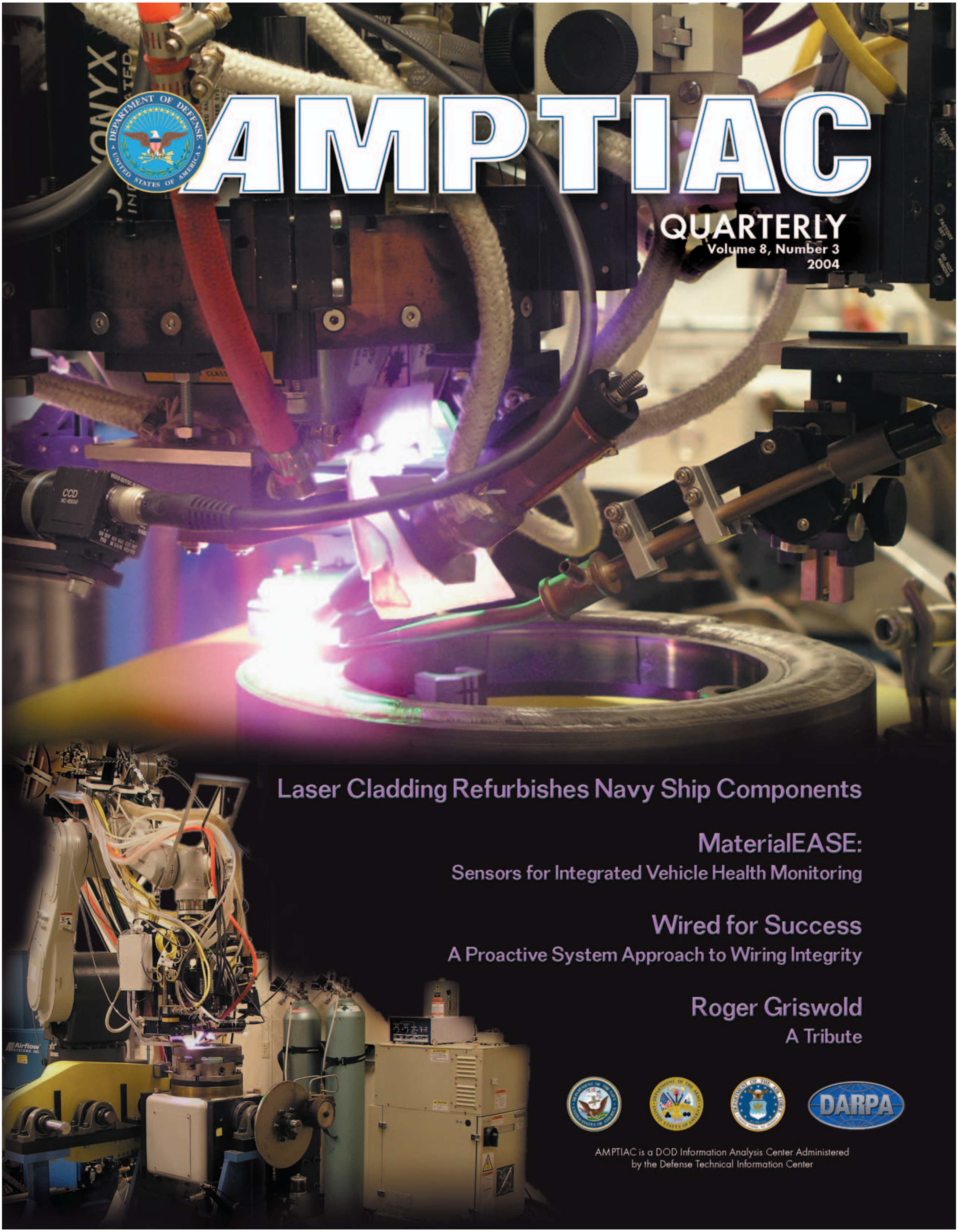

AMPTIAC

QUARTERLY
Volume 8, Number 3
2004

Laser Cladding Refurbishes Navy Ship Components

MaterialEASE:
Sensors for Integrated Vehicle Health Monitoring

Wired for Success
A Proactive System Approach to Wiring Integrity

Roger Griswold
A Tribute

AMPTIAC is a DOD Information Analysis Center Administered by the Defense Technical Information Center

Editorial: Looking back ... and forward

Recently, a significant milestone will has passed unnoticed by most among our readership, but certainly not by us. It was November 1, 1996 when AMPTIAC was chartered as the DOD's unified center for materials and process information. Our genesis was the product of merging four Information Analysis Centers (IACs), each dedicated to a specific materials area: metal matrix composites (MMCIAC), high temperature materials (HTMIAC), metals (MIAC), and ceramics (CIAC). A year later, the US Army's Plastics Technical Evaluation Center (PLASTEC) also became part of the fledgling center. More than a mere consolidation, the confluence of these five organizations with parallel missions represented a unique opportunity to bring the DOD's material resources under a single banner. Our user community benefited in two ways: first, the new combined center (by leveraging its collective information resources) was able to provide a level of service previously not possible. Second, AMPTIAC provided solutions to customers which considered the entire spectrum of material classes (solutions to specific material problems frequently reside in more than one class), and not from the narrower range of choices that any of our predecessors offered.

AMPTIAC's formation was also reflective of the period. Reinventing government and streamlining DOD entities were high priorities in 1996. Numerous agencies, organizations, and even facilities were consolidated in response to changing needs within the department.

Looking back, AMPTIAC focused its energies in different areas than today. Among the prominent material issues were aluminum metal-matrix composites, titanium turbine blade processing, advanced ceramics, optical materials, conductive polymers, and environmentally-friendly, or "green" materials. Also receiving significant attention were a series of material-related issues (recall the last Quarterly's editorial); life extension, system reliability, metal fatigue, and affordability.

During the past eight years, 9-11 was, without a doubt, the single greatest influence to the direction and level of support of material and process technology. Many material R&D efforts within the department were greatly reduced in scope, or even eliminated as funding priorities were shifted to support the war.

Despite these cutbacks, the new environment has also created opportunities in the materials field. Just as the War on Terror has caused Americans to reexamine the world around them, it has similarly compelled those of us working in enabling technologies (such as materials) to look anew at how they could be applied. Nowhere is this truer than in protective technologies; where new material innovations will prove beneficial to national defense, and also to the fledgling field of homeland security. Most notably, interest in armor systems and armoring materials has grown substantially in the past three years – be it aircraft, vehicular, or even personnel armor. Armor applications are even becoming more common in the commercial sector as well (e.g. hardened cockpit doors). In recent years, AMPTIAC's technical staff has dedicated a steadily increasing fraction of their time to supporting armoring and hardening efforts.

Homeland Security is still a relatively new term in the American lexicon, but the number of technical professionals engaged in developing technologies to protect our public facilities and structures, as well as the general citizenry, is growing. Hardened structures and transportation systems; blast and penetration-resistant materials; and biological and chemical protection technologies represent some of the major technical thrusts within homeland security. Materials are pivotal to the success of each.

However, don't get the idea that the Global War on Terror has completely usurped material-related R&D. New and emerging materials and technologies continue to spring forth on their own merits, many of which are revolutionary in nature. Nowadays, some of the marquis material activities are microelectromechanical devices (MEMs), nanotechnology and nanomaterials, smart materials and smart sensors, electro-optic and photonic materials, corrosion mitigating compounds, thermal control coatings, and space-capable materials.

Looking forward, the one thing the future of material technology can promise is that it will be interesting. We can't predict what technologies will be in vogue eight years from now anymore than we could have foreseen today's trends eight years ago. However, AMPTIAC's mission has evolved to reflect these changing trends, empowering us to provide our community with the high-quality information and services that you, our customer, have come to expect. No doubt, AMPTIAC's mission will evolve again in the future; in response to shifting needs within the department. Regardless of what those changes to our mission might be, we are extremely confident as we begin our ninth year of operation, that when such change occurs, we will continue our proud legacy of meeting the technical information needs of the defense community.

Chris Grethlein
Editor-in-Chief

About the cover: The cover depicts the Low Volume Production Program's Robotic Laser Cell in the process of refurbishing a Navy ship component. The laser adds new material to the worn part, then is machined to tolerance (see our feature article).

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Laser Cladding Helps Refurbish US Navy Ship Components

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INTRODUCTION

A major challenge in maintaining the readiness of the US Navy is the rapid acquisition of spare or refurbished components for the fleet's aging weapon systems (Figure 1). To address this challenge, Alion Science & Technology's DuPage Manufacturing Research Center has been working in cooperation with the US Navy's Puget Sound Naval Shipyard Intermediate Maintenance Facility (PSNS/IMF) to pioneer the use of high power direct diode lasers to refurbish worn ship components. Conducted under the Low Volume Productivity (LVP) program, this effort uses a direct diode laser as the key component of a highly automated, low-cost efficient system being developed to apply a cladding on worn or damaged parts. The Navy in the past had employed two neodymium-doped, yttrium-aluminum-garnet (Nd:YAG) laser cladding systems at Puget Sound, but has since discontinued their use because of various problems. The direct diode laser approach promises to significantly reduce refurbishment costs and increase process flexibility over the earlier process. The LVP program has already won recognition from the shipyard for saving the Navy millions of dollars in replacement part costs. In addition, the program recently received industry recognition when it won a prestigious R&D 100 award for 2004 from *Research and Development Magazine*.

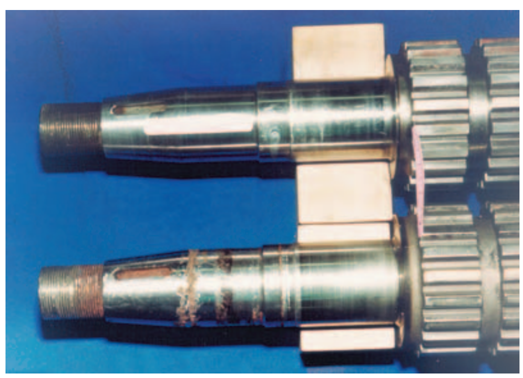

Figure 1. Typical Ship Components before (bottom) and after Repair (top).

THE NEED FOR REFURBISHED PARTS

Corrosion and wear are two processes known to degrade the performance of mechanical parts. For situations where thousands of systems utilize the same parts, it is reasonable to have a pipeline of replacement parts in the logistics stream. However, in cases where the parts are complex and expensive, and very few are in service, it may be economically advantageous to either construct a new part when needed or refurbish the old part. Procuring a new part, especially if it is large or complex, can be an unacceptable choice; since lead times can be long, the original vendor may be out of business, or the part may be extremely expensive. In these cases, refurbishment may be the only viable option to ensure that the system becomes operational in the shortest possible time and at the least cost.

Many components found aboard US Navy ships and submarines fall into the above category. Because these systems are critical to the readiness of the Navy, it's essential to minimize the time required to put them back into service. Shorter component repair times can often reduce the turn-around time for a ship in port. This is of great interest to the Navy in terms of readiness; but also represents a significant cost savings beyond the cost of repairing the component alone. Repair time reductions offered by the technologies being developed under the LVP program are achieved mostly through the automation and integration of two types of auxiliary operations – presetting and changeover. Presetting entails setting up a machining operation, and changeover involves changing to a different cladding material or part geometry. These two operations typically account for most of a part's processing time.

For many of these hard-to-procure, high-ticket items, refurbishing may be the most feasible approach. Once having made that decision, the question becomes *which technique would one utilize*? One approach that has been employed extensively is rebuilding a surface using arc-welding techniques. Another technique gaining considerable interest is laser cladding. Most prior laser cladding efforts have proven too inflexible to be economical or timely. Another problem plaguing the process is the poor surface finish of parts due to thermally-induced distortion. The approach discussed in this article has already overcome many of the problems associated with existing laser cladding processes, and when mature, will reduce processing time by major fractions in comparison to other traditional approaches.

In addition to reducing part processing times, laser cladding is an effective technique to yield refurbished parts that offer improved performance and longer service lives as compared to original parts. Laser cladding rebuilds the original part geometry by depositing a new surface that is subsequently machined to specified tolerances. The filler material used in the laser cladding process does not need to be the original material, but can be chosen from a substantial array of candidates, many of which can provide improved wear or corrosion resistance as compared to the original material. For example, the use of a nickel-based alloy filler material, such as Inconel 625, will offer improved corrosion resistance, while a higher wear resistance can occur when using filler made from cobalt-based Stellite 6.

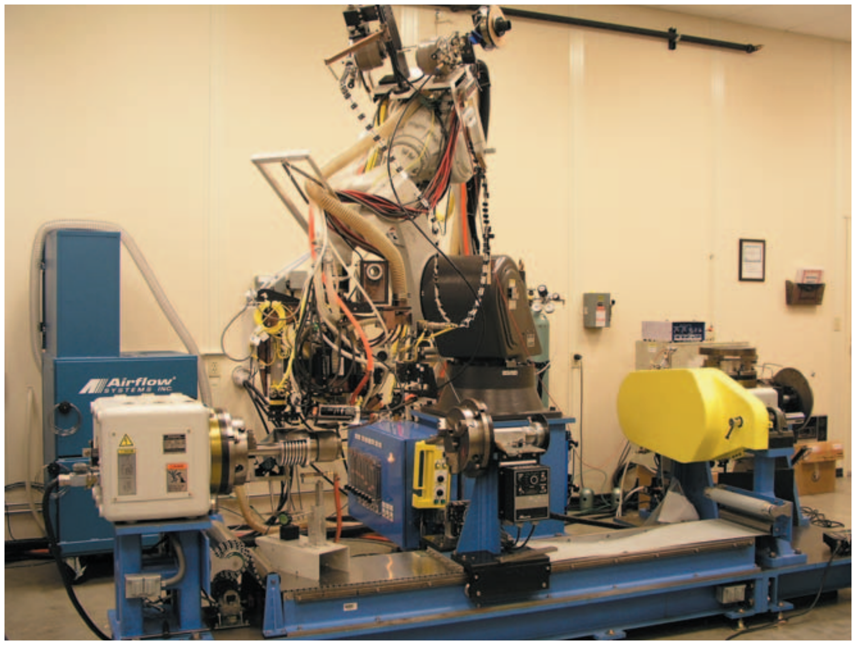

Figure 2. Robotic Laser Cell (RLC).

