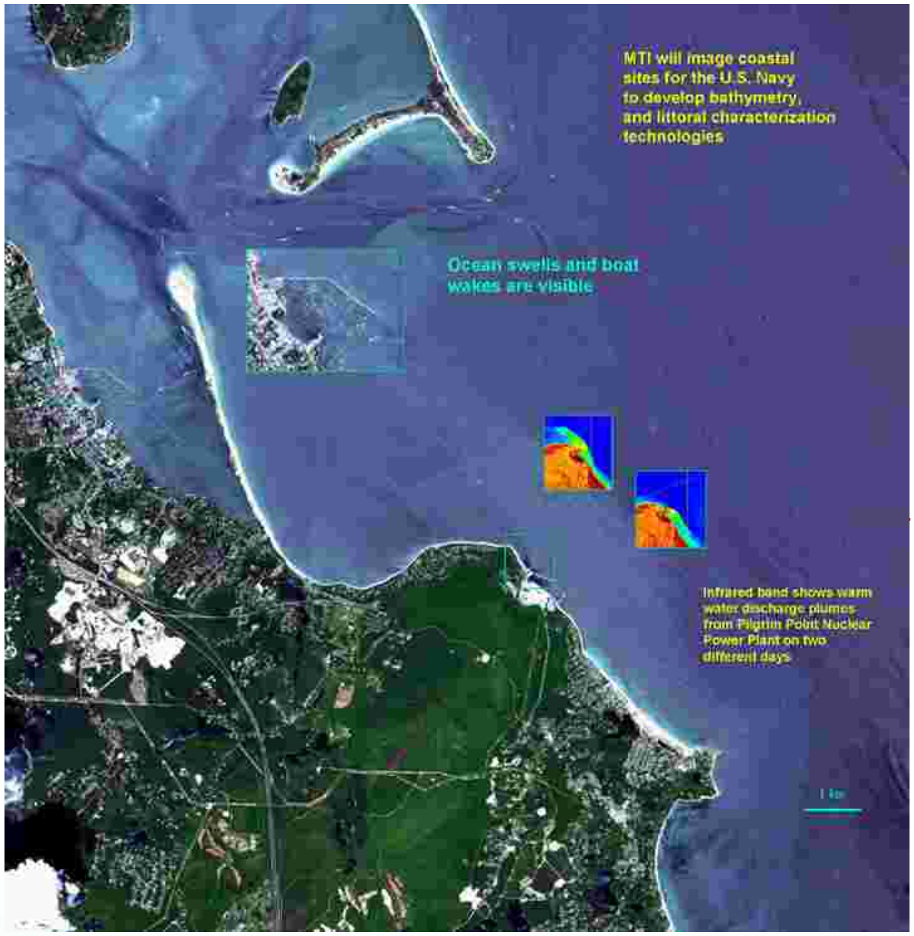
The satellite's cryogenically cooled image detectors collect data in 15 spectral bands, ranging from visible light to long-wave infrared. The detectors depend on the satellite system's true workhorses—its thousands of integrated circuits. Each of these silicon circuits is less than one-quarter of an inch square. Some of them work together to create the high-speed payload data network, the backbone of the satellite's internal communication between its functional components. The data network provides high-speed communication between sensor-readout electronics, image-compression hardware, and the satellite-control processor.

The Sandia MTI Satellite development team designed a packet transceiver module (PTM) to handle the high-speed data transfer for the payload data network. The function of the PTM is very complex and must operate reliably while the satellite orbits in the radiation environment of space. It cannot be easily implemented by commercially off-the-shelf integrated circuits. Therefore an application-specific integrated circuit (ASIC) is designed into the PTM. The PTM ASIC acts as a data traffic controller, making sure messages are sent and received properly throughout the system. As part of the MTI satellite development team, Sandia's Microelectronics Development Laboratory (MDL) is responsible for the development of the PTM ASIC. MDL is one of the few facilities in the nation that specializes in developing radiation-hardened ASICs.

While the MTI satellite was in development, another experimental satellite provided an earlier application of the payload data network. This provided an opportunity to evaluate the PTM and the ASIC operating in a real environment, and to make any necessary design modifications prior to the MTI scheduled launch date. The evaluation uncovered a minor problem

Turkey Point (Florida) Nuclear Power Plant showing temperature gradients on cooling canals.

Today, the MTI satellite continues to collect data that is useful in treaty monitoring, military operations, hazardous waste site characterization and cleanup, environmental and climate research, resource exploration, crop health and yield assessment, and other scientific research.



Pilgrim Nuclear Power Plant, near Cape Cod, showing warm water discharge plumes.

of the PTM ASIC handling real-life data in some rare situations. The problem was quickly corrected through an alliance between Sandia's Satellite Department and the MDL, saving substantial taxpayer dollars and allowing Sandia to stay on track with critical program schedules for the MTI satellite.

The incident prompted a redesign of the PTM ASIC for the MTI satellite. MDL handled the design modification, fabrication, packaging, testing, and qualification of the redesigned ASIC as part of its mandate to support government-funded programs when commercial suppliers cannot meet project needs. The redesigned ASIC was one of the key components that Sandia could not get from industry within the satellite program's timeframe.

"You can't build a high-reliability, radiation-hardened integrated circuit overnight," said Brian Brock, MTI project manager for Sandia. "The development of an integrated circuit is a complicated process."

Fabrication of the PTM ASIC integrated-circuit proceeded wafer by wafer, with each wafer producing about 20 circuits. The process involved multiple layers of work at sub-micrometer resolution. As photo-resist masks were used to etch patterns on the silicon substrate, metal was laid in place, and transistors were connected.

Since the MTI satellite launch, the PTM ASIC has been operating flawlessly. The imager transmits raw data from low Earth orbit several times a day. The data are received by a ground station and operations center at Sandia, then relayed to Los Alamos National Laboratory, where they are analyzed, turned into reports, and distributed to researchers at Sandia, Los Alamos, Savannah River, and dozens of other government organizations. The images are analyzed with the aid of ground truth, simultaneously collected data obtained from ground instruments operated by the Department of Energy's Savannah River Technology Center and other agencies.

The MTI satellite project is sponsored by the National Nuclear Security Administration's Office of Nonproliferation and National Security. Other government organizations collaborating in the project are the Air Force Space Test Program Office, the Air Force Research Laboratory, and the National Institute for Standards and Technology. Industry partners include Ball Aerospace Systems, Raytheon Optical Systems, Orbital Sciences Corporation, and TRW.

