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Engineering & Scientific Consulting

Lawrence E. Eiselstein, Ph.D., P.E.

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Professional Profile

Dr. Eiselstein specializes in failure analysis, accident reconstruction, risk analysis, and materials science (corrosion, metallurgy, composites, polymers, ceramics, and glass) as applied to product design, manufacture, intellectual property issues, and materials testing and evaluation.

Dr. Eiselstein has more than 30 years of experience assisting clients in the areas of design and failure analysis of a wide range of commercial and civil structures. His research includes the mechanical behavior of materials (strength, fracture, fatigue, and creep), armor development, corrosion science, and testing as applied to material selection, coating evaluation, breakdown potential, repassivation, polarization, galvanic, stress corrosion cracking (SCC), and hydrogen embrittlement issues.

Dr. Eiselstein's medical device consulting includes: aerosol delivery devices, anastomosis devices, catheters, cochlear implants, delivery systems, electrosurgical tools, feeding tubes, fertility control devices, guidewires, heart valves, heart valve repair devices, aneurysm repair devices, orthopedic devices, hypodermic needles, batteries, intra-aortic balloon pumps, pacemakers, stents and stent grafts, syringe, trocars, as well as other medical devices. His consulting includes design analysis and testing for FDA approval of implantable devices manufactured from plastics, ceramics, stainless steel, superelastic nitinol (NiTi), elgiloy and MP35N, support for 510K and PMA submissions to FDA as well as FMEA (failure modes and effect analysis) for medical devices, failure analysis of implantable medical devices, and intellectual property issues.

Dr. Eiselstein has applied his materials and corrosion science skills to investigate and prevent accidents involving chemical releases, fires, and explosions. He has extensive experience dealing with fatigue, deformation and fracture of materials, fractography, electronic and microelectronic failure analysis, and all aspects of corrosion (including corrosion fatigue, environmentally assisted cracking, hydrogen embrittlement) as applied to bridges, chemical and power plant components, construction industry, condensers, boilers, consumer products, electrical and electronic products, fire and explosion investigations, oil and gas pipelines, plumbing and piping, pressure vessels, reactor vessels, steam turbines, solder joints, thermal interface, underground storage tanks, and welds and brazing.

Prior to joining Exponent, Dr. Eiselstein was a metallurgist with SRI International, worked as a Research Associate at Stanford University, was a consultant for EPRI, and worked at Huntington Alloys, an INCO company.

Academic Credentials & Professional Honors

Ph.D., Materials Science, Stanford University, 1983

M.S., Materials Science, Stanford University, 1976

B.S., Metallurgical Engineering, Virginia Polytechnic Institute and State University, *with distinction*, 1974

International Nickel Company Scholarship

Townsend Fellowship

Wire Foundation Competition Prize

A.O. Smith-Inland Company 4th Annual Ferrous Powder Metallurgy Competition prize winner

Licenses and Certifications

Licensed Professional Corrosion Engineer, California, #1067

Licensed Professional Metallurgical Engineer, California, #1779

Professional Affiliations

Surface Mount Technology Association — SMTA

American Water Works Association (member)

American Society for Testing and Materials, Committee on Medical and Surgical Materials and Devices (member)

American Society for Metals (member)

American Institute of Mining and Metallurgical Engineers (member)

National Association of Corrosion Engineers (member)

Publications

Spece, Hannah, Richard J Underwood, Doruk Baykal, Lawrence E Eiselstein, Daniel A Torelli, Gregg R Klein, Gwo-Chin Lee, and Steven M Kurtz. "Is There Material Loss at the Conical Junctions of Modular Components for Total Knee Arthroplasty?". The Journal of Arthroplasty (2019).

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Sjong A, Eiselstein LE. Marine atmospheric SCC of unsensitized stainless-steel rock-climbing protection. J Failure Analy Prev 2008; 8(5).

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Eiselstein LE, Proctor DM, Flowers TC. Trivalent and hexavalent chromium issues in medical implants. Materials Science Forum 2007; 539-543:698-703.

Eiselstein LE, James BA. Medical device failures. 2nd International Conference on Engineering Failure Analysis, Toronto, Canada, September 12-15, 2006.

Beaudet RA, Berkowitz JB, Doherty RM, Eiselstein LE, Gekler WC, Gollin M. Review and assessment of the proposals for design and operation of designated chemical agent destruction pilot plants (DCAPP-Blue Grass II). National Research Council of the National Academies, July 2006.

Caligiuri RD, Eiselstein LE, Schmidt CG, Giovanola JH. Stable deformation at very high strain rates in UHCS. THERMEC'2006, International Conference on Processing and Manufacturing of Advanced Materials, Chandra T (ed), Trans Tech Publications, July 2006.

Eiselstein LE, Proctor DM, Flowers TC. Trivalent and hexavalent chromium issues in medical implants. THERMEC'2006, International Conference on Processing and Manufacturing of Advanced Materials, Chandra T (ed), Trans Tech Publications, July 2006.

James B, Wood L, Murray S, Eiselstein LE, Foulds J. Compressive damage-induced cracking in nitinol. Proceedings, International Conference on Shape Memory and Superelastic Technologies, Baden-Baden, Germany, October 3-7, 2004; ASM International, pp. 117-124, 2006.

Eiselstein LE, Sire RA, James BA. Review of fatigue and fracture behavior in NiTi. Proceedings, Materials and Processes for Medical Devices Conference, Boston, MA, November 14-16, 2005; ASM International, pp. 135-147, 2006.

James BA, Foulds J, Eiselstein LE. Failure analysis of NiTi wires used in medical applications. Journal of Failure Analysis and Prevention 2005; 82-87.

Beaudet RA, Barton C, Berkowitz JB, Doherty RM, Eiselstein LE, Forsen HK, Gekler WC, Gill CF, Roy CM, Smith KA, Stenstrom MK, Webler T. Interim design assessment for the blue grass chemical agent destruction pilot plant. Committee to Assess Designs for Pueblo and Blue Grass Chemical Agent Destruction Pilot Plants, Board of Army Science and Technology, National Research Council of the National Academies, The National Academies Press, Washington, DC, 2005.

James BA, Foulds J, Eiselstein LE. Failure analysis of NiTi wires used in medical applications.

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Eiselstein LE, Caligiuri RD. Particulate composite of white cast iron. Materials Science Forum, Trans Tech Publications, Switzerland, Vol. 426-432, pp. 895-900, 2003.

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Andrew SP, Caligiuri RD, Eiselstein LE, Parnell TK. Evaluation of a failure in a chlorine production facility. Proceedings IMECE2001, ASME International Mechanical Engineering Congress and Exposition, New York, NY, November 2001.

Moncarz PD, Eiselstein LE, Saraf V. Prestressing wire failures in prestressed concrete pipeline. Proceedings, Awarie Budowlane, 20th Engineering Conference on Construction Failures, Szczecin-Miedzyzdroje, Poland, May 2001. (In Polish).

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Moncarz PD, Eiselstein LE. Loss of composite system reliability due to long term environmental