Low-cost refurbished parts are rapidly becoming a reality as a result of the automatic, flexible, and productive Robot Laser Cell (RLC) developed under the LVP program. Aircraft carrier catapult trough covers are a good example of the benefits that can be achieved by refurbishing existing parts using laser cladding. Initial tests indicate laser clad covers will last at least 100% longer than new replacement steel castings, providing the Navy with a fleet savings of $33.3M over ten years. Refurbished cooling pump shafts for Dock Landing Ships are another example. Shafts refurbished using laser cladding last three times longer than the originals, providing a fleet savings of $10.8M over a 30-year life.

CURRENT CLADDING SYSTEMS

As mentioned above, two methods currently used to refurbish worn or corroded parts include arc welding processes and laser cladding. Until recently, PSNS operated two 2000-watt Nd:YAG laser systems to refurbish parts. These systems delivered the laser beam to the part through a fiber optic cable and were capable of using either wire or powder forms of the filler material. The systems did not employ robotics, so changing over from one part (geometry) to another was not a simple process since custom tooling fixtures were required. Both systems were almost ten years old and recently ceased operation because they could no longer be maintained (the original vendor had left the laser business and was no longer able to support them).

Another approach for refurbishing parts is to use an arc welding technique to deposit additional material on a worn or damaged part. For noncritical assemblies this can be an effective and inexpensive process. However, a variety of problems can result from the high temperatures of the welding process itself. Among these are the loss of the beneficial properties the part obtained from the original heat treatment, distortion of the part geometry, and a large heat affected zone within the part.

Laser and arc cladding processes are similar in that the regions of each part that need refurbishment are machined to remove damage and corrosion, thus yielding stable and clean substrates. Filler metal is then deposited upon this region in excess of the original dimensions of the finished part geometry. Lastly, the part is machined back to original tolerances, yielding a repaired part that functions as new.

LVP PROGRAM

The Low Volume Productivity Program is focused on developing state-of-the-art approaches to refurbishing small quantities of existing components. The major feature of LVP is the Robotic Laser Cell (RLC), which is used to apply cladding and hard facing to damaged surfaces by either a high-power direct diode or Nd:YAG laser. The major differences between the system being developed and those systems previously used by the Navy relate to the use of a different class of laser, the availability of an additional filler material product form, and the use of robotics to facilitate the rapid refurbishment of the desired surface. There are many challenges in addition to developing the hardware and software needed to refurbish parts via laser cladding. Since an entirely new laser system is being employed (along with the addition of automation and a different product form for filler material), other equipment and systems had to be developed to ensure high-quality laser welding of the filler to the substrate. These include the Laser Power Measurement and Diagnostics Calorimetric system, and a Vision Image Control system that enables the operator to control the cladding process remotely from the safe confines of a control room. The Office of Naval Research (ONR) is sponsoring the development of the RLC and associated systems under the LVP Program.

The RLC is designed to virtually eliminate the time needed to set up a machining operation. This has been achieved by integrating the multitude of auxiliary devices into one easily adjustable, multifunctional laser head support system. Also key to minimizing presetting operation time is pre-defining the laser welding and motion schedules. These operations are carried out by integrated programming and computer control. Incorporating design measures that facilitate switching from one processing mode to another, the RLC has also provided a significant reduction in the time needed to change from one filler material to another. The time required to complete this process has also been almost completely eliminated. For example, the RLC design includes two corresponding filler-feeding systems that are installed on the robot arm, which enables rapid switching from wire to strip modes of processing. Also, the devices that guide the wire, strip, and powder filler metals to the weld pool are designed to be easily interchangeable, which allows for rapid switching between the various modes of processing. The system also includes a mechanism for rapid switching from diode laser to Nd:YAG laser processing, using the same auxiliary devices, including the guides for the wire or the powder, the shielding gas nozzle, the devices for pre-positioning and adjustment of the beam, and the video camera among others.

Figure 3. Cladding of a Simulated Part (Shaft with Groove) Using Strip Feeder.

THE ROBOTIC LASER CELL

The most critical element needed to automatically repair worn and/or corroded ship components is the Robotic Laser Cell (Figure 2). The cell became operational this past spring and is being used to produce sample parts as well as to conduct research. The RLC concept is based on a philosophy of efficient, integrated welding automation[1-10]. Adhering to this design approach, the main objectives for the RLC were:

- Maximum processing flexibility
- Minimum repair time (turn-around time for a repaired component)
- Low cost of repair in a low-volume production environment
- Predictably high quality of cladding
- Safety for the operator and protection of equipment.

Robotic Laser Cell Processing Flexibility

The RLC is a highly flexible system, capable of processing a wide variety of components using numerous methods. It was designed as a universal automatic system that allows all necessary equipment and controls to be integrated into one unit under common control. Currently, this includes a high power direct diode laser (HPDDL) laser; a six-axis robot; two rotating positioners (one axis each); a universal fixture; a laser support system; an interchangeable filler metal feeding system that can use wire, strip, or powder; and a fume exhaust system. In addition to the six axes provided by the robot, there are three additional axes for in-process filler metal positioning and laser beam height adjustment.

The recently developed, multi-kilowatt HPDDL, represents a new heat source suitable for use in cladding and hard facing operations. The advantages of HPDDL (in comparison with Nd:YAG lasers) include:

- High electrical-to-optical conversion efficiency (up to 60% vs. 5% in Nd:YAG)
- Small equipment footprint (an order of magnitude smaller than that for Nd:YAG)
- Lower maintenance cost
- A solid-state heat source that does not need warm up time
- A much wider range of power control
- Higher absorption of the laser energy into substrate
- A rectangular (linear) laser spot that allows higher productivity

While these advantages have been documented, little is known about HPDDL's use as a cladding tool. This is especially true when the application utilizes filler metals. Therefore, one of the major objectives of the LVP program is to develop techniques and procedures for HPDDL cladding, including applications that use:

- Various substrates (carbon steel, 410 stainless steel 70:30 CuNi and others),
- Various types of filler metal (wire, strip and powder), and
- Various filler materials (steel, Ni-based Inconel 625, 70:30 CuNi and others).

The RLC has been designed to accommodate both

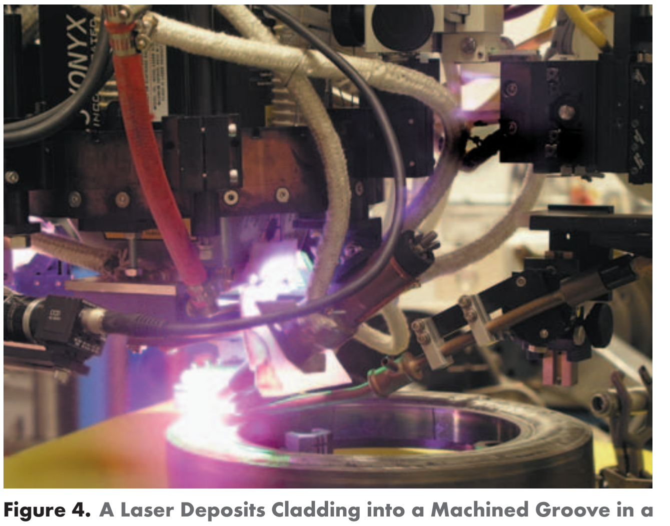

Figure 4. A Laser Deposits Cladding into a Machined Groove in a Ring Being Held by the Universal Fixture.

HPDDL and Nd:YAG laser systems. The HPDDL delivers a rectangular laser beam directly through a compact laser head installed on the robot wrist, while the Nd:YAG system utilizes a round beam. To combine advantages of the different laser processing methods, three main types of filler metal can be used for laser cladding. The first two, powder and wire, can be used with either the Nd:YAG or the diode laser, and are typical for most current processes. However, the rectangular nature of the HPDDL beam also allows cladding with strip (this is a unique advantage of the HPPDL system). Figure 3 shows a close up of the strip feeder being used to fill a groove in a shaft.

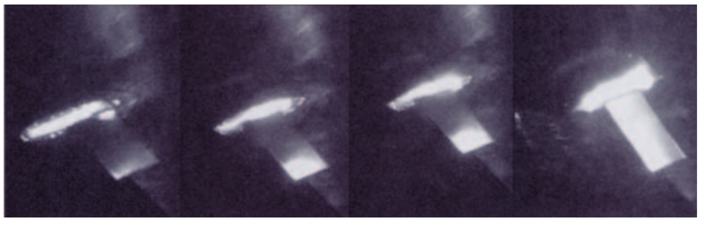

Figure 5. **Visualization of Strip Filler Entering Molten Pool (sequence of images taken from video footage).**

In order to accommodate a wide variety of repair parts, including shafts, disks, rings, and parts with non-rotating flat surfaces, and to facilitate their manipulation, a universal fixture was designed to interface with the positional components of the RLC. (Figure 4) The robot, a horizontal positioner (providing rotation of parts about the horizontal axis), and a tailstock mechanism were incorporated to allow cylindrical parts (such as shafts) to be processed. The addition of removable adapters to the fixture allows flat non-rotating parts, such as plates of various sizes to be processed in any position. The robot and a vertical positioner (providing rotation of parts about the vertical axis) allows for flat parts, such as disks and rings, to be processed as well. Furthermore, the addition of a removable transmission mechanism allows one positioner to be used as a driver to tilt the other positioner. As a result, a flat surface of a disk can be inclined up to 90° to perform cladding in the horizontal position of any chamfers or other tapered surfaces.

The high degree of automation on the RLC provides precise control over all cladding process variables, resulting in a repeatable and predictable geometry and an outstanding quality in the deposited metal. The robot controls the welding variables, such as travel speed, wire/strip feed speed, and laser head position over the substrate. Also, a rotating positioner provides highly accurate control of the angular (or linear) speed of a rotating disk, and closed-loop automatic filler metal feeder controls are used to adjust feed rate with very high accuracy.

Vision System

The Vision Image Control system monitors the wire/strip tip position, or powder trajectory, in relation to the weld pool. This system provides front and side view images of the weld pool area on a split-screen video monitor. The operator is able to manually or automatically make fine adjustments to the feed metal position from a remote location. The height of the laser head over the substrate is monitored by the Beam Height Control system that measures the height in front of the weld pool area and provides the information on a video monitor. The operator is also able to adjust the laser head position from a remote location, and can use an infrared sensor to measure the interpass temperature† of the part being cladded. This will ensure that the highest part quality will be maintained (from a metallurgical standpoint).

Operator Safety

Safety of the operator and the cladding equipment were major considerations in the development and design of the cladding cell. A specially designed fume exhaust system protects the operator from airborne particles containing Cr, Ni, Cu, and other harmful elements potentially released during cladding. The system collects the pollutants in the vicinity of the weld pool and transfers the gases to the fume filtration system, where the particles are removed. The vision control system allows the operator to remotely control the position of the filler metal and laser head height, thus protecting them from harmful laser radiation. A specially designed lens protection system (Air Knife) protects the lens of the diode laser from radiation and spatter from the molten metal. A unique counterbalance system reduces the load on the slide that supports the laser head and numerous auxiliary devices, and a collision sensor protects the laser head from collision with the other parts of the RLC.

SUPPORTING TECHNOLOGIES

Vision Image Control System

Due to the small size of the weld pool in HPDDL cladding, the filler metal (wire, strip, or powder) should be accurately directed into a certain portion of the pool to achieve the highest deposition rate and adequate weld formation. However, in the case of wire or strip, the filler may drift from a preset position due to excessive wear of the guide tip or the variable size of the filler. As a result, the filler position may need to be frequently monitored and adjusted by an operator. This need led to the development of the Laser Vision Image Control (LVIC) system, which allows the operator to remotely monitor the process and make adjustments as necessary.

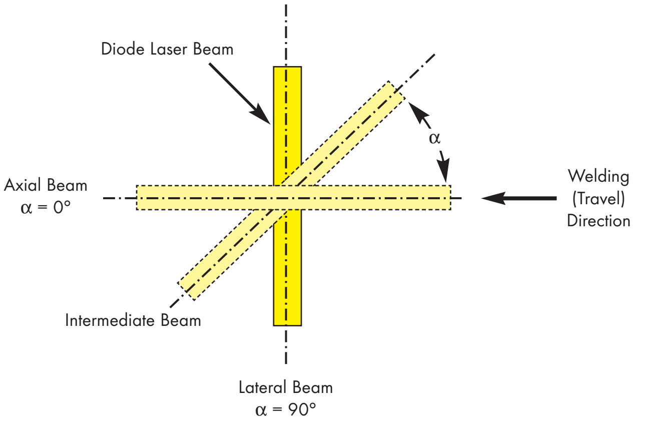

Figure 6. **Beam Travel Orientations.**

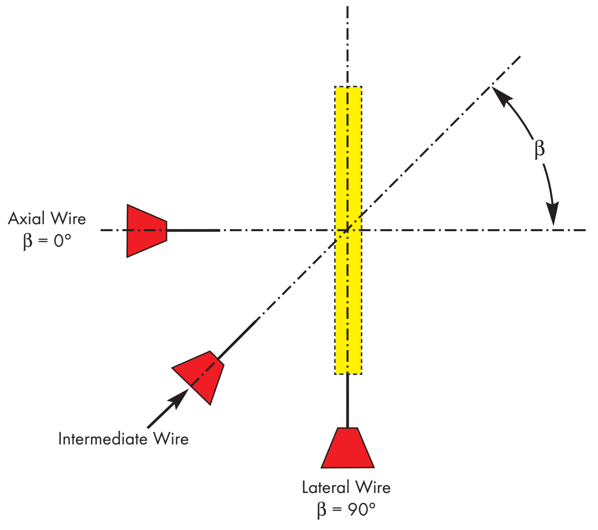

Figure 7. **Wire-Beam Orientations.**

Visualization: The visualization effort began using wire filler metal, and has now moved to strip filler metal, as can be seen in Figure 5. In order to obtain clear images of the strip and the weld pool, very small cameras are used to transmit images to the operator. Two cameras (at perpendicular orientations) are used to provide sufficient visibility of the welding area.