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Integrated Circuits Gain the Stamp of Approval

Sandia has been named a War Reserve backup supplier of radiation-hardened integrated circuits

Radiation hardening, a process that gives electronic components the ability to continue operating under extreme levels of radiation, is a vital feature of components used in Department of Energy (DOE) and Department of Defense (DoD) weapon and space systems. Sandia's Microelectronics Development Laboratory (MDL) recently received the DOE's diamond stamp of approval for its radiation-hardened integrated circuit design and manufacturing capabilities, making Sandia a supplier of integrated circuits for such strategic defense applications as the Trident missile and B-61 bomb.

"Sandia does not compete with other defense contractors for rad-hard integrated circuit production contracts. We're strictly a backup, what the weapons complex calls 'a supplier of last resort'" said Tim Mirabal, a project leader in Sandia's Digital Microelectronics Department. "But backup resources like Sandia offers are vital to national defense, because the demand for rad-hard components is small and few manufacturers handle small quantities."

Sandia has over 30 years of experience in developing radiation-hardened microelectronics design and fabrication technology. Prior to 1995, Sandia focused on transferring this technology to industry vendors for production.

However, due to the reduced market for radiation-hardened integrated circuits and the high cost of microelectronics manufacturing, there currently are only two industry manufacturers of radiation-hardened integrated circuits and their viability is tenuous. Therefore, Sandia's Microelectronics Development Laboratory has extended its radiation-hardened microelectronics research and development to include high-reliability, low-volume manufacturing production.

[The Department of Energy's Diamond Stamp also allows Sandia to supply small quantities of integrated circuits for other industrial applications requiring high reliability and radiation hardening.]

Although DOE "Mark Quality" integrated circuits have been delivered previously, the first DOE War Reserve Diamond Stamped integrated circuits were delivered in June 2001. These deliveries were the SA3954 Intent application-specific integrated circuits (ASICs), which are used on the B-61 bomb trajectory sensing signal generator.

The SA3954 Intent ASIC is fabricated in Sandia's MDL using 0.5 micron CMOS (complementary metal-oxide semiconductor) technology. This technology has been qualified to manufacture high-reliability, radiation-hardened integrated circuits. It is the current "work-horse" of the MDL foundry. The MDL is developing a new 0.35 micron radiation-hardened CMOS SOI (silicon-on-insulator) technology. This next-generation technology can produce high-performance integrated circuits as large as four million transistors in about one-quarter of an inch square. It will be on-line by the end of 2001. Mirabal said ASICs provide a number of important advantages, including higher performance, lower power demands, faster command execution, and reduced manufacturing cost. Sandia manufactures the Intent ASIC in Albuquerque and ships them to Honeywell's Kansas City facility for installation in the B-61 trajectory sensing signal generator.

Sandia's Microelectronics Department and Microelectronics Development Laboratory are available as a radiation-hardened products partner on other defense aerospace projects. The Department of Energy's Diamond Stamp also allows Sandia to supply small quantities of integrated circuits for other industrial applications requiring high reliability and radiation hardening.

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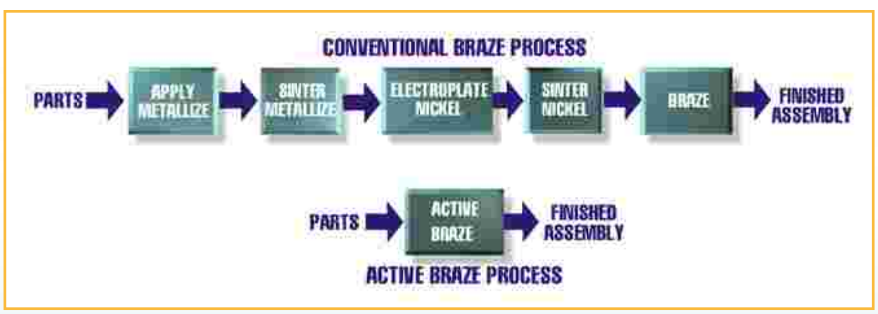
The Emerging Science of Brazing

Sandia is applying a science-based approach to high temperature furnace brazing

As the primary supplier for the neutron tubes used in Trident missiles and other warheads, Sandia must produce high-reliability joints between metals and ceramics using a furnace process called *brazing*. Brazing is distinct from soldering processes in that it is done at temperatures above 450°C, but below the melting point of the base materials to be joined. Researchers in Sandia's Joining Department continue to make advances in brazing science and technology.

Thermal expansion occurs at different rates for different materials. Tolerance requirements are extremely precise. Using that knowledge, the team has worked to control, predict, and optimize all aspects of brazing. Its science-based research includes alloy development and furnace modeling. Sandia's goal is to determine the mechanical and physical properties of brazing materials through characterizations and stress analysis of metal alloys at high temperatures. Once compiled, this information is an invaluable manufacturing resource—a database that ensures consistency in processing and properties.

Temperature is only one factor that determines a successful braze. As in any recipe that requires an exacting series of steps, brazing involves a number of variables. Correct proportions are essential for each item on the ingredients list. Heating times and rates must be precisely followed, and the narrow temperature range where brazing reactions occur requires careful monitoring. One mistake in any of these areas could make the product unusable or prone to failure.



Sandia has reduced the number of manufacturing variables by eliminating several steps that normally are required for conventional ceramics brazing. These include the need to bond molybdenum metal to the ceramic and plate the molybdenum with nickel prior to brazing. The key is using an active metal brazing alloy that promotes direct chemical reaction between the braze alloy and ceramic.

"I am enthusiastic about using the active brazing process," said Keith Meredith, lead process engineer for the new neutron tube. "It reduces direct labor and the fabrication time required to make a complete tube, and makes the product less expensive."

Sandia's collection of active brazing alloys has been estimated to reduce the number of steps in a neutron tube production process by up to 20 percent.

"In brazing, acceptable tolerances can be very tight, sometimes as small as five ten-thousandths of an inch," said John J. Stephens of Sandia's Joining and Coating Department (1833). "It could amount to the difference between an ordinary bench top project and assembling a precision analog Rolex watch. The precise tolerances we achieve in neutron tubes assure that subcomponents on neutron tubes and other high-consequence applications have high-quality joints for the U.S. Department of Energy's Defense Programs."

Sandia shares its brazing knowledge and expertise with industry. Companies like WESGO Metals, Pratt & Whitney, and Honeywell are incorporating brazing test data and innovations into their high-temperature processes for application in a variety of products that operate in high-temperature environments—spacecraft subassemblies, auxiliary power units, stainless steel hydraulic lines on commercial jet engines, and automotive metal-ceramic components.