Imaging: The LVIC system was designed to perform real-time image analysis of the visual images received from the cameras and subsequently generate the corresponding digital information. LVIC uses multiple cameras to provide information either to an operator for adjusting the filler metal position (manual mode) or to an intelligent controller for a real-time automatic adjustment of the filler position by the feedback control (automatic mode).

Feedback Control System for Clad Material Placement: The feedback control system is designed as a part of the laser support system. It consists of a motorized cross slide that can move a wire, strip or powder guide in two perpendicular directions. The automatic controller is programmed to detect a faulty condition and to generate the corresponding commands for the servomotor of each slide.

Laser Power Measurement and Calorimetric System (PMCS)

Application of HPDDL lasers requires measurement of the beam power transferred to the substrate. Quantifying beam power is required to:

- Calibrate the net power of the beam for the purpose of controlling the cladding process.
- Detect and offset gradual loss of power resulting from the degradation of the individual diodes in the laser head.
- Determine thermal efficiency of the laser beam.
- Determine power degradation that may occur during prolonged cladding operations.

However, due to the novelty and unusual shape of the HPDDL beam, commercially available devices and methods of laser power measurements cannot be used. Therefore, a special automatic measurement and calorimetric system for the diode laser was developed. It was designed to be remotely controlled from the laser lab control room. The system is capable of measuring the input power of diode laser beams as well as other types of laser systems. Although the PMCS is designed mainly for measuring the amount of energy transferred from the stationary diode laser beam to a substrate, it can also measure the energy lost through beam reflection, radiation, and convection. This is made possible by the incorporation of multiple calorimeters in the PMCS design.

Design and Principles of the PMCS: The main PMCS calorimeter measures the amount of energy transferred to a substrate by the incident beam.[11] It is designed as a well-insulated, copper, cylindrical cup covered with a removable-disk substrate. The disk is cooled by running water that circulates through the system at a constant flow rate and pressure created by the pump of a special chiller. The input temperature of the water is preset, automatically controlled, and maintained constant by the chiller. The PMCS uses a side calorimeter to measure the amount of energy lost due to reflection, convection, and radiation.

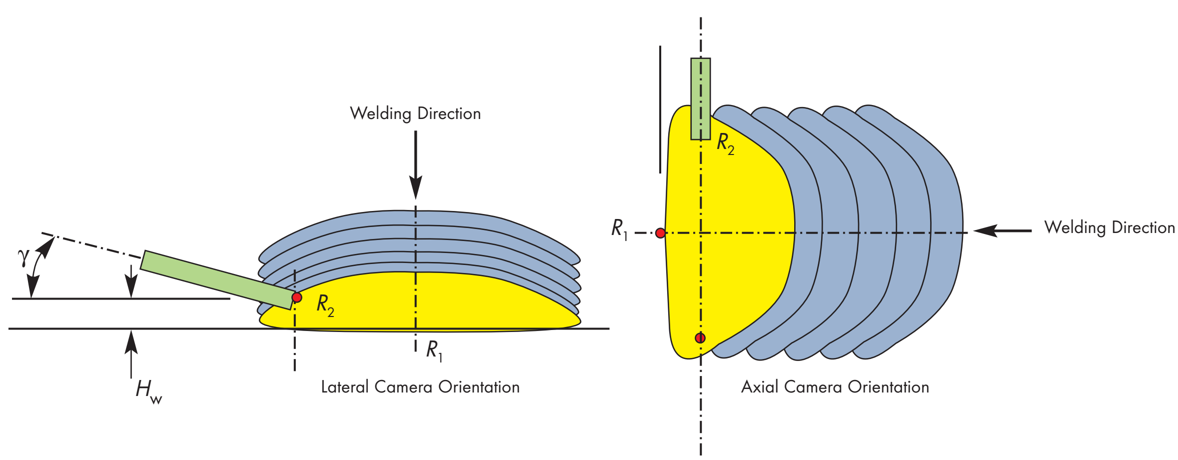

Figure 8. **Wire-Substrate Orientations and Reference Points (R) for Imaging System.**

Figure 9. Cladding Results Using RLC with Strip Feeder.

Laser Beam Height Control System

The power density of the laser affects important characteristics such as weld size, penetration, and dilution, and depends on the height of the laser head (or beam) from the substrate. However, the laser head may drift out of the preset height due to lack of straightness or distortion of the substrate. As a result, the height may need to be frequently adjusted by an operator during cladding.

The Laser Beam Height Control (LBHC) system is designed to adjust the height of the laser head during cladding if a faulty condition occurs. Based on the triangulation principle, the system measures head height at a single point using a laser diode emitting green light and a line scan camera as a sensor. This information is available to the operator for adjusting the height of the laser head in manual mode or to an intelligent controller for a real-time adjustment by the feedback control system in automatic mode. The automatic controller is programmed to detect faulty conditions and generate the corresponding commands for the servomotor, which controls the vertical positioning.

DEVELOPMENT OF TECHNIQUES AND PROCEDURES FOR DIODE LASER CLADDING

In comparison with a Nd:YAG laser, the application of wire for HPDDL cladding presents certain difficulties because of numerous variables. Most important of these variables are beam orientation relative to the travel direction, wire orientation relative to the beam (in the horizontal plane), wire orientation relative to the substrate, beam power, wire speed, travel speed, and wire diameter.

Laser Beam-to-Travel Direction Orientation

The inverted pyramid-shaped diode laser beam incident on the substrate forms a 12 mm × 0.5 mm laser line when the beam is at its focus (i.e. at its focal length of 94 mm). The linear shape of the diode laser spot introduces a new welding variable not known in other laser processes: a beam orientation relative to the travel direction that is defined by beam angle (α), as shown in Figure 6.

It was found that angle α may affect the width and penetration of the fused zone formed by the laser beam on the surface of the substrate. At the same wire speed and travel speed, if the beam is in line with the travel direction (axial beam orientation, $\alpha = 0$), the width is at a minimum and the penetration is at a maximum. If the beam is perpendicular to the travel direction (lateral beam orientation, $\alpha = 90°$), the width is maximal and penetration is minimal. Intermediate wire orientations ($0° < \alpha < 90°$) produce results between the extremes.

Thus, by turning the beam relative to the travel direction, it becomes possible to control the width of the deposit, penetration, and consequently dilution of the filler metal by intermixing molten material from the substrate. The design of the laser support system provides the capability for easily adjusting the beam angle. Research continues to determine the optimal beam angle for cost-effective cladding.

Wire-to-Beam Orientation

The wire-to-beam orientation is defined by wire angle (β) between the beam and the projection of the wire on the horizontal plane as shown in Figure 7.

It was determined that wire angle, β, may affect the shape and the dimensions of the deposit. At the same wire speed, if the wire is in line with the beam (axial wire orientation, $\beta = 0$), the deposit width is maximal. The deposit width is minimal if the wire orientation is lateral ($\beta = 90°$). In fact, the axial wire orientation allows the wire speed (and consequently deposition rate) to be doubled in comparison with the lateral orientation due to more efficient power utilization, thus considerably increasing the height and cross-section of the deposit. Since achieving the highest possible deposition rate was one of the objectives, the experiments using the lateral wire orientation were abandoned, and most of the experiments were conducted using the axial wire orientation.

Wire-to-Substrate Orientation

This orientation is defined by two parameters: the wire entry angle (γ) and the height at which the wire tip enters the pool (H_w) as shown in Figure 8. Both parameters were found to affect the deposition rate and stability of the deposition process, and thus, the weld appearance.

The wire entry angle γ is the inclination of the wire to the substrate in the vertical plane. It was found that keeping this angle as small as possible (5-10°) allows a longer interaction between the wire and the melt pool and, thus, a higher deposition rate is achieved.

Deposition Rate

The deposition rate is the amount of filler metal deposited per unit time. It was found that the HPDDL allows more metal to be deposited when compared to the Nd:YAG laser previously used by the Navy. To date, cladding using a 4kW HPDDL with filler wire has achieved a deposition rate of 0.79 kg/hr. This is a 30% improvement over the baseline rate of 0.60 kg/hr obtained using the 2kW Nd:YAG laser system. However, when considering the deposition efficiency (deposition rate per 1kW of supplied power), the HPDDL deposition techniques explored so far achieve only 66% of deposition efficiency of the Nd:YAG laser, thus further improvement is needed.

CURRENT STATUS OF THE LASER CLADDING SYSTEM

Although some minor modifications are being made to the cell, the RLC design and fabrication is complete, with tests having already begun on refurbishing sample parts. To date, the RLC has been successful in cladding flat disks, grooved channel rings, smooth shafts, and a grooved shaft (Figure 9). These parts are currently being evaluated using metallurgical and NDE analyses. Preliminary results indicate that the cladding would be acceptable by current Navy standards. Figure 10 shows a cross section of the channel ring with groove. Analysis of this sample indicated the heat-affected zone* around the weld was very small, and that there was a minimal amount of dilution (<2%)‡. In all cases the cladding is applied to such an extent that excess material can be machined off and the part returned to original design tolerances.

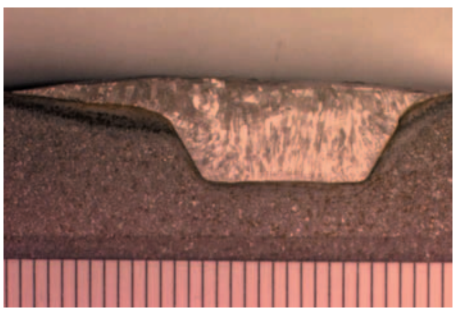

Figure 10. Cross Section of Groove Filled with Inconel 625 Strip (right side, Figure 9).

SUMMARY

Refurbishment of costly or complicated parts is a method that has been employed by maintenance activities for some time. Unfortunately, most of these methods were either quite slow, as was the case for the Nd:YAG laser cladding systems that were utilized at Puget Sound Naval Shipyard's Intermediate Maintenance Facility, or the techniques induced so much heat into parts that they experienced significant thermal distortion. Alion's sophisticated, robotic laser cladding system represents a major advance in the application of automation and technology. The Navy has already saved millions of dollars annually using a manual cladding system using a Nd:YAG laser. The automated, high power direct diode laser cladding process will not only realize savings over and above its manual counterpart, but will also turn out refurbished parts with new levels of repeatability and markedly higher standards of quality.

ACKNOWLEDGEMENT

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NOTES & REFERENCES

† The temperature in a multi-run weld and adjacent parent material immediately prior to the application of the next run. It is normally expressed as a maximum temperature.

* The portion of the base metal near the weld that receives sufficient heat to alter (but not melt) its internal crystalline structure. The resultant change in structure can significantly alter local properties of the base metal.

‡ Frequently in welding applications, the alloying elements of either the weld material or the base material diffuse or migrate towards the other, thus reducing their original concentration in solid solution.

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Mil Handbook 17 Holds Meeting on CMC Design, Testing, and Data

The Mil Handbook-17 Ceramic Matrix Composite (CMC) committee held a 2-day working conference in Norwalk, CA on May 19 and 20, 2004. The purpose of the meeting was to review progress on the CMC Handbook, develop near-term action items, and update the community on CMC technology. The Goodrich Corporation's High Temperature Composites Division in Santa Fe Springs was the meeting's corporate sponsor. Prior to the start of the meeting, Goodrich gave a tour of their CMC production facility to the thirty participants from industry, government, and academia.

The meeting was organized into two sections: technology and working groups. During the technology section, speakers provided detailed reviews of design and testing issues for CMCs in spacecraft applications and land-based turbines. The presenters were:

- Bob DiChiara - *The Boeing Company*
- Paul Matheny - *Florida Turbine Technology*
- Wayne Steffier - *Hypertherm High Temperature Composites*

In the working group sections, representatives from engine companies, CMC producers, engineering design shops, government agencies, and academia reviewed progress in the four sections of the CMC handbook (design & analysis, testing, material property data, and materials/processing). A detailed list of action items were developed in technical writing and review, data organization and collection, resource development, and publicity. The next Mil-17 CMC meeting is scheduled to be held the week of 21 February 2005 in San Diego. More detailed information on this meeting will be available on the Mil-17 website in November.

The CMC handbook is the fifth volume of a six-volume set of handbooks, which comprise Mil-17, The Composite Materials Handbook. Mil-17 provides information and guidance necessary to design and fabricate end items from composite materials. Its primary purpose is the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials.

For more information about Mil Handbook-17, please visit the Mil Handbook-17 website at http://www.mil17.org, or you can contact one of the following personnel:

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NAMIS Update: The Tri-Service Corrosion Conference

AMPTIAC is pleased to announce the addition of a new module to the National Materials Information System (NAMIS): the Tri-Service Corrosion Conference.

Initiated by the Air Force in 1967, the conference is held biennially by one of the services in an alternating fashion. The purpose of the Conference is to have an open exchange of the latest corrosion issues relevant to military systems; and to promote interaction among corrosion technologists and program managers in the military services, the defense contractor base, suppliers, and academia. Moreover, these conferences provide increased visibility of DOD corrosion prevention and control efforts and promote novel and innovative solutions to corrosion problems.

This exchange of information encourages cooperative efforts which will aid in the development of integrated corrosion prevention and control technologies. Furthermore, these conferences provide DOD the benefit of feedback, assessments, and recommendations from recognized experts in the corrosion field. The overall goal of these interactions between DOD, private industry, academia, and other Government agencies is to reduce life cycle costs through advances in corrosion control and prevention.

AMPTIAC would like to thank the following individuals for their help in locating and obtaining copies of selected proceedings that were used to develop the electronic reports accessible through NAMIS.

- Mr. Fred H. Meyer, Air Force Research Laboratory, Materials and Manufacturing Directorate (AFRL/ML), retired.
- Dr. Airan J. Perez, Office of Naval Research (ONR).
- Dr. Vinod S. Agarwala, Naval Air Systems Command (NAVAIR).
- Dr. Ralph Adler, Army Research Laboratory – Weapons & Materials Research Directorate (ARL-WMRD).

Like other NAMIS conference modules, users can access the proceedings of any conference year, and through our user-friendly search functions, can retrieve documents of interest. All documents are in PDF format and are fully text-searchable. This data module can be found at http://namis.alionscience.com, under the Conferences/Workshops section. To subscribe to NAMIS, please contact our Product Manager, Ms. Gina Nash, at gnash@alionscience.com, or by phone at (315) 339-7080.