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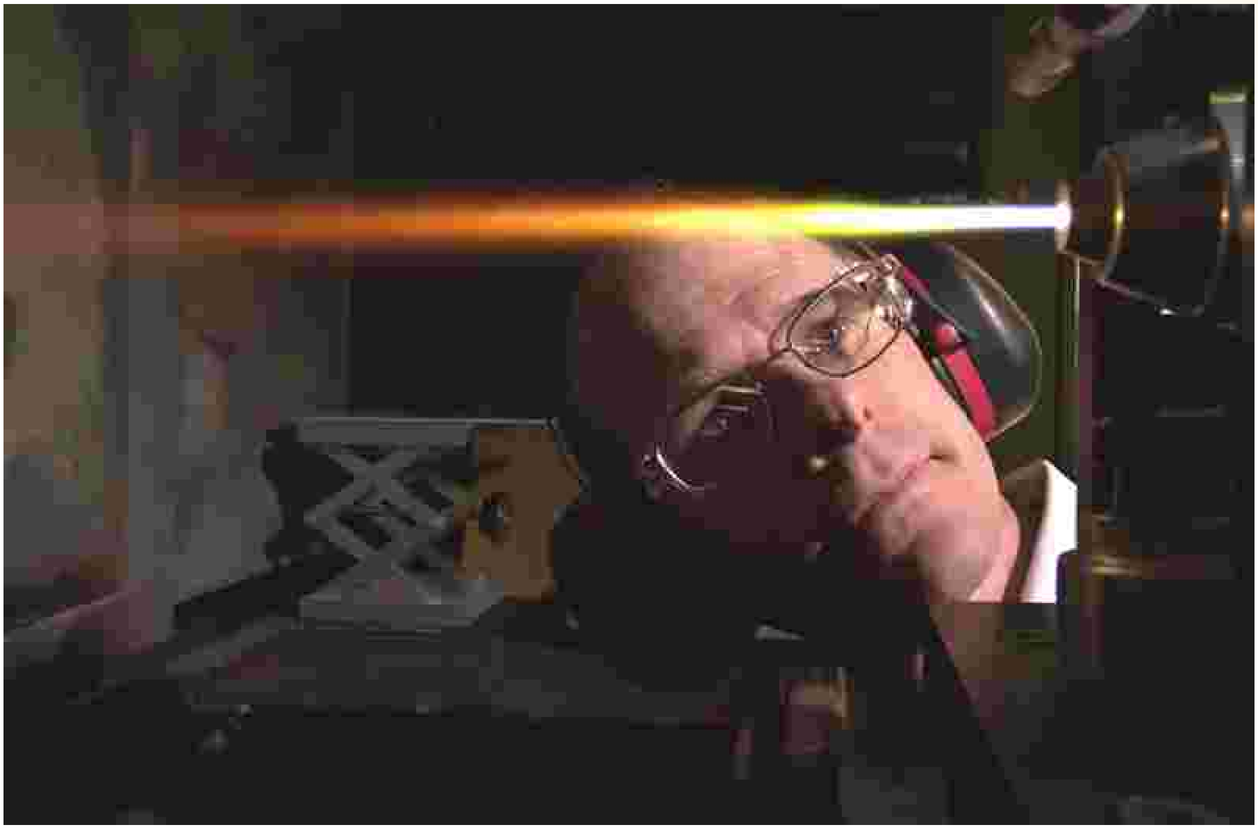


Richard Neiser, manager of Sandia's Thermal Spray Research Lab, studies the molten high-velocity particles in a flame spray jet.

New Approach to Process Control Revolutionizes Flame Spraying

Increased value and reduced risks are sparking interest in the concept of process-based quality

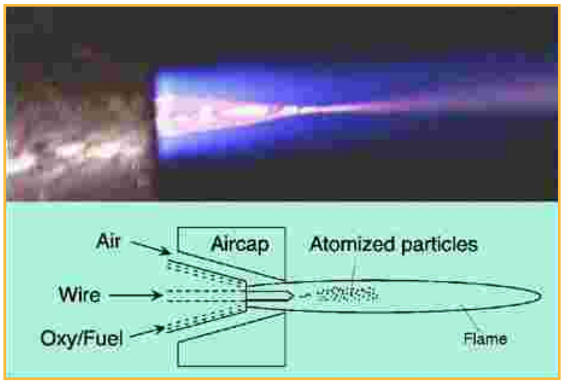
Thermally sprayed metal or ceramic coatings can greatly improve a component's performance in many demanding environments. In combustion wire-spray processing, coatings are produced by melting and atomizing a metal wire using a high-temperature flame. Sandia uses a new and more accurate approach to control the flame spray process in the production of defense components, including war reserve production of neutron generator subassemblies. Wire-flame production is used to coat neutron generators that go into ballistic missiles.

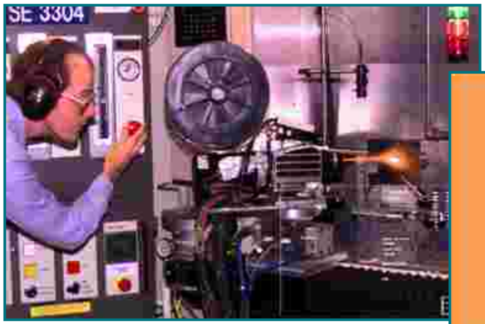
"No application is more central to our mission of national defense than this one," said Richard Neiser, manager of Sandia's Thermal Spray Research Lab. "Thermal spray also is used at numerous Department of Energy (DOE) facilities. This simple, powerful control scheme can readily be adapted to other spray processes and has broad impact within DOE."

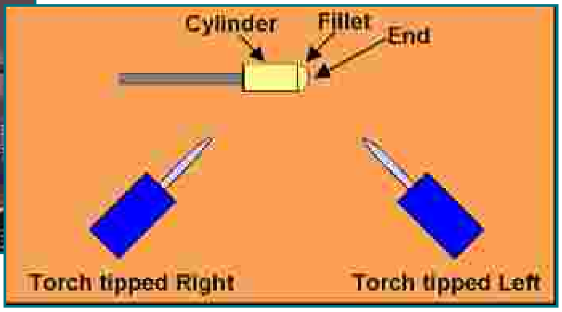
The process must be carefully controlled to produce high-quality deposits. Traditionally, the process has relied on regulating the inputs, such as holding gas flow rates constant. But this method cannot produce the desired coating quality when equipment becomes worn and tolerances change, or when the wire is not perfectly straightened and centered in the flame. Sandia researchers have developed a more effective output-based process control, which uses a combination of sensors and computer controls that fine-tune process inputs several times per second to ensure the routine production of high-quality coatings.