27 AMPTIAC

Material EASE

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Sensors and Sensing Technologies for Integrated Vehicle Health Monitoring Systems

INTRODUCTION

Integrated vehicle health monitoring (IVHM) is a rapidly growing field. Although health monitoring is not a new concept, recent advancements in sensors and sensing technologies (along with the drive to decrease maintenance costs, increase life, and vehicle safety) have brought about a renewed interest in the field of IVHM.

IVHM is the collection and analysis of data concerning operating parameters and damage information of vehicles in real-time. In the past, global monitoring strategies of vehicle systems were implemented; where the real-time operating parameters were recorded and compared to both test and field data to assess potential damage and required maintenance of vehicle components. Continuous operational monitoring helps manage the frequency and extent of maintenance procedures for various components within a vehicle. This approach is known as condition-based maintenance (CBM). The incorporation of localized inspection methods, also in real-time, adds the ability to pinpoint damage in vehicles; reducing or perhaps even eliminating the need for lengthy periodic inspections covering large areas of a vehicle.

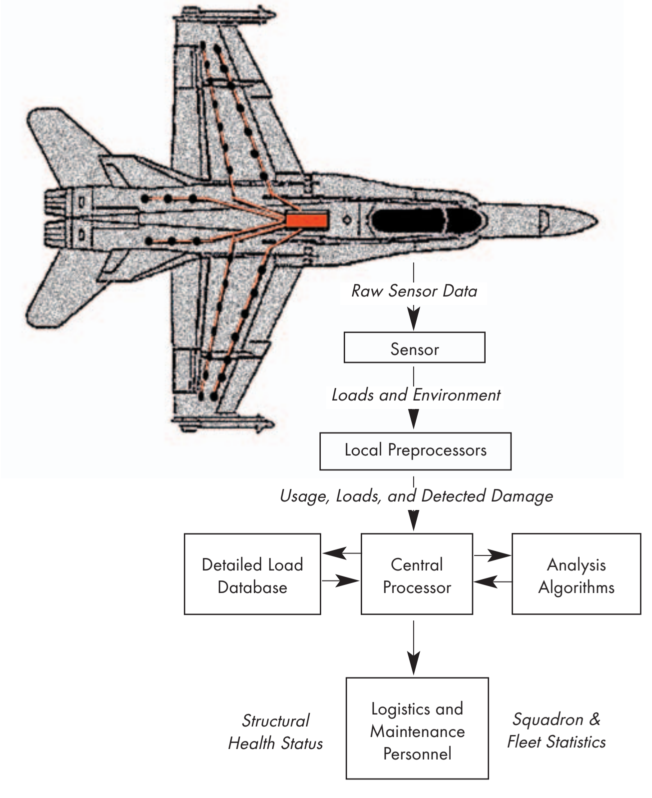


Figure 1. **IVHM System[1,2].**

The successful use of IVHM depends on a network of sensing technologies, local preprocessors, a central processing unit, and logistics and maintenance personnel (Figure 1). The limiting factor of IVHM systems is the array of sensing technologies. Sensors must be small, lightweight, easily networked to an onboard preprocessing unit, capable of withstanding the vehicle's operating conditions and environment, insusceptible to or protected from electromagnetic interference, require low power input (for active technologies) and be both reliable and accurate.[1] This article will focus on the sensors and sensing technologies in use and under development for IVHM systems, with an introduction to some of the technologies. It is intended to be introductory to the field of IVHM and by no means covers the entire gamut of sensors and sensing technologies available or under research and development.

OPERATIONAL MONITORING

Operational monitoring methods in real-time have been around for decades. These methods are used for IVHM, and can also be used for autonomous control of vehicles. The technologies implemented for operational monitoring detect vibration, strain, temperature, corrosivity, and wear. Vibration monitoring via accelerometers can be used to assess the condition of rotating machinery. All rotating components vibrate and the extent of vibration can help assess a component's health and efficiency. For drive shafts, excessive vibration usually indicates poor alignment. This can lead to overstressing of components and subsequently to fatigue damage.

Mechanical loading can be measured through the use of strain gages or fiber optic sensors. These sensors provide information on the amount and location of applied stresses over a component or structure, such as an aircraft wing. Temperature is measured using thermocouples or fiber optics, providing information on engines and aerodynamic surfaces. Temperature profiles can be obtained using infrared cameras. This technology is used to evaluate the efficiency of heat transfer components, such as the thermal protection systems of a spacecraft. Environmental composition and corrosivity monitoring are used to assess the level of degradation in components and structures. Technologies include chemical sensors for gas and ion detection, humidity sensors, pH sensors, and electrochemical corrosion sensors. Lubrication monitoring methods are used to detect changes in viscosity or the presence of particulate contaminants. Detecting and addressing contamination and viscosity breakdown early on can preclude component wear.

DAMAGE DETECTION

Damage detection methodologies employ fiber optics as well as some nondestructive inspection technologies, all of which can be incorporated into IVHM systems. These include acoustic emission, ultrasonics, eddy current inspection, and thermography. An acoustic emission (AE) is the formation of an energy wave from a crack or delamination event. Piezoelectric materials and fiber optic sensors are used to detect acoustic emission waveforms. Arrays of sensors can pinpoint the source of the wave/damage event. Piezoelectric materials can also be used to produce acousto-ultrasonic (AU) signals (Lamb waves), which are detected by other piezoelectric sensors. In this manner, arrays of sensors are used to locate damage such as cracks, delaminations, and corrosion. Eddy current devices are used to detect defects and can also measure material thicknesses. Thermography, using infrared cameras, is used to detect leaks in propulsion components.

NOTABLE TECHNOLOGIES

Fiber Optics

Fiber optic sensors can be tailored to measure strain, temperature, and pressure.[1] They are most widely used for measuring strain and temperature, but additional applications are under development. Fiber optic sensors are active systems requiring a light source such as a laser, light emitting diode, or incandescent light. A Bragg grating* within the fiber core provides the sensing apparatus to measure changes to the light signal. The fiber core of refractive index, n_1, is surrounded by a cladding material with an index, n_2, slightly less than n_1. This causes a majority of the light to be reflected at this surface and remain in the core. A series of gratings within the core are equally spaced, with period Λ_B. Only light having a particular wavelength will be reflected back towards the light source. An applied stress on the fiber moves the Bragg grating producing a shift in the reflected wavelength as represented in Figure 2. The

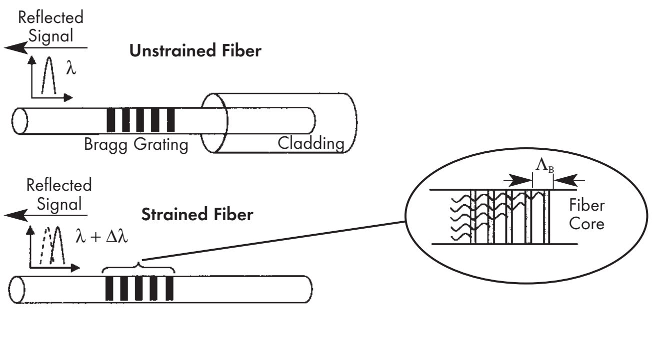


Figure 2. **Wavelength Shift in a Strained Fiber[1].**

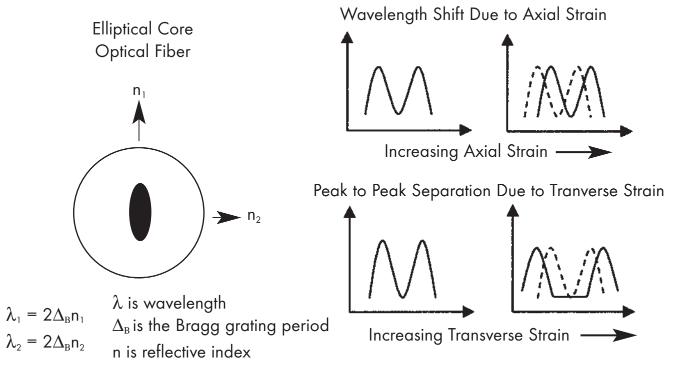


Figure 3. **Fiber Optic Sensing of Axial and Transverse Strains[1].**

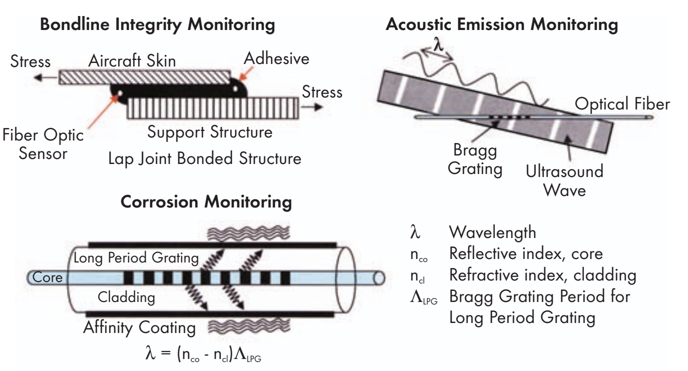


Figure 4. **Fiber Optic IVHM Concepts[1].**

orientation of strain can be determined by using an elliptical core as seen in Figure 3. The degree of wavelength shift relates linearly to the amount of applied strain, as do wavelength shifts from temperature changes.

Fiber optic sensors can also be used for bondline integrity, acoustic emission, and corrosion monitoring, see Figure 4. Fiber optic sensors have several advantages: they are highly sensitive, may be surface mounted or embedded, and are insusceptible to electromagnetic interference. Multiple Bragg grating sensing systems, known as multiplexing, can be incorporated into a single fiber. They are lightweight and can be used in a number of component geometries. Fibers must be handled carefully due to their brittleness. Embedding them into components significantly complicates manufacturing and repair practices without any real performance increase over surface mounted systems. Commercial fiber optic sensors are currently available with research continuing into higher sensitivity sensors.

Piezoelectric Materials

Piezoelectric materials can be used for IVHM in a couple of different ways. First of all, piezoelectric materials have the ability to convert a mechanical stress into an electrical signal (i.e. a *sensor*), or convert an electric pulse into a mechanical strain (i.e. an *actuator*). Piezoelectric

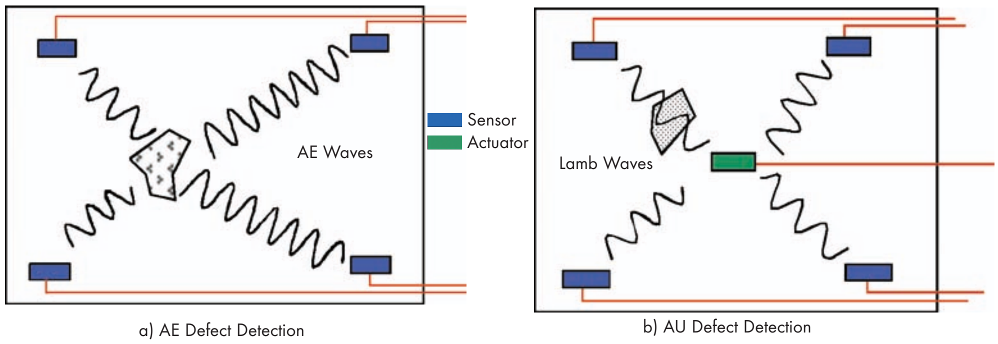


Figure 5. **Passive and Active Piezoelectric Defect Detection Techniques[4].**

sensors can detect energies emanating from impact events and defect generation, including crack formation and delamination. In this manner, arrays of sensors are used to monitor or detect such events. Each event has a particular energy signal associated with it, and through extensive testing and field monitoring, real-time events can be identified. There is always a certain amount of background noise (AE from non-defect events), so significant experience and expertise is required to accurately diagnose the source.

Arrays of sensors also allow a pinpoint determination of an energy source's location. Sensors have been able to detect cracks 0.005 inches in length from a distance of six inches on flat plate samples.[3] Sensors can be placed farther apart for more realistic crack sizes. The problem with this sensing method is that although crack and delaminations are readily detected, the exact size of the defect cannot be well-determined in the field. Crack and delamination lengths are critical parameters in determining maintenance of components. Piezoelectric sensors are passive devices requiring no energy input, which is also the case with fiber optics. They may be used on metals or composites, and may be surface mounted (patches) or embedded.

A second potential use for piezoelectrics is active defect detection. This method is currently under research and development, particularly for use with composite materials. Here, an electric pulse is sent to a piezoelectric actuator which produces Lamb waves within a structure.[4] An array of piezoelectric sensors will pick up the resultant Lamb waves for processing. If a defect such as a crack, delamination, or corrosion exists within the array of sensors, a change in the signal results, which is distinct from the original non-defect component. These systems are calibrated by recording the signals in a structure before it is placed in service. The sensors will be able to locate the position of the defect within the structure, and in this case, the defect size can be determined from the degree of signal change. Figure 5 depicts these two methods of using piezoelectric materials.

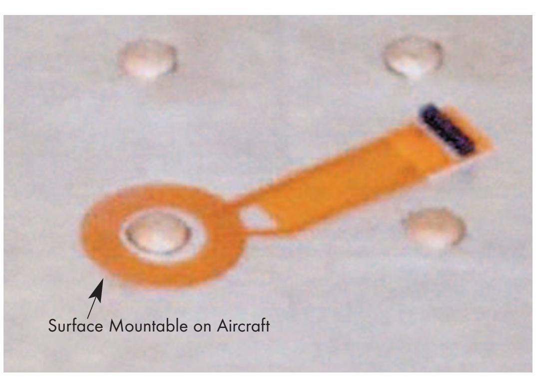


Figure 6. **Eddy Current Sensor[6].**

Eddy Current

Eddy current inspection can be used to detect material defects and also thicknesses of materials. The principle involves producing a secondary magnetic field in a material below an induced primary magnetic field on the material's surface.[5] The secondary magnetic field is characteristic of the material, both in terms of its thickness and defects. It is measured/recorded using an oscilloscope or galvanometer. This method is only effective on conductive materials and can detect cracks, corrosion, heat-effected areas, and thicknesses. Eddy current monitoring is limited to the area directly below the device. It may be used for large-scale inspection with the use of a mobile hand held device. But for real-time monitoring, small devices have been produced to look at specific areas of interest. These devices are currently under development for real-time aircraft monitoring and are designed to be placed in key areas (such as the device in Figure 6) to look primarily for fatigue cracks around fasteners.

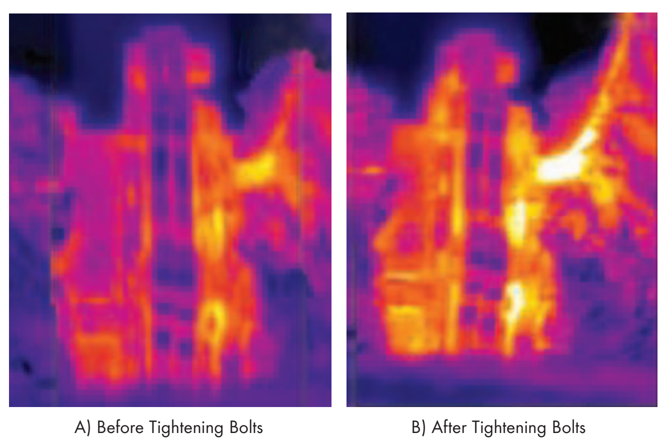


Figure 7. **Heat Signature of a Hydraulic Valve[7].**

Thermography

Thermography is a nondestructive inspection method that detects heat signatures via infrared imaging and uses this heat signature to detect leaks, cracks, debonding, corrosion, poor electrical wiring and contacts, and to assess overall thermal profiles. Thermography is most often used for IVHM in the form of leak detection in propulsion systems. Figure 7 shows the heat signature of a hydraulic valve before and after tightening the bolts.

Material EASE

Oil Analysis

A high majority of gear and bearing systems failures are the result of wear and degradation due to solid particle contaminants within the lubricant. Analysis of a lubricant typically is performed after its removal and subsequent replacement with fresh lubricant. A sample of the used lubricant (or a sample of particles collected in a filtration unit) is examined for content, particulate size and mass. Clearly, the ability to analyze particulates in real-time can have benefits as to when to perform lubricant change out, and thus prevent damage to moving parts.

The strategies developed to evaluate lubricants have been largely based upon the collection of particulates from the lubricant using magnetic collectors.[8] One such device uses an electrical circuit with a gap serving as a switch. When the gap is filled with particulates, collected by the magnetic field, an electrical signal is produced. An alternative approach is to measure the cumulative mass of collected particles. This technique is based upon a shift that occurs in the oscillation of an alternating current due to the mass of collected particles. Another device capable of measuring particle mass (and indirectly computing particle size) is an alternating field generated by a coil around the lubricant line. The advantage of this technique is that no interruption of the lubricant flow occurs and both ferromagnetic and non-ferromagnetic particles can be detected.

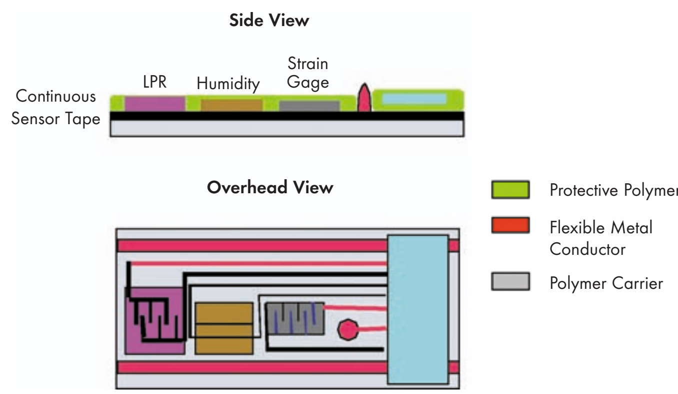
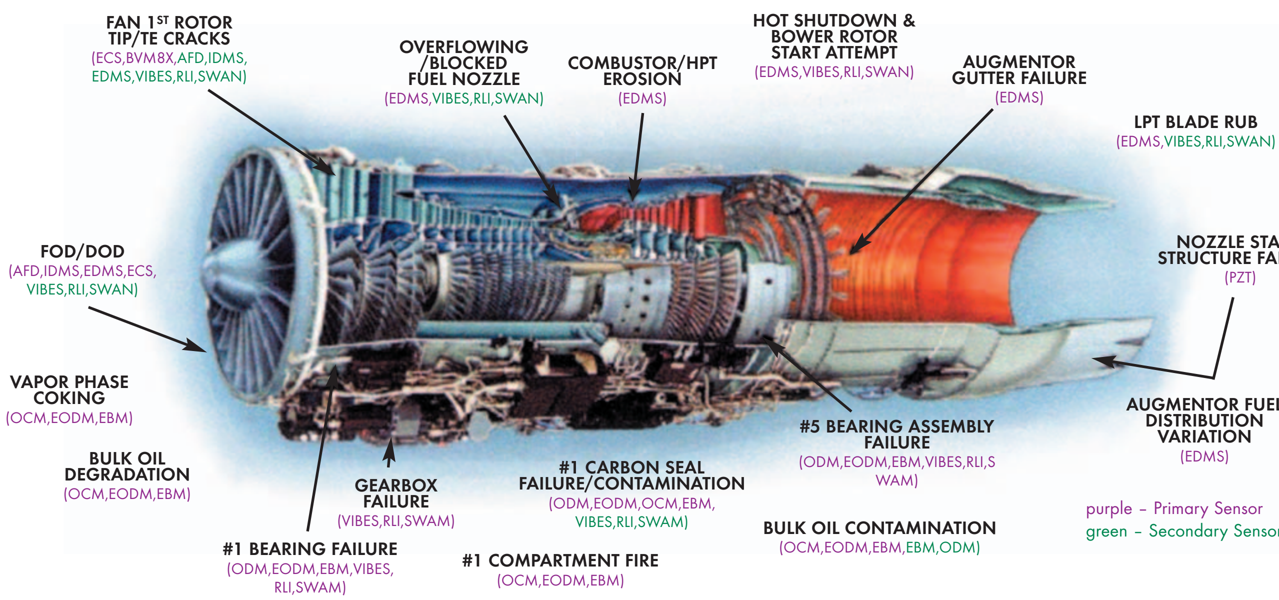


Figure 8. **MEMs Sensor for IVHM[10].**

The difference in methods discussed here lies in the relation of component wear to either a critical particle size or the overall mass of particles. The prognosis of component wear from collected data is still questionable. There is a need for continued testing to more accurately relate component wear to the particulates and other contributing factors.



AFD:	Acoustic FOD (foreign object damage) Detector	OCM:	Oil Condition Monitor
BVM8X:	Blade Vibration Meter	ODM:	Oil Debris Monitor
EBM:	Electrostatic Bearing Monitor	PZT:	Lead Zirconate Titanate ($Pb(Zr_{1-x}Ti_x)O_3$) Piezoelectric Sensor
ECS:	Eddy Current Blade Sensor	RLI:	Robust Laser Interferometer
EDMS:	Engine Distress Monitoring System	SWAN:	Stress Wave Analysis
EODM:	Electrostatic Oil Debris Monitor	VIBES	Vibration Energy Scavenging
IDMS:	Ingested Debris Monitoring System		

Figure 9. **JSF Engine Health Monitoring Technologies[11].**

Corrosion Sensors

Most corrosion sensors are based upon measuring some aspect of the electrochemical corrosion reaction. Covering them all is beyond the scope of this article and therefore only one sensor type will be introduced here. Linear polarization resistance (LPR) sensors measure a solution's electrical conductivity, which is indicative of its corrosion reaction rate.[5] Their use is well-established for monitoring aluminum alloy corrosion in sodium chloride (NaCl) environments. Their small size allows placement beneath coatings and incorporation into MEMs devices. Humidity and pH sensors similarly measure an electrical property such as capacitance or resistance using materials that are electrically sensitive to moisture or pH level.

MEMs Devices

Microelectromechanical devices (MEMs) incorporate an existing sensing technology, or multiple technologies into one device. Sensing technologies that have or are being transitioned to MEMs devices include strain gages, accelerometers, temperature sensors, humidity sensors, and corrosion sensors. Figure 8 depicts such a device. In addition, wireless MEMs devices using radio frequency communications have been implemented. Such devices typically use a radio frequency identification chip (RFID) which is activated through a local processing unit.[9] The RFID chip responds to the processing unit with a signal identifying the sensor as well as information from the sensing mechanisms. One downfall of MEMs devices is their susceptibility to electromagnetic interference.

Prognostics and Health Management for the Joint Strike Fighter

One example of IVHM integration into a military platform is the Joint Strike Fighter (JSF). A prognostics and health management (PHM) program is being designed into the aircraft, covering numerous components and structures. The health monitoring and management system tracks airframe structures, engine, electronics, mission systems, and various components including hydraulics, drive shafts, fuel and electric power systems.

The engine itself will utilize several sensing technologies that monitor and detect damage. These systems are crucial for safety as the JSF is a single engine aircraft. Figure 9 depicts the various technologies that may be incorporated into the JSF engine. The IDMS and EDMS monitor the debris present in the engine inlet and exhaust by measuring the electrostatic charge of the debris. The EODM and EBM use the same principle to monitor particles in the oil and bearing systems respectively. The laser interferometer monitors dimensional changes of components. The remaining sensing technologies are based upon the techniques and sensors covered previously in this article.

SUMMARY

Integrated vehicle health monitoring is a rapidly growing field dependent on the improvement and development of sensing technologies. The implication of employing an IVHM method that includes continuous operational monitoring and damage detection technologies is monumental. It enables less reliance on statistical based scheduled maintenance, and moves to a condition based maintenance approach which can substantially reduce ownership costs. The major problems with current IVHM systems are the accuracy of prognosis from collected data and the distribution of sensors on a vehicle with minimal impact to the vehicle's operation, maintenance, and repair. There are numerous sensing devices (in addition to the ones covered here), with new technologies emerging which will help to surmount these technical challenges and ensure their place in the design and manufacture of high-performance systems.

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*A *Bragg Grating* is an optical waveguide with series of periodic (or aperiodic) perturbations in the refractive index of the wave guide material. Each individual perturbation or *grating* can reflect a predetermined portion of the total spectrum of transmitted wavelengths incident to the grating, while allowing the remainder to pass through to successive gratings, which perform similarly with the remaining wavelengths. These series of reflected signals produce a characteristic signature for each measured phenomenon.

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In Memoriam: Roger D. Griswold

AMPTIAC Director's Note: With sadness on news of his death, and appreciation for and celebration of his life's work, we note the passing of Roger Griswold. Roger was well known and respected within the DOD materials science community, having had a long and distinguished career with the Air Force. He was a friend, a supporter, and for many years, one of AMPTIAC's Associate Contracting Officer's Technical Representatives (ACOTRs). Since Roger had touched so many people in our field, we felt it wholly appropriate to inform our readers of his passing and to highlight the important contributions he made to our community. Like our colleagues at the Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ML), we mourn his loss.

Roger D. Griswold of Enon, Ohio, passed away on Thursday, August 12, 2004. He was 57 years old. Roger devoted over three decades of his life in helping to maintain the security of our country. Most recently he was the Chief of the Systems Support Division of the Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ MLS) at Wright Patterson Air Force Base. During his tenure at MLS, Roger worked to obtain additional external funding, which improved support to the operational fleet in corrosion prevention and control, nondestructive inspection, advanced composite materials, and coatings. As Chief of MLS, he supported many initiatives, including the Aircraft Structural Integrity Program (ASIP). He served as a key member of the USAF ASIP Conference Steering Committee and played a major role in helping organize and conduct the very important annual ASIP Conference. Most recently, he also assisted the Defense Science Board's Corrosion Task Force as it considered solutions to the corrosion problems facing the DOD.

Roger began his government career by joining the United States Navy. Upon completion of a six-year enlistment in the Nuclear Powered Submarine Service, he enrolled at Wright State University and graduated in 1977 with a BS degree in Materials Science and Engineering. He joined the Air Force Materials Laboratory (the predecessor to AFRL/ML) Metals and Ceramics Division in 1975 as a Co-op student in the Nondestructive Evaluation (NDE) Branch, and upon graduation became a full-time employee of the Branch. Roger held many positions during his career, and we will highlight a few to illustrate his contributions. Perhaps his most important accomplishment relates to how he enabled, inspired, and supported his coworkers to perform at their very best.

One of the most demanding positions Roger held at AFRL/ML was as the Plans Group Leader in the Integration and Operations Division, where he helped plan and advocate the entire ML program and budget. Roger was instrumental in helping develop ML's first-ever Technical Area Plan (TAP), a new Air Force Systems Command (AFSC) process used to describe the lab's technical program based upon the President's budget request. ML's TAP was so well received that it became the model for AFSC's entire science and technology program. Roger was awarded the Directorate's 1991 Russell S. Lyle Support Person of the Year Award because of the initiative he displayed by helping develop this new process.

Roger then moved on to the Nonmetallic Materials Division's Structural Materials Branch (AFRL/MLBC) where he became the Technical Area Manager for the Non-Metallic Structural Materials Group and later went on to become Branch Chief. MLBC had been examining thermoplastic composites for space applications, but the use of these materials presented many challenges. Trusting his staff's recommendations, Roger embraced the idea of developing graphite/cyanate ester composites, and he worked to attain the resources needed to advance this new class of composites. Industry has since adopted cyanate ester composites as the material of choice for many satellite structures. Roger also enabled the development of other space-related technologies, including composites for thermal management applications. Under his leadership, AFRL/MLBC's composites for space program grew significantly.

Roger made certain his people were recognized for their hard work, as demonstrated by the fact that many of them have won Directorate awards. In 1994, Roger nominated a team of his coworkers, along with representatives from the former Sacramento Air Logistics Center, for the Air Force Materiel Command's inaugural Lt. General Thomas R. Ferguson Award for Excellence in Technology Transition, which they won. The 1994 award was for the transition of the ML-developed high-temperature polymer composite resin (AFR700B) technology onto the trailing edges of the F-117A wings.