"The challenge is that the right combination of 'knob settings' can

Top right: Properly atomizing the molten metal is crucial to producing a high-quality coating. The new control technology continuously adjusts the gas flows to stabilize the atomization process.
Bottom left: Sandia flame spray production station shows a particle sensor above the flame, which keeps watch on the process.
Bottom right: This schematic diagram shows that a neutron generator gets coated by a combination of right and left passes of the flame spray torch.







change from day to day or even from part to part in a production environment," Neiser said.

Previously, the lack of an appropriate sensor for measuring the temperatures and velocities of the hot metal particles in the flame prevented researchers from developing effective output-based processing. Earlier particle-sensor systems were too complicated and difficult to use in production, took several minutes to process data, cost hundreds of thousands of dollars each, and were the size of a suitcase. By contrast, the state-of-the-art sensors used in output-based process control update data ten times a second, carry a relatively modest $10,000 to $40,000 price tag, and are miniaturized.

Sandia's latest flame spray production system no longer tries to rigidly hold key process conditions stable. Special computer algorithms monitor sensor data and make adjustments whenever particle temperature and velocity drift. Keeping the temperature and velocity constant is vital to consistently spraying good coatings. An important part of the algorithms are the mathematical relationships that link process inputs with process outputs. These linking relationships have proven effective since they are simple, cost- and time-effective to produce, and do not have to be precisely accurate in order to produce very stable temperatures and velocities.

The improved sensor and new software logic that are used in output-based process control ensures the thermal spray jet is carefully regulated as the system feeds a wire or powder into the hot gas. The flame spray coating process is similar to spray paint, but unlike paint, does not tend to puddle as the material or combination of materials is deposited on the manufacturer's choice of surfaces. The new process-control system's smart software adjusts variables on the fly to maintain a constant particle temperature and velocity.

Sandia's innovative approach to process-based quality is also improving American manufacturing. Output-based process control has a potentially widespread application in aerospace, jet engines, automotive manufacturing, power generation, and petrochemical manufacture. It also can be used for biomedical products ranging from dental implants to replacement hips, where thermal spray techniques are used to spray artificial bone onto titanium implants, producing a better quality product and reducing patient recovery time.

Sandia has worked on numerous industrial applications such as helping General Motors develop cylinder bore coatings for engine blocks. In this partnership, the objective was to replace traditional expensive cast iron liners used in lightweight aluminum blocks with thin steel coatings for improved gas economy and better durability. Sandia also has a major industrial program in cold-spray processing, a new coating technology that fabricates dense, oxide-free metal deposits at room temperature. Sandia is working with a consortium of eight companies to make this technology available commercially.

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The LENS™ Success Story

Six years ago, the concept of laser engineered net shaping was a simple research idea in a Sandia laboratory. Now, it promises to revolutionize the way one-of-a-kind parts are made.

An engine component breaks aboard a military aircraft carrier during mid-ocean maneuvers. The ship is not carrying a replacement part. A similar situation could also arise on a NASA space platform, where the earliest delivery of a replacement part would be weeks or months away. In both situations, Sandia's laser engineered net shaping process, LENS™, is now able to provide quick solutions.

LENS™ is an innovative rapid-prototyping system that is small enough to set up in a field location yet capable of producing complex, one-of-a-kind components. An additive process, the LENS™ system uses four nozzles to make three-dimensional, high-density parts and molds from the inside out. The nozzles direct a stream of metal powder in argon gas at a movable central point while a high-powered laser beam heats the point. Throughout the process, the substrate continuously moves, guided by thin sections of computer-aided design solid models. Layer by layer, nozzles and laser work together to deposit metal.

Blade preform for aerospace application created with LENS™

LENS™ is different from other rapid-prototyping methods because it goes directly from raw materials to metal components, eliminating intermediate steps. LENS™ works well with most kinds of metals, including difficult materials like titanium and other super-hard alloys, which are prone to developing microscopic cracks when machined. LENS™ creates fully dense, or useable, components, and the range of material properties obtainable through the process can exceed conventional techniques.

Michelle Griffith, Sandia's LENS™ project manager, says it is possible to mix and match materials during processing, allowing the designer to tailor the part properties within a component.

A relatively inexpensive way to produce parts in quantities of ten or less, LENS™ is ideal for custom weapons components. Its direct-laser, metal-deposition process also can be used to modify or repair existing hardware. Industrial applications include not only the fabrication of finished parts but also the development of tooling for plastic part production.

It is possible to mix and match materials during processing, allowing the designer to tailor the part properties within a component.

Project engineer Lane Harwell (retired) uses LENS™ to fabricate a Sandia thunderbird emblem from stainless steel.

LENS™ is allowing Lockheed Martin Tactical Aircraft Systems in Forth Worth, Texas, to accomplish in two weeks processes that previously had required many months. "The potential savings in cost and time are dramatic," said Lockheed Martin spokesperson Brian Rosenberger. "LENS™ technology enables us to make one part out of what takes hundreds of pieces using conventional technology. Our move to unitized parts is improving the structural integrity and reducing the weight of products."

Lockheed Martin is a member of the LENS™ consortium formed by Sandia in 1997 to develop the process. Other consortium partners include 3M, Honeywell, Optomec, Wyman-Gordon, Laser Fare, KAPL, NASA, and Ford. Partners are looking to incorporate LENS™ into their fabrication processes to reduce part fabrication time and cost, and to improve component performance.

What was once a simple laboratory research project has become an almost overwhelmingly successful invention and one of Sandia's all-time biggest generators of partners and R&D revenue. "We really didn't know what LENS™ would accomplish when we started the project. But we were able to make all the right matches in terms of adding benefits for partners," said Griffith, a materials scientist who has been involved on the project team since its startup six years ago.

The technology's method for transforming pure metals into finished parts is unique among rapid-prototyping processes, and project partners expect it to revolutionize the fabrication of complex prototypes, tooling, and small-lot production parts. Optomec, an Albuquerque-based supplier of laser-directed material deposition systems that markets LENS™, has been involved with Sandia for four years as part of the LENS™ CRADA.

"Working with the CRADA has helped us in our commercialization efforts for the laser-deposition systems that we manufacture. We also are using the LENS™ system to supply low-volume components back to Sandia to fill their part quotas for stockpile surety, completing the supply cycle," said David Keicher, Optomec's chief technical officer.

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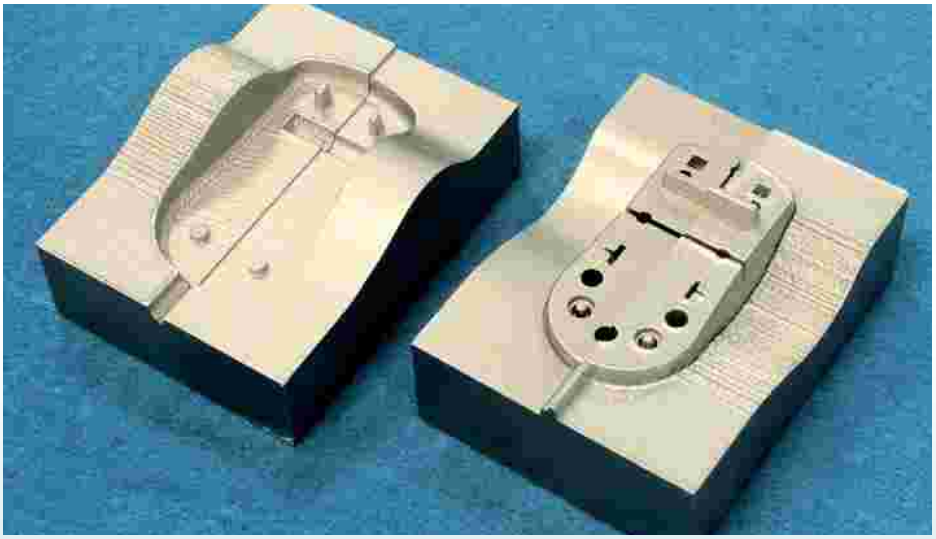

Injection-molding tool set fabricated by LENS™ in H13 (premium quality) tool steel material. The tooling core and cavity show as-deposited surfaces as well as sinker electro discharge machining surfaces to illustrate finishing techniques. Various plastic parts have been made from this tooling set.

Machining in the Meso-Range

New capabilities produce smaller, lighter weight products

In many defense applications, machined part features in the 1-to-50 micron range often improve product design and extend performance. These mesoscale parts are larger than silicon-based micromachines but smaller than miniature parts. And they require advanced-manufacturing processes to produce. Sandia's Manufacturing Science and Technology Center specializes in the production capabilities for this midrange need. These meso scale processes are used to produce better replacement components for aging nuclear weapons.

Sandia researchers Gilbert Benavides, David Adams, and Pin Yang started the mesomachining project as a Laboratory Directed Research and Development program, and it now has become a customer-driven capability. This advanced R&D effort employs four subtractive mesomachining technologies. The technologies are capable of creating both two- and three-dimensional features in a variety of materials and offer significant advantages over other fabrication processes used in micromachining and miniature machining.

Focused ion beam machining. Working with colleagues at Louisiana Tech University, Sandia is developing a focused ion beam machining technique that creates features in a variety of metals by bombarding them with a nano-sized gallium ion beam. Because it is a relatively slow process, the focused ion beam has been used to fabricate tools such as end mills, photolithography masks, and laser-machining masks, which in turn are applied repetitively to remove material at a considerably faster rate than is achievable with the focused beam ion.

Micromilling and microturning. Sandia's machining technologies have extended conventional milling and turning techniques into the mesoscale, enabling fabrication of complex features as small as 25 microns—equivalent to one-thousandth of an inch, or about one-third the diameter of human hair—in a variety of materials.

Excimer and femtosecond laser. Excimer and femtosecond lasers are Sandia's tools for creating holes, channels, and complex cuts. The excimer laser is used for mesoscale features in polymers and ceramics, and the femtosecond laser is for extremely short duration pulses that burn cleanly on the microscale, breaking atomic bonds layer by layer. The femtosecond laser produces exceptionally clean features with no heat-affected zone and no particulates from solidified melted material.

When the drilling job involves deep, small-diameter holes, the femtosecond laser offers the best approach. Developed in collaboration with colleagues at the University of Nebraska in order to create a neutron tube part, Sandia's femtosecond laser technology operates at scales down to five microns, close to the lower end of the mesomachining range. Before the invention of the femtosecond laser, deep metal holes were limited to a minimum diameter of about 50 microns, the smallest of the conventional drill bits

Sandia's Micro-Electro Discharge Machine (Micro-EDM) (above). On the upper right inset is the Micor-EDM electrode in copper that was made with the LIGA (electro-forming) process. On the lower right inset is a screen fabricated into .006 inch kovar sheet using the Micro-EDM electrode. The walls of the screen are 0.002 inch wide by 0.006 inch deep.

Micro-Electro Discharge Machining. Sandia's micro-electro discharge machining technologies offer two approaches: sinker and wire.

The electrode for the sinker method, which uses a solid three-dimensional electrode to fabricate smoothly contoured parts in a variety of conductive materials, can be made with LIGA, a process that combines lithography, electroplating, and molding for parts an order of magnitude smaller than the present miniature machining technology.

The wire method uses an electrically charged wire about one-third the diameter of a strand of human hair to cut three-dimensional tapered prismatic parts. Sandia technologists say working with a wire electrode is like using an electrically charged bandsaw.

Both the sinker and wire micro electro-discharge machining processes are suitable for difficult-to-machine materials like stainless steels, tungsten, rare earth magnets, and kovar alloy. By blending mesomachining technologies with LIGA, Sandia has overcome limitations in working with electroplated materials such as copper and nickel.

In traditional fabrication processes, gear and shaft are fabricated separately and then assembled by press-fitting the shaft into the gear. This assembly requires mere microns of interference for mesoscale parts. Mesomachining permits fabrication of gear and shaft as a single three-dimensional part, eliminating the need for a press fit. Transferred into industry, Sandia's suite of mesomachining tools may improve products in commercial aerospace, the automotive industry, and biomedical industry through a variety of component innovations such as the next generation of lightweight aerospace parts, sensors for automotive and aerospace, and medical products.

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Rooting for a Cause

Failure Analysis Expertise Enhances Sandia's Production Capabilities

The development of a new thermal battery. The redesign of a gas generator that has reached the end of its safe design life. Pinpointing a problem in an aging weapon electronics component.

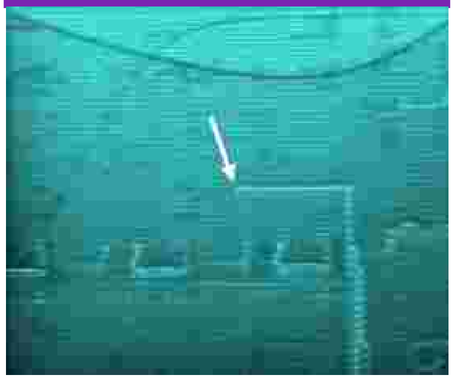
Although diverse, these challenges have a common thread at Sandia: the labs' Concurrent Design and Manufacturing program, where researchers apply new technologies, ultra-high quality manufacturing processes, and leading-edge failure analysis techniques to maintain the vitality of the nation's weapons complex.