In his next position, Roger served as the Deputy Division Chief for the Nonmetallic Materials Division (AFRL/MLB). During his time in MLB, the business aspects of the research program took on new prominence. Roger helped establish many improved processes for R&D budgeting and subsequent technology transfer/transition opportunities. As might be expected, he had a people-oriented vision for morale and team-building activities. He initiated off-duty social "outings" that helped to build camaraderie within and between divisions. Following his time in MLB, he became the Chief of the Systems Support Division.

Roger showed the same enthusiasm towards his off-duty pursuits. Over the years he was active in several youth organizations including soccer, baseball, basketball, and scouts. He also enjoyed fishing, cycling, and golf. He truly led a rich life that touched those of us who knew him best. Typical of the testimonials we received was that of Mr. Robert Rapson, Chief of AFRL/MLB: *"(Roger) was such a special person that everyone considered him to be their friend. His career progressed from an enlisted tour in the nuclear Navy to the top rungs of Air Force research and development. Everyone who knew him has commented that he never changed as he moved up the leadership ladder. He was a true gentleman; he cared about others, he took the time to make you feel special, and was up-front on all of the lab activities that put people first, whether it was a party or a golf tournament."*

We at AMPTIAC convey our deepest sympathies to the Griswold family. At the same time though, we celebrate his life and are grateful for the opportunity to know such a fine man. His demeanor in all aspects of his life, and the respect he held for his coworkers should be an inspiration to all who knew him.

Wired for Success

Ensuring Aircraft Wiring Integrity Requires a Proactive Systems Approach

George A. Slenski
Peter S. Meltzer, Jr. (Anteon Corporation)
Materials and Manufacturing Directorate, Air Force Research Laboratory
Wright-Patterson AFB, OH

Wiring integrity has become a highly visible aging aircraft issue in recent years, both for military and commercial aircraft. This level of heightened attention can be attributed to two factors: First, military aircraft are flying longer than originally intended. Second, there have been a recent string of commercial airline mishaps attributed to electrical wiring problems. As the nation's commercial and military air fleets are pressed into longer service lives, gaining mastery over the aging phenomena plaguing major systems (aircraft wiring among them) is paramount.

INTRODUCTION

Wiring or *conductors* are, in reality, just one part of an aircraft's electrical interconnection system. This "system" also includes connectors, relays, circuit breakers, power distribution panels, and generators. Degraded performance of one of these components or combinations thereof, can occur from accumulated damage. While damage has numerous sources, most are caused by long-term exposure to the surrounding environment as a result of chemical, thermal, electrical, and mechanical stresses. Installation and maintenance practices can also induce stress*. For legacy (long-term inventory) aircraft, aging wiring systems have been plagued by intermittent failures that are difficult to document and result in unscheduled maintenance.

Managing aging wiring systems has been primarily *reactive*, since few tools exist for employing *proactive* approaches. This article highlights some recent events that have resulted in an increased emphasis on wiring interconnection and power distribution, both of which are considered highly critical to the safe and successful operation of modern aircraft and space vehicles. It also looks at the emergence of proactive approaches designed to safeguard wiring system performance.

Recent cooperative efforts by government and industry organizations have created new opportunities for significant improvements in wire system integrity and the use of more proactive approaches. This is being accomplished through the use of more robust materials, greater understanding of failure mechanisms, the successful application of advanced computer modeling techniques, advanced protection devices, new inspection tools, and advanced diagnostics. Properly applied, these new technologies and tools are expected to result in wiring systems with long-term, failure-free operating periods and lower sustainment costs; significant strides that will benefit both the military and the commercial aerospace industry.

In July 1998, the Federal Aviation Administration (FAA) issued a report titled, "FAA Aging Transport Non-Structural Systems Plan" [1]. The report addressed concerns raised by the White House Commission on Aviation Safety and Security, which concluded that existing procedures, directives, quality assurance, and inspections might not be sufficient in preventing safety-related problems. These problems, the commission asserted, can result from corrosion and other deteriorating effects to non-structural components on aging aircraft, such as the wiring system.

In response to the public attention being drawn to commercial aircraft wiring issues, such as those that resulted in the TWA 800 and Swiss Air 111 crashes [2], a White House Interagency Working Group (IWG) was formed in June 2000 to examine policy, programs, investment priorities, and direction across the Executive Branch. Findings by the IWG were published in an interagency report titled, "Review of Federal Programs for Wire System Safety," issued in November 2000 [3]. This report highlights not only the importance of wiring systems but concern for their aging.

IMPORTANCE OF WIRING SYSTEM

Similar to commercial industry, the Air Force typically does not directly report wiring as a cause for maintenance actions. In many cases, a wiring maintenance action is listed as a minor repair or a subsystem failure (i.e. radar or radio). As a result, cursory computer searches of Air Force maintenance data tend to infer wiring is an infrequent maintenance item [4].

The Air Force Research Laboratory Materials and Manufacturing Directorate (AFRL/ML) has initiated an aging wiring program to address sustainment issues related to wiring systems. This program was established in response to continuing extensions in the operational life of several aircraft. Given limited budgets, the Air Force, and more specifically AFRL/ML, is collaborating with the Navy, Army, FAA, and the National Aeronautics and Space Administration (NASA) to optimize and share the benefits of the research program. This multi-agency group has challenged aerospace companies to address wiring system issues. The group is also collaborating with other principal industry sectors, such as housing, automobiles, consumer products, and nuclear power plants.

Electrical wire distribution in aircraft has become more critical as aircraft performance and flight stability have become

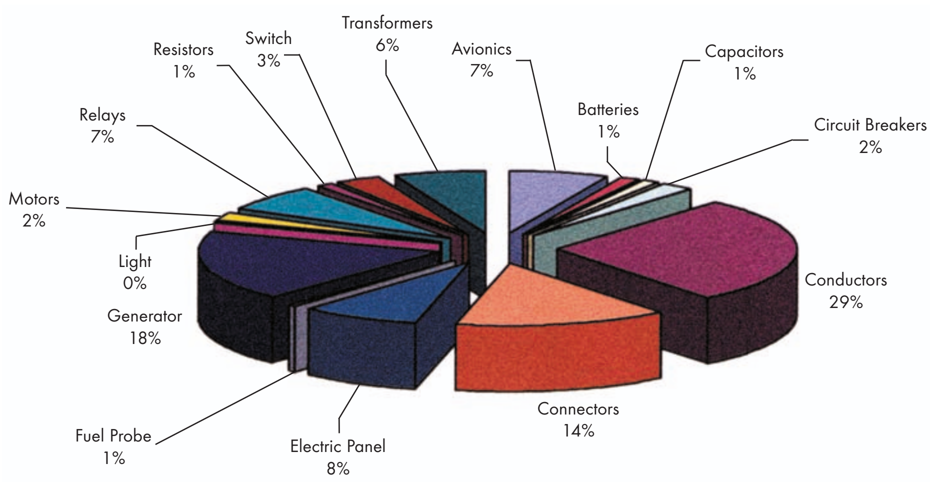

Figure 1. **Failure Demographics of USAF Aircraft Electrical Components.**

more dependent on avionics. This increased emphasis and reliance on electronic systems for modern aerospace vehicles has elevated wiring to the level of a major safety-of-flight issue.

An increasing number of aerospace systems now use fly-by-wire technology and avionics, both of which rely extensively on electrical wiring, to control and manage many of the critical onboard subsystems. According to a recent AFRL study on Air Force mishaps, no less than 43 percent of the mishaps related to electrical systems were due to connectors and wiring problems [5]. The types of failures identified in this study included hydraulic and fuel fires initiated by electrical arcing or degraded interconnections, which in turn caused malfunctions in flight control circuits and other critical systems. Wiring-related problems, in fact, comprised more than 271 separate incidents over an investigated 10-year period. A breakout of component failures is illustrated in Figure 1. Note that wiring (conductors) and connectors make up 43% of the population.

REACTIVE MAINTENANCE APPROACH

The wiring on an aircraft is no longer just a commodity but a complex system. The failure of key components within that system can disable an aircraft or compromise an aircrew's ability to control it effectively. All wiring systems are subject to aging during their service life. Aging results in the progressive deterioration of physical properties and performance with the passage of time. It's important to note that this process can be greatly accelerated by frequent handling, or maintenance actions on or near the wiring systems. Wiring failures often appear as broken conductors or damaged insulation that can disrupt electrical signals and lead to arcing. As shown in Figure 2, damage can occur from a number of different stresses.

Electrical failures on an Air Force transport aircraft illustrate why wiring-related failures can be misidentified and difficult to resolve. For more than 15 years, overheated splices plagued a particular aircraft's direct current (D.C.) power system. This condition was tolerated, since maintenance personnel could quickly locate marginal connections through inspection. They would then replace the crimped butt splice or ring terminal connections that were discolored. An example of this procedure is shown in Figure 3. One splice is discolored from excessive heating (arrow). Note the short distance between the splice and connector, and that the splices are side-by-side.

Several of the transport aircraft experienced partial loss of D.C. power in flight when the primary D.C. circuit breakers tripped. This caused numerous instruments and critical systems to fail. Several missions had to be aborted and an investigation was initiated. An extensive failure analysis was conducted, which revealed that the failures were related to installation issues, electrical power fluctuations, materials degradation, and manufacturing variations in several wiring system components. Examples of overheated splices are shown in Figure 4. Note that the insulation covering the two splices has melted together

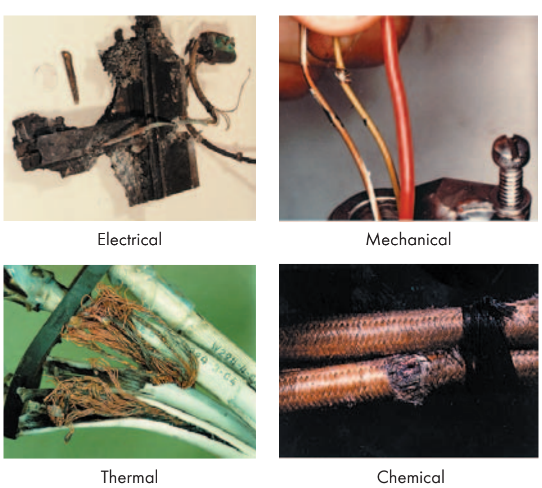

Figure 2. **Wiring Failure Mechanisms.**

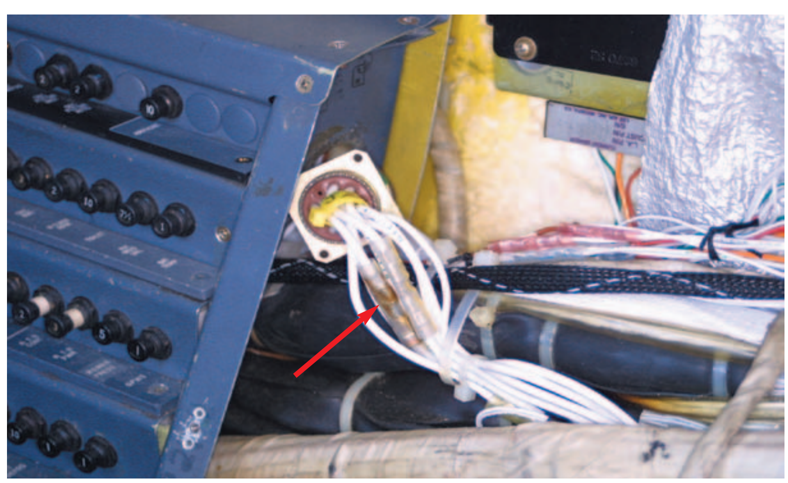

Figure 3. **Close-Up Of Butt Splice Terminations in a Circuit Breaker Panel.**

(arrow). The plating has been completely degraded by the high temperature (over 800°C) exposure (lower splice).

In the aircraft examined, the D.C. power system was distributed through two circuit breaker panels and powered by two channels (right and left generators). These channels were tied together, so that if one side failed the other would provide power to both. The presence of the bus tiebreaker allowed the tripping of one breaker to propagate to the opposite breaker. Under this scenario, the remaining breaker carried the load of both branches (which exceeded the rating of the breaker). This increased load caused the remaining breaker to also trip. The result was loss of partial D.C. power and all avionics controlled by this power source.

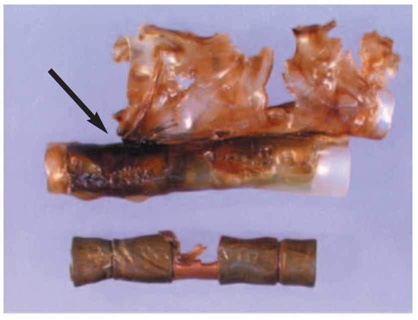

Figure 4. **Overheated Butt Splices from an Aircraft.**

The 40-ampere breaker terminated in a 12-gage size wire. The investigators discovered that breakers removed from D.C. power loss incidents failed the minimum ultimate trip test (115 percent overload for at least one hour) for a new breaker. In at least one case, the arcing damage was severe and the breaker reached temperatures that could cause a catastrophic failure (163°C). The 12-gage wiring connected to the 40-ampere breaker, in fact, altered the trip characteristic of the thermally activated device. This is because the wiring functions as a heat sink for the internal contacts.

In this aircraft, a 12-gage wire was connected to the 40-ampere breaker using a ring terminal. Prior to entering the circuit breaker panel, a butt splice was used to reduce a 10-gage wire down to a 12-gage wire size. The butt splices and ring terminals associated with the essential busses were overheating. This was due to high resistance, primarily at the 12-gage wire connection. The application of load currents showed there was excessive heating at the crimp connections for terminations removed from the aircraft. (An infrared image of a crimp connection with the maximum load current is shown in Figure 5.)

The investigating team also discovered that a gas-tight interface was not being formed between the wire and crimp terminal. This was due to the use of wire conductors with diameters below minimum specification and the type of tool used to form the crimp. Testing revealed the crimp tool used in the field (different from the butt splice manufacturer's tool) produced marginal or inadequate crimps on 12-gage butt splices and ring terminals. The recommended approach to eliminate the re-occurring electrical failures was to replace the butt splices with continuous 10-gage wiring terminated with crimped environmental ring terminals. The team also recommended that the degraded 40-ampere breakers be replaced.