Concurrent Design and Manufacturing offers a vital solution to the weapons complex's need for low-volume precision parts that are not obtainable through normal commercial channels, and for substitutes for materials and processes that are no longer available. In meeting the challenges of an aging stockpile, Concurrent Design and Manufacturing draws upon Sandia's world-class expertise in advanced manufacturing, engineering sciences, microelectronics, and materials and process sciences to provide critical skills.

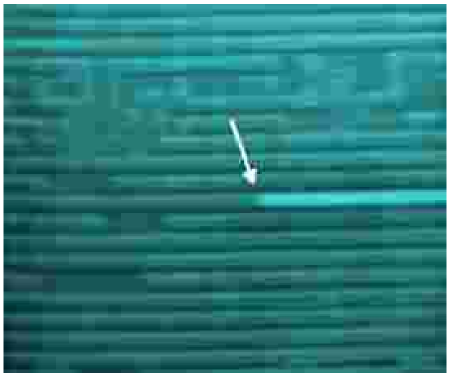
Since its inception in 1992, the Concurrent Design and Manufacturing Department has produced more than 40,000 custom parts ranging from capacitors and magnetics to frequency devices and microelectronics components. Sandians have solved many problems over the nine years the program has been in place, saving both government agencies and industry time and resources.

Uncovering the cause
Case No. 1

A memory circuit used in a weapon system malfunctioned during an acceptance test conducted on a small sample of components by a leading defense aerospace company. Faced with the prospect of replacing numerous circuits and nervous about the reliability of other parts in the same production lot, the manufacturer turned to Sandia's Rapid Response Problem Team to analyze the failure. During the analysis, Sandia researchers discovered a problem in the acceptance testing procedures rather than in the memory-circuit product itself. The acceptance tests subjected the memory circuits to excessive electrical stressing which damaged the circuit's electrical inputs. Understanding why the failure occurred averted the needless and costly replacement of numerous parts.



Low magnification electron beam voltage contrast image showing the location of an open-circuit in a metal interconnection. The white line indicates a particular electrical connection that is open at the spot indicated by the arrow.



High magnification electron beam voltage contrast image showing the precise location of the open circuit.

In meeting the challenges of an aging stockpile, Concurrent Design and Manufacturing draws upon Sandia's world-class expertise in advanced manufacturing, engineering sciences, micro-electronics, and materials and process sciences to provide critical skills.

Case No. 2

In another instance, weapon-systems component that had been in stores for about 15 years awaiting subsystem assembly was found to be nonfunctional when retested before use. Sandia's microelectronic experts were asked to identify the problem. The team discovered breakage in the form of a void in the metal wiring of the electrical integrated circuit. Their analysis revealed the reliability implications of the failure for other components of that vintage and helped identify the corrective actions needed to maintain system reliability.

Case No. 3

Eagle Picher Technologies, a manufacturer of Sandia's MC2736A thermal battery design, reported battery failure to Sandia's project realization support group. The group put together a failure-analysis team, which soon identified the problem to be electrolyte leakage due to excessive deformation of the wafers separating the anode and cathode electrodes. The team also found that the battery's magnesium oxide content exceeded Sandia's specifications, indicating that the manufacturer had not properly processed the battery's separator material. Sandia's report declared the lot unacceptable for use and recommended a new wafer processing procedure. Eagle Picher reprocessed the materials and restored its thermal battery production program to schedule.

These real-life scenarios from aerospace defense highlight Sandia's world-class reputation in failure analysis—an expertise that in 1995 and 1998 brought the microelectronics failure analysis program two of *R&D* magazine's prestigious R&D 100 Awards, an awards program that annually spotlights the 100 most promising inventions in the United States.

"Through the years, the Concurrent Design and Manufacturing program has benefited from Sandia's failure-analysis capabilities," said Cesar Lombana, Concurrent Design and Manufacturing program manager. "When our designers or suppliers experience problems during the critical development or production phases, our failure-analysis teams develop solutions in real time before our delivery schedules are affected. This capability makes the program more effective and truly concurrent when compared with other organizations in the nuclear weapons complex."

An expertise in failure analysis

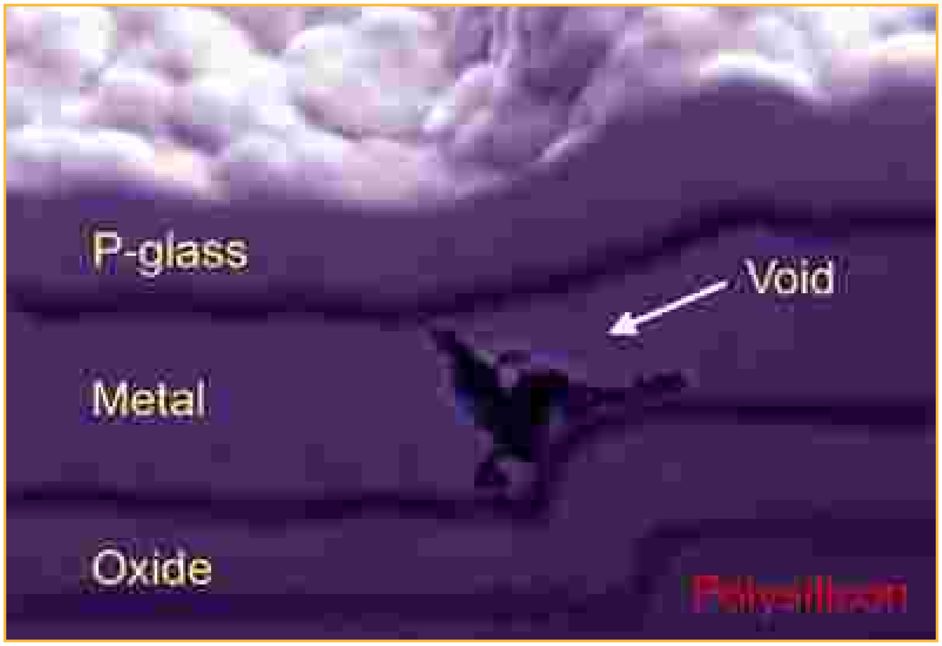
Sandia's expertise in failure analysis is integral to its mission in stockpile stewardship. "Taking responsibility for weapon life cycle includes identifying system failures before they become problems," said Richard Anderson, manager of Sandia's Microelectronics Failure Analysis Department. "The root cause of failures must be understood."

In failure analysis, determining the root cause of the failure is vital to solving the problem. Is the failure a random defect, the one component in 10,000 that can be expected statistically to go awry? Or is it a product problem that heralds the first of many similar failures? And where, exactly, did it start? In the case of weaponry, the answers to these questions may be related to materials and aging, or they may point to a manufacturing process issue. Or they could even reveal improper component use and testing.

In some partnerships, simultaneous with problem solving, Sandia acquires expertise that ultimately will improve other aspects of national security technology. For example, in the course of microelectronics projects with Intel and Advanced Micro Devices, Sandia is exposed to advanced digital integrated circuits that operate at higher frequencies than any Sandia currently manufactures or uses. These advanced circuits eventually will be modified for use in the weapon environment.

"While we develop the microelectronics failure analysis know-how that industry needs, industry leaders work on advanced technology problems Sandia hasn't tackled yet but will be facing in the future, such as new failure modes in 0.15 micron minimum feature size microcircuit components," said Michael Knoll, manager of Sandia's Design and Products Department. "These advanced microelectronics solutions will find a place in national security applications when they have matured for our high-consequence applications."

Materials science problems call for an array of tools that few companies can afford, including a battery of electron microscopes, many of which come with a seven-digit price tag. "We're often looking for a needle in the haystack, something completely unknown and unexpected," said Paul Kotula, one of Sandia's experts in transmission electron microscopy.



Cross-section of failing integrated circuit metal interconnection showing a void that caused the open circuit.

Sandia is one of the few laboratories in the world that is equipped to conduct forensics at the atomic level using a variety of analytical methods including focused ion beam, scanning electron microscopy, or X-ray diffraction. These capabilities are not available for hire either collectively or individually outside of Sandia's Materials Characterization Department.

The effectiveness of the Concurrent Design and Manufacturing program is reflected in its product acceptance rate. Last year, the program delivered 99 percent of manufactured components on schedule, and 95 percent of the product was accepted. Use of new technologies has extended the performance of non-nuclear components in the nation's nuclear stockpile by as much as three or more generations beyond the original components, and in many cases has reduced the number of parts in nuclear weapons.

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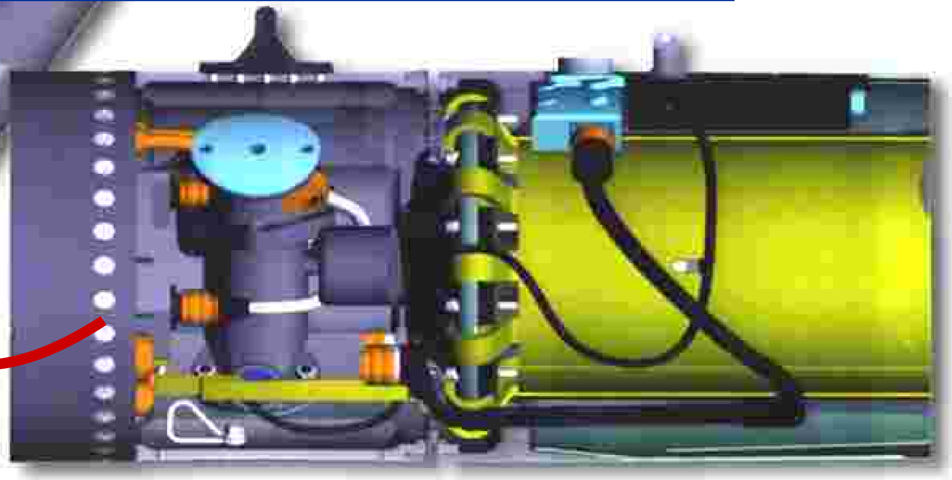
Buying Time

Extending the shelf life of aging weapon components

A limited-life component is a part with a useful shelf life that is shorter than the life of the weapon itself. To ensure the reliability of the nation's weapons stockpile, the Department of Energy requires the replacement of all limited-life components before their useful limit is reached.

In the B-61 bomb family, the shelf life of the MC3002 gas generator is determined by the 20-year shelf life of the gunpowder. When the bomb is dropped, the gunpowder ignites, generating gas that deploys a parachute. The parachute slows the bomb's descent. Parachutes are used in weapons testing because a slow descent preserves the bomb casing, permitting the reuse of components and saving tax dollars. In an actual military application, the parachute buys the aircraft pilot extra seconds of getaway time.



B-61 bomb showing MC3002A gas generator.

"The B-61's gas generator is like a big shotgun shell that, when fired, pushes out the parachute by telescopically expanding the ejection tube to a locking point at its extreme position," said Mike Kopczewski, Sandia's MC3002A gas generator project lead. "But in a couple of decades, this gun powder propellant loses its stability and is more difficult to ignite. It could even self-ignite."

The program to replace the B-61's gunpowder propellant with an improved formulation started as a joint idea of Sandia and Pacific Scientific, Inc., a Chandler, Ariz., explosives manufacturer that produced the original MC3002 gas generator. Working as a team, Pacific Scientific and Sandia searched for a replacement propellant. They chose Hipel 430, a propellant developed by Pacific Scientific. Theoretically, Hipel 430 has 300 times the stability of the original gunpowder. Hipel 430 does not use stabilizers, giving it a useful life of at least 30 years—for practical purposes, an unlimited shelf life.

Sandia's project participation included technical contributions to the propellant change. Kopczewski's team designed the generator to fit the space requirements of the original system and matched the electrical requirements of the original igniter connection. Sandians handled research and development, design, and testing of the new component. Prototypes were subjected to temperature extremes ranging from minus 70 degrees to plus 180 degrees Fahrenheit. Because the system requires a certain timing range to work properly, the timing of the parachute ejection was also a critical focus of Sandia's testing.

In January 2001, Sandia turned the new generator design over to Pacific Science for manufacturing. In June, Pacific Scientific delivered 400 of the new MC3002A gas generators to Pantex, a nuclear weapons assembly plant in Amarillo, Texas, for installation. The Department of Energy's current requirements call for the production of MC3002A gas generators for the next few years. By extending the life of the gas generator, Sandia enabled the Department of Energy not only to improve the safety of the system, but also to save money by reducing future generator orders and eliminating periodic maintenance requirements.