EMPHASIS ON PROACTIVE, SYSTEM APPROACH

This example serves as an excellent illustration as to why wiring distribution needs to be treated as a complete system. In this case, the overall electrical failure was due to the interaction of the aircraft current loads, terminations, wiring, connectors, and circuit breakers. Interestingly, the load on each component by itself was not sufficient to cause an overall electrical failure, and the maintenance community considered periodic replacement of terminations and circuit breakers a standard practice. The engineering community was unaware of the failures, due to the ineffective data reporting process. Both communities were also unaware of the subtle changes that had occurred in the wire and crimp tool or the increased avionics loading that had occurred over a period of several years.

Many aircraft accidents can be traced to how an aircrew responds to a system failure. In the above case, the aircrews were able to successfully land the affected aircraft. While no aircraft were lost, several missions were aborted and considerable aircraft downtime and cost were required to implement the recommended fixes.

Many of the current maintenance approaches today are reactive (such as the example above) and therefore only address wiring when a failure cannot be resolved. Once the root cause of the electrical failures was identified, an effective solution could be developed. The example also demonstrates how *components in a wiring system are mutually dependent on each other*.

In another example, an Air Force field study on wiring

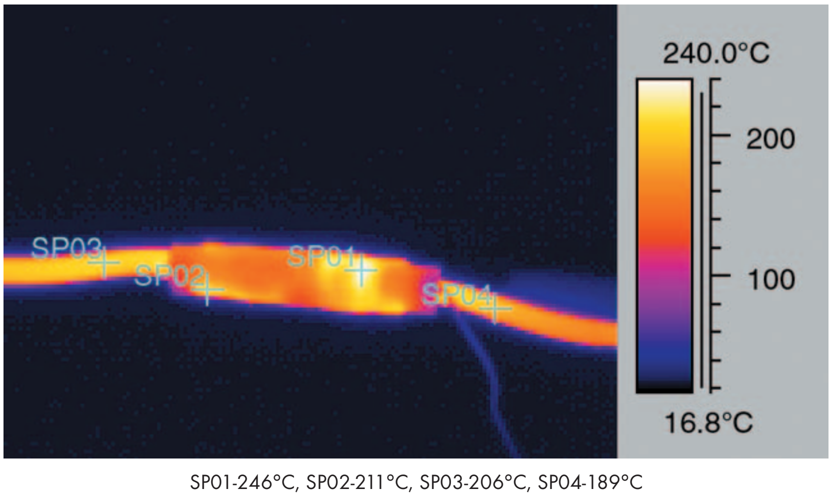

Figure 5. **10/12-gage Butt Splice from the Field. The High Temperature of the Splice (246°C) is Being Conducted Down the Length of the Wiring.**

SP01-246°C, SP02-211°C, SP03-206°C, SP04-189°C systems revealed wiring would only be examined after a black box had been replaced several times [3]. This not only placed functional systems into a depot line, but resulted in extended aircraft down times. However, it was accepted that replacing a black box was much easier than troubleshooting an interconnection problem. Typically wiring faults can take 10 to 15 times longer to troubleshoot than box-related problems. This is because technical order manuals provide limited troubleshooting guidance for wiring. The lesson here is that *significant improvement in wiring integrity can only be achieved by moving from a reactive to a proactive wiring system maintenance approach*.

Many of the technologies required to make a proactive approach a reality are only concepts today and the infrastructure to make them successful have yet to be fully developed. This can only be accomplished with a focused industry and government teaming to exchange ideas, develop new technologies, assess their effectiveness, and accelerate implementation of the most promising areas.

The large number of legacy systems makes a proactive maintenance approach particularly challenging. New maintenance approaches will need to be applied into existing aircraft operations and maintenance without compromising the original design. A proposed strategy is to develop research initiatives in five broad technology areas: failure characterization, new materials, advanced diagnostics, interconnection devices, and maintenance tools.

FAILURE CHARACTERIZATION

The causes and mechanisms of aging or degradation and the ultimate failure of wiring systems need to be fully characterized. The Air Force and other federal agencies are currently documenting failure mechanisms in wiring, connectors, and circuit breakers. Degradation mechanisms, time-dependent mechanisms, and defect sensitivities will need to be established in order to correlate failure mechanisms with field performance. The overall goal will be to develop models that can be used to design new wiring systems and predict failures in existing systems.

NEW MATERIALS

Many of the interconnection technologies currently in use are the result of incremental improvements over the past 30 years. There have been few revolutionary changes. New design approaches and materials are needed to achieve significant improvements in wiring integrity. This will require new interconnection designs and the application of new materials such as conductive polymers, fiber optics, and wireless systems. Additional research that explores innovative design approaches and materials is needed to realize revolutionary improvements in wiring system integrity.

ADVANCED DIAGNOSTICS

A current challenge is to develop nondestructive evaluation (NDE) or diagnostic techniques for inspection and detection of defects before they affect electrical system operation. Most systems currently available measure impedance changes to locate shorts or opens in connectors and cables. Electrical shorts and opens, and their relative distance from a test signal can be reliably determined for controlled impedance systems, such as coax or twisted pair wiring. Extending this capability to unshielded primary single conductor wiring offers significant challenges. The Air Force is currently evaluating several technologies that show promise is this area. These systems will initially be used to aid in locating and repairing wiring failures. Once proven and optimized, they can be used to check the integrity of selected wiring sub-systems. This would begin a transition from a “fix-it-when-it-breaks” maintenance approach to a proactive one that allows wiring maintenance to be scheduled prior to a system failure. If successful, this proactive methodology could replace current general visual inspection methods.

Several programs are attempting to develop embedded or remotely controlled sensors that can monitor the integrity of wiring systems. This advanced approach could lead to wiring systems that automatically reconfigure to maintain critical circuit paths or conduct a diagnostic check on their integrity without having to disconnect connectors.

INTERCONNECTION DEVICES

Research in this area is addressing interconnection technologies such as circuit breakers, connectors, modular wire systems, and fiber optical systems. The development of arc-fault circuit breakers is an excellent example of a government and industry team effort. This technology, originally designed for the building industry and now being applied to aircraft, has the potential to protect wiring from arcs of short-duration, which typically are not detected by conventional circuit breaker devices. Efforts, thus far, include developing plating systems and materials for connectors that are resistant to corrosion, maintaining electrical bonding resistance over extended periods, and minimizing the use of heavy metals and other materials considered hazardous.

Additional research is needed to improve the reliability of electro-mechanical devices, such as circuit breakers, relays, and switches. One approach uses microelectromechanical systems (MEMs) to improve reliability and reduce component costs. An area that merits further development is the use of wireless communication technology for critical control paths. This will require research into technologies that ensure secure and reliable communication channels.

MAINTENANCE TOOLS

A variety of tools and technologies are required to manage aging wiring systems effectively. Table 1 summarizes some of the current technology needs by technology area. One technology need not be listed—repair technology; since many of the current repair techniques were originally developed as temporary fixes but in several instances have become permanent installations. New materials and processes are needed to make permanent repairs rapidly.

Finally, from a management perspective, the areas below need to be addressed to cost effectively manage the overall health and integrity of the wiring system:

Table 1. **Example of some Wiring System Technologies Area Needs.**

Technology Areas	Need	Available Today	Available within 2-6 years
Failure Characterization	Models/Life prediction	Definition of model needs	Models that can predict field performance
New Materials	Stronger, lighter and higher temperatures	Metal plated polymers for shielding glass fiber optics	Conductive polymers for shielding/conductors Polymer based fiber optics Self-healing wire insulations
Diagnostics	Detection of wiring system faults	Shorts and opens	Intermittent and damaged wiring
Interconnection Devices	Mitigate arc propagation	Fault sensitive breakers for transports	Fault sensitive breakers for fighters
Maintenance Tools	Effective application of tools	Needs identified	Complete suite of tools for managing aging wiring system

1. *Vehicle Modeling*—the wiring system architecture and system requirements need to be fully documented. Limits need to be identified for proper system operation, including configuration management
2. *Test Planning/Monitoring*—planning, tracking and managing systems are needed for validating and testing each wiring system component over the course of a vehicle's lifetime
3. *Testing*—test equipment is needed that is capable of detecting anomalies in the wiring system, including the degradation (by contamination, physical abuse, or aging) of conductors, insulation and electromechanical components
4. *Data Management*—collection, display and archiving of wiring system data, generated via a comprehensive wire integrity program, is needed

FUTURE OBJECTIVES

A significant improvement in wiring system integrity will require a focused investment in technology through collaboration among industry, academia, and government. The "Review of Federal Programs for Wire System Safety" report of 2000 provides a roadmap to achieve this significant objective. The recommendations of the report are worth reviewing, since they provide a good starting point for developing wiring systems that operate for extended failure-free operating periods.

Significant improvements in wiring system integrity will be dependent on implementing four basic strategies [2]. These include: altering the perception of wiring systems; increasing collaboration between industry, academia and the government; improving the management and functionality of wire systems; and developing advanced wiring system technologies.

ALTERING THE WIRING PARADIGM

Wiring is often treated as a "fit-and-forget" commodity, rather than as an indispensable system. A significant cultural shift is necessary to ensure wiring systems are designed, installed, and maintained for long-term integrity. An emphasis on prevention of damage through prognostics and diagnostics is needed. Damaged components of a wiring system must be located in a non-intrusive manner, before the system fails to function properly or function at all. Locating such damage will require a change in philosophy from a largely reactive to a more proactive maintenance approach.

INCREASING COLLABORATION

A partnership between industry, academia, technical associations, and the government is essential to develop synergy and to take advantage of the abundant experience and expertise in the wiring system community. The improvement of data collection and sharing is of primary importance. Air Force (AFRL/ML) research is driven by the needs of the warfighter community. This group relies heavily on field data and industry recommendations for improvement.

Currently, no common database exists among industry, academia, and the government for wiring failure histories. In addition, no common method exists for disseminating data on wiring system failures. Wiring system failures are often attributed to systems or identified as minor repairs.

To a considerable extent, good data leads to good policy. Data will provide the feedback needed to implement the four basic strategies. The cultural shift in attitude toward building and maintaining systems with extended failure-free operating periods will be largely driven by data. These data are also needed to help evaluate current practices and to set priorities for research initiatives based on cost, time, and overall risk. There will also be a need to more effectively focus resources on the identified wiring issues and move towards the goal of increasing wiring system integrity.

IMPROVING MANAGEMENT AND FUNCTIONALITY

Standardized design tools are needed to develop and track design parameters and changes in the configuration of wiring systems. These tools should alert those who design, maintain, and operate wiring systems to conditions that may cause failures or jeopardize system redundancy.

New prognostic and diagnostic technologies and maintenance tools are needed for managing aging systems and new systems that are even more complex and dependent on electrical functions. Repair processes are needed that are rapid, permanent and reliable. Failure characterization data and non-intrusive diagnostic tools need to be integrated into a comprehensive wiring management system. Research is also needed to develop models for ascertaining when systems should be replaced or retrofitted. In addition, more intensive and detailed training is required in the installation, inspection, and maintenance of wire systems.

DEVELOPING ADVANCED WIRING SYSTEM TECHNOLOGIES

Wireless, micro-electronic, multiplexing, and fiber-optic technologies offer great promise in reducing reliance on multiple copper conductors. The best opportunity to achieve revolutionary improvements in wire systems is to develop these and other new technologies and new materials through aggressive research initiatives.

SUMMARY

In the past, wiring has been treated as a commodity. Recent events have highlighted the need to treat wiring as a whole system. There are several new technologies from multiple industry sectors that have the potential to significantly improve overall wiring system integrity and lead to wiring systems that have extended failure free operating periods. This can only be achieved through a partnership with industry, academia, technical associations, and the government.

REFERENCES & NOTES

* The term *stress* as it is used here refers not necessarily to a physical or mechanical stress, but rather to any factor within the operating environment of a system that contributes to degrading that system, and thus depleting it of remaining service life. Most systems experience multiple "stresses" during the course of their use.

[1] *FAA Aging Transport Non-Structural Systems Plan*, 1998
[2] Swiss Air Flight 111 and TWA Flight 800 were lost in electrical system-related accidents
[3] *Review of Federal Programs for Wire System Safety*, National Science and Technology Council; Committee on Technology, Wire System Safety Interagency Working Group; November 2000
[4] J. D'Angelo, D. Dicks, G Slenski, *Wire Integrity Analysis of Air Force Weapon Systems*. Paper at the Fifth Joint NASA/FAA/DOD Conference on Aging Aircraft, Orlando, FL; October 2001
[5] S. Sullivan, G. Slenski, *Managing Electrical Connection Systems and Wire Integrity on Legacy Aerospace Vehicles*; Paper at the Fourth Joint NASA/ /FAA/DOD Conference on Aging Aircraft, St. Louis, MO; September 2000

The US Army's Mobile Parts Hospital Receives Recognition

The Mobile Parts Hospital (MPH) program, an ongoing research and development effort sponsored by the Tank Automotive Research, Development, and Engineering Center (TARDEC) in Warren, Michigan was recently recognized for developing one of the Army's Top Ten Greatest Inventions for 2003. The MPH is a transportable, self-contained manufacturing center designed to support the logistics and maintenance needs of our military forces. Even though still in development, the MPH was airlifted to Kuwait where it became operational in October of 2003.

While operating at Camp Arifjan, Kuwait, MPH staff members were alerted to the need for a redesigned mount that would enable increase mobility of Squad Automatic Weapons (SAW) mounted on 'Humvees'. Existing mounts restricted motion of the weapons, so that overhead threats; such as insurgents located on rooftops, overpasses, and other overhead structures; could not be targeted. Literally overnight the MPH staff designed and developed a prototype mount that provided the much-needed capability. The new pintle mount assembly is now in production, and is helping to improve the safety and combat effectiveness of Army troops operating in urban areas. It provides soldiers the ability to defend themselves from both sides of the vehicle, and can be operated by crewmembers in either the front or rear seats.

In a ceremony held on July 22nd, team members were recognized for their roles; receiving certificates from General Paul J. Kern, Commander of the US Army Materiel Command. The team was further honored by having their efforts acknowledged in the Congressional Record.

The MPH is being developed by Alion Science and Technology of McLean, Virginia; along with its partners, Focus Hope, a nationally recognized civil and human rights organization from Detroit, Michigan, and CAMP, a professional services organization from Cleveland Ohio. MPH has been under development for several years. The program began at, and is the product of our sister IAC, the Manufacturing Technology Information Analysis Center (MTIAC), which is sponsored by the Defense Technical Information Center.