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The Virtual Captures the Reality

Linking staff and resources through an integrated manufacturing enterprise

In 1994, the Department of Energy reconfigured the weapons complex. Production lines in the defense aerospace industry were shut down and neutron generator production shifted to Sandia as part of its mission of nuclear stockpile stewardship.

For Sandia, becoming the primary supplier of the nuclear-triggering devices has involved much more than simply developing the tools to support a new production assignment. Basic data management, Web access, interfaces to production floor and suppliers, business and accounting practices, hardware, and stockrooms have all become a part of the previously unfamiliar yet vital side of manufacturing. Together, they form a complex manufacturing infrastructure.

To help ensure the high product reliability that is crucial to weapons design and production, Sandia needs a data-management system capable of providing complete accountability throughout the entire life of the product. In the design of a product like a neutron generator, neutron tube, or thermal battery, hundreds of mechanical and electrical drawings are required. Complete documentation of the process, including all revisions and support materials, needs to remain accessible through the life of a project so that progression of the product design is traceable.

Sandia is not the only weapons producer interested in a system for integrating computer-aided design data and manufacturing data. By 1993, Honeywell's Kansas City weapons production facility had already considered the problem and was familiar with a product data-management tool from Workgroup Technology Corporation in Lexington, Mass. Workgroup's software application is capable of linking all aspects of project information—from product requirements to work instructions and access to the product's as-built archive—in a complete picture of the device at any point in its design history.

Implementing product data management into the manufacturing process has enabled Sandia to more effectively manage its products and processes. The integration also benefits the production team by allowing faster engineering changes.

When we achieve a simple, practical, electronic link, we will have direct access within minutes to everything both sides offer.

"All team members now have direct, on-line access to the information they need for their work, reducing the time required to get information into and out of the system from days or even weeks to just minutes or, at the most, a few hours," said product engineer Gregory Neugebauer.

Sandia's product data-management system provides the following additional advantages:

- Integration of document control and electronic sign-off, for improved review cycle
- A recorded account of a transaction
- Extension of document control beyond drawings, to encompass work instructions, operating procedures, requirements maps, qualification reports, and data
- One central storage location for text and graphics, allowing placement of embedded illustrations in documents for improved work instruction clarity
- Resource sharing with Sandia's weapon systems integration departments, facilitating management of design and documentation at all levels of high-consequence production
- Closer collaboration with key suppliers and production agencies

"Product data management is only half of the story," said Eric Detlefs, a Sandian who has been involved in manufacturing and the implementation of manufacturing infrastructure for almost 10 years. "The rest is knowing by lot number or component serial number exactly which parts are on site, and being able to trace all of these in the various subassemblies and assemblies we fabricate."

To meet these tracking requirements, Sandia utilized an Oracle software-based enterprise resource planning system that linked to the data system. Product data management tells Sandia how the product was designed, and enterprise resource planning tells the production team how the component was fabricated. Together, the two systems are an important step toward total configuration control.

"Although the interface between the two systems is still manual and therefore not entirely smooth, practical, or convenient, it goes beyond anything we've had in this business," Detlefs said. "Most companies have not been able to achieve a fully functional, integrated system."

The Sandia team will soon begin work on taking the infrastructure to the next level of product development management using Matrix One. The goal is the achievement of an integrated, totally electronic interface between Matrix and Oracle. "When we achieve a simple, practical, electronic link, we will have direct access within minutes to everything both sides offer—drawings, manufacturing work instructions, equipment instructions, and administrative procedures. And, on the planning side, what to build, and how many, when, how, and from what material. This is going to save a lot of time as well as be a big convenience," said Detlefs.

When electronic integration is achieved, Sandia will combine product data management and enterprise resource planning into a virtual manufacturing enterprise. The product will move through its entire lifecycle, from inception to ongoing production and support, in a fully integrated series of steps.

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INSIGHTS

By J. Leonard Martinez

Vice President
Manufacturing Systems, Science, and Technology Division
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Manufacturing Capabilities Make Sandia Stronger

I define *manufacturing* at Sandia as the integration of manufacturing science, manufacturing technologies, manufacturing systems, and what I call "manufacturing with a little *m,*" the ability to produce a tangible product. Sandia's design and manufacturing operations are divided into four major areas: design to make, design to buy, design to prototype, and design to prototype and transfer the process. The Labs' manufacturing niche developed from its nuclear weapons heritage, and Sandia applies this capability to all of its business units. Our vision is that Sandia will be seen as *"the first choice for integrated design and manufacturing for low-volume, high-consequence, and high-complexity products required for the less predictable future."*

While nuclear weapons are at the core of manufacturing at Sandia, manufacturing touches all of its business units. Sandia's manufacturing community unifies its manufacturing systems, science, and technology capabilities in a way that helps the Labs meet today's deliverables and positions it for tomorrow's challenges.

Sandia's manufacturing community consists of the Manufacturing Systems, Science, and Technology (MSST) Division, with its two centers—the Manufacturing Science and Technology and the Neutron Generator Production Centers—at its core. The Manufacturing Science and Technology Center develops science, technology, systems, and prototyping solutions, and produces product in small volumes. The Neutron Generator Production Center focuses on deployment, producibility, and repeatability, and also (and fundamentally) on the neutron generator technologies and associated products. The MSST Division encompasses all of Sandia's manufacturing areas of process and product development, as well as the Labs' hardware deliverables.

Additional centers across Sandia with critical roles in manufacturing are the Microsystems Science, Technology, and Components Center; the Intelligent Systems and Robotics Center; and the Energy Components and Metrology Center. Other centers and activities have critical relationships to manufacturing, such as the Materials and Processes Science Center, the Simulation Enabled Product Realization Center, and the Corporate Business Development and Partnerships Center, specifically when it comes to Regional Partnerships. As one can see, Sandia has developed manufacturing into a virtual organization aimed at providing the technology and hardware needed to support its business units. As appropriate, the intellectual capital that is developed in this endeavor is shared with industry and other federal agencies.

Sandia's manufacturing culture, with its different disciplines and rewards, is unlike that of the rest of the Labs. But Sandia's manufacturing community works side by side with the Labs' scientists and engineers, thereby producing a synergy that makes Sandia stronger.

Manufacturing is indeed an enabler for Sandia. It has prompted us to establish systems to produce highly complex, high-consequence, low-volume component parts and systems that solve our customers' problems. Our manufacturing capabilities have made Sandia more well-rounded and better able to contribute to the nation's future, whatever it may bring. In the final analysis, manufacturing is critical to Sandia's quest *"to become the laboratory that the nation turns to first for technology solutions to the most challenging problems that threaten the peace and freedom for our nation and the globe."*

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J. Leonard Martinez
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