For more information on MPH, please refer to our article in Volume 6, Number 3 (2002) of the *AMPTIAC Quarterly*, which is available in electronic form on the AMPTIAC website at http://amptiac.alionscience.com/pdf/AMPQ6_3.pdf.

And you thought we only printed this magazine!

As you already know, the *AMPTIAC Quarterly* promotes technical awareness within the community by bringing technologies of interest to light. But what if you're looking for more than an overview? Where does an interested professional turn for substantial information dedicated to that one topic? AMPTIAC! We offer a variety of products, printed and electronic, to serve as an educational resource for the community. Our complete and interactive product catalog, along with descriptions of our other technical services, are available for viewing at the AMPTIAC website, http://amptiac.alionscience.com/ProductsAndServices. Regardless of your specific discipline, there is an AMPTIAC product for you. If you have any questions about any of our products, or if you would like to order one or more of them, please contact our Product Sales Manager, Gina Nash at (315) 339-7047 or e-mail at gnash@alionscience.com.

Textile Preforms for Composite Material Technology

This publication is the first and only one of its kind – A panoramic and thorough examination of fiber/textile preform technology and its critical role in the development and manufacture of high-performance composite materials. This product was prepared in collaboration with Drexel University and authored by Dr. Frank Ko, the Director of Drexel's Fibrous Materials Research Center. Dr. Ko is one the world's foremost authorities on fibrous preforms and textile technology.

Order Code: AMPT-19 Price: $100 US, $150 Non-US

Applications of Structural Materials for Protection from Explosions

This State-of-the-Art Review provides an examination of existing technologies for protecting structures from explosions. The report does not discuss materials and properties on an absolute scale; rather, it addresses the functionality of structural materials in the protection against blast. Each chapter incorporates information according to its relevance to blast mitigation. For example, the section on military structures describes concrete in arches, and concrete in roof beams for hardened shelters. The discussion on concrete is not limited to materials only; rather, it addresses the issue of structural components that incorporate concrete, and describes the materials that work in concert with the concrete to produce a blast-resistant structure. The report also illustrates various materials used for concrete reinforcement.

Order Code: AMPT-21 Price: $100 US, $150 Non-US

Material Selection and Manufacturing for Spacecraft and Launch Vehicles

A first of its kind publication, this State-of-the-Art Review provides a comprehensive overview of the unique requirements, problems, and opportunities faced by engineers designing and manufacturing spacecraft and launch vehicles. The book is authored by Dr. Carl Zweben, a major leader in the materials and space communities over the past several decades. While all material aspects of spacecraft and launch vehicles are addressed in this work, a special emphasis is placed on the unique qualities of materials used in space and highlights differences between them and their counterparts used in air/land/sea applications.

Order Code: AMPT-22 Price: $100 US, $150 Non-US

Computational Materials Science (CMS) – A Critical Review and Technology Assessment

AMPTIAC surveyed DOD, government, and academic efforts currently studying materials science by computational methods and from this research compiled this report. It provides an in-depth examination of CMS and describes many of the programs, techniques, and methodologies being used and developed. The report was sponsored by Dr. Lewis Sloter, Staff Specialist, Materials and Structures, in the Office of the Deputy Undersecretary of Defense for Science and Technology. BONUS MATERIAL: Dr. Sloter also hosted a workshop (organized by AMPTIAC) in April 2001 for the nation's leaders in CMS to discuss their current programs and predict the future of CMS. The workshop proceedings comprise all original submitted materials for the workshop – presentations, papers, minutes, and roundtable discussion highlights and are included with purchase of the above report.

Order Code: AMPT-25 Price: $65 US, $95 Non-US

Blast and Penetration Resistant Materials

This State-of-the-Art Review compiles the recent and legacy DOD unclassified data on blast and penetration resistant materials (BPRM) and how they are used in structures and armor. Special attention was paid to novel combinations of materials and new, unique uses for traditional materials. This report was sponsored by Dr. Lewis Sloter, Staff Specialist, Materials and Structures, in the Office of the Deputy Undersecretary of Defense for Science & Technology. BONUS MATERIAL: Dr. Sloter also hosted a workshop in April, 2001 (organized by AMPTIAC) for selected experts in the field of BPRM and its application. The workshop focused on novel approaches to structural protection from both blast effects and penetration phenomena. Some areas covered are: building protection from bomb blast and fragments, vehicle protection, storage of munitions and containment of accidental detonations, and executive protection. The proceedings of this workshop are included with purchase of the above.

Order Code: AMPT-26 Price: $115 US, $150 Non-US

$YBa_2Cu_3O_x$ Superconductors – A Critical Review and Technology Assessment

An up-to-date report highlighting recent research on the processing of $YBa_2Cu_3O_{(7-\delta)}$ (YBCO) superconducting materials to produce high critical current densities. The processing of powders through the fabrication of bulk materials and the deposition of films is covered, along with advantages and disadvantages of the various manufacturing methods. Problems in finding suitable substrate materials along with the associated property characterizations are presented. Some applications for YBCO superconductors under research, and ones that have been realized, complete the report.

Order Code: AMPT-27 Price: $50 US, $75 Non-US

Recent US Patents

Patent Number	Title
6,785,461	Blockless fiber optic attenuators and attenuation systems employing dispersion tailored polymers
6,785,457	Optical waveguide device and coherent light source and optical apparatus using the same
6,785,435	Waveguides and devices incorporating optically functional cladding regions
6,785,313	Distributed Bragg reflector laser and fabrication method
6,785,307	Method and arrangement for the self-calibration of a diode pumped solid state laser, particularly a tunable, diode pumped solid state laser
6,785,214	Polymeric nanocomposite materials with a functional matrix and method of reading and writing
6,785,150	Method and apparatus for preventing warpage of printed circuit boards
6,785,143	Semiconductor memory module
6,785,120	Methods of forming hafnium-containing materials, methods of forming hafnium oxide, and capacitor constructions comprising hafnium oxide
6,785,099	Read gap improvements through high resistance magnetic shield layers
6,785,035	Optical element, optical element composition and method for controlling stimuli-responsive polymer gel
6,784,998	Sheet-material foreign-matter detecting method and apparatus
6,784,989	Process and apparatus for real-time determination of a solid sample composition as a function of the depth within the sample
6,784,975	Method and apparatus for irradiating a microlitho-graphic substrate
6,784,969	Liquid crystal display panel and method of injecting liquid crystal into the display panel
6,784,962	Method for fabricating a laminate film and method for fabricating a display device
6,784,960	Liquid crystal display device, compensator layer and method of manufacturing a retardation foil
6,784,948	Touch panel for display device with pet film having transparent gel layer
6,784,618	Glass plate provided with electrodes made of a conducting material
6,784,602	Organic electroluminescent device
6,784,600	Ultrasonic membrane transducer for an ultrasonic diagnostic probe
6,784,549	Semiconductor device having a capacitor and a metal interconnect layer with tungsten as a main constituent material and containing molybdenum
6,784,538	Heat transfer structure for a semiconductor device utilizing a bismuth glass layer
6,784,535	Composite lid for land grid array (LGA) flip-chip package assembly
6,784,522	Electronic semiconductor device having a thermal spreader
6,784,515	Semiconductor integrated circuit device
6,784,459	Organic electroluminescent device
6,784,401	Welding electrode and method for reducing manganese in fume
6,784,398	Apparatus for controlling twist curvature of a disc head slider
6,784,356	Phase change material with inhibitor and a method of making the same
6,784,328	Process for producing adamantane compound
6,784,287	Organic dye molecules and nonlinear optical polymeric compounds containing chromophores
6,784,271	Odorless modified silicone compound, cosmetic preparation containing the same, and method of purifying modified silicone compound having branch polymer comprising hydrophilic group
6,784,263	Catalyst compositions for polymerizing olefins to multimodal molecular weight distribution polymer, processes for production and use of the catalyst
6,784,250	Resin composition for calendaring and polyolefin material for leather-like article
6,784,247	Powder coating compositions having improved mar and acid resistance
6,784,244	Anti-lubricant compositions
6,784,237	Water-and oil-repellent, antistatic composition
6,784,230	Chlorinated vinyl resin/cellulosic blends: compositions, processes, composites, and articles therefrom
6,784,220	Polyurethane foam

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Phone: 703.247.2587
Fax: 703.522.1885
Email: cbuck@ndia.org

SAMPE 2004
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Aging Aircraft 2005
01/31/05 - 02/03/05
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NAVAIR, Aging Aircraft Program
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22347 Cedar Point Rd Unit 6
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Fax: 301.342.2248
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25th High Temple Workshop
02/14/05 - 02/16/05
Point Clear, AL
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Phone: 216.433.3226
Fax: 505.846.8265
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46th AIAA/ASME/ASCE/AHS/ASC Structure, Structural Dynamics, and Materials Conference
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Phoenix, AZ
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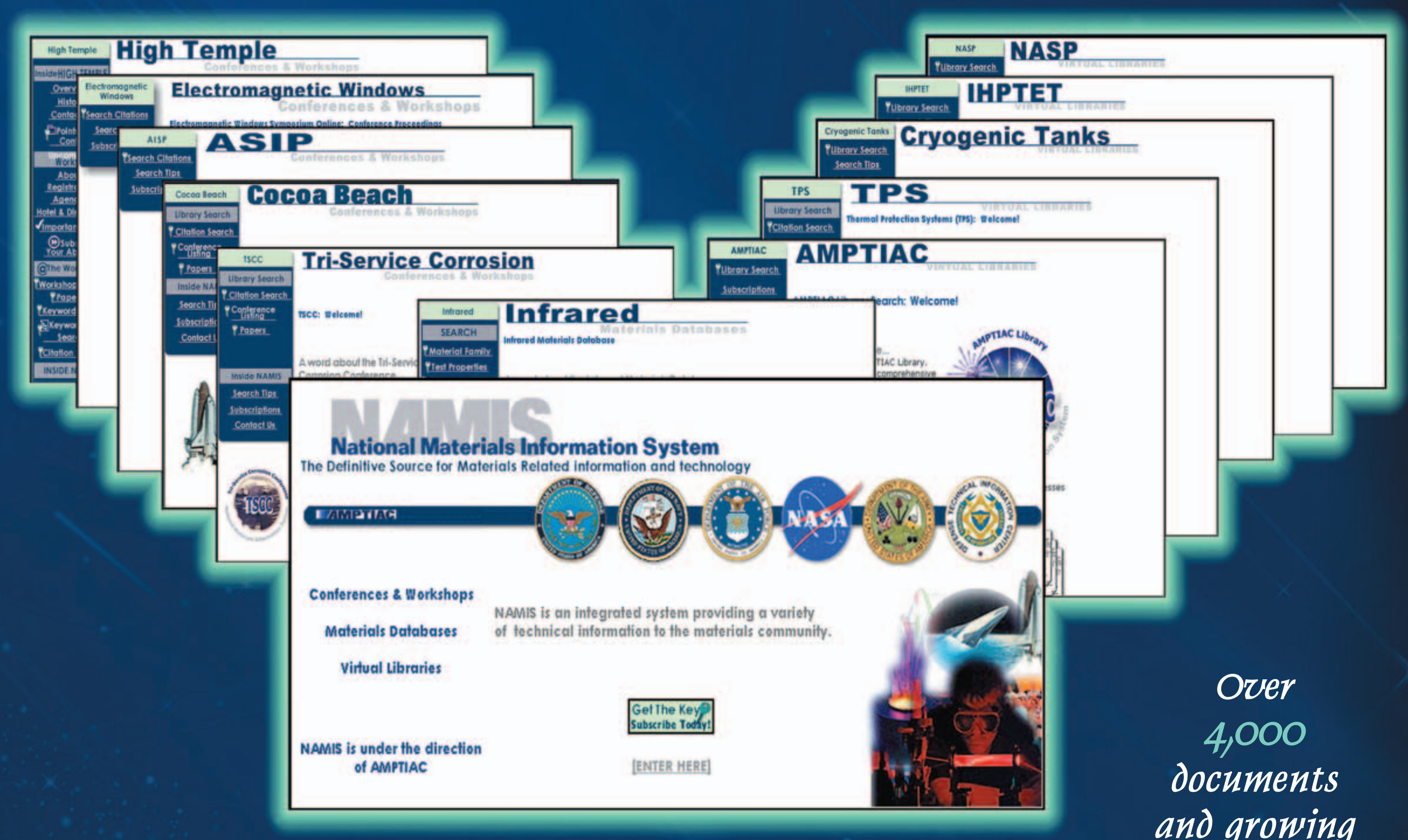
Our Apologies...

In the most recent edition of the *AMPTIAC Quarterly* (Volume 8, Number 2), we published an article that reviewed some of the nanotechnology research ongoing within the Air Force ("AFRL Nanotechnology R&D Efforts to Advance Aerospace Systems for the Next Century"). As presented, the article implied that it represented a panoramic review of nanotechnology efforts across all the constituent organizations of the Air Force Research Laboratory (AFRL). This assertion was in error: the article exclusively examined research efforts within AFRL's Materials and Manufacturing Directorate (AFRL/ML). Our staff authored the article, based upon publicly-released materials furnished to us by AFRL/ML, but was not reviewed by the Air Force prior to being published. As always, AMPTIAC takes full responsibility for the content and accuracy of every article we publish, regardless of ownership.

We originally prepared this article for inclusion in our recent special issue (Vol. 8, No. 1), which highlighted AFRL/ML achievements in materials research for space applications, and was written in that context. When read concurrently with the other articles addressing AFRL/ML research, its scope is implicit. For logistical reasons, we "bumped" the article from that issue and published it in the next issue. The article thus became a 'standalone' piece, and in doing so, its ML context was lost.

Nanotechnology is a pervasive field with potential application to most technology areas and high performance systems, both military and civilian. Most of the other Directorates within AFRL are actively engaged in their own groundbreaking research to harness the benefits of nanotechnology for their respective disciplines. AMPTIAC salutes all these organizations for their contributions in advancing the state of the art, and extends its sincerest apologies for this misperception.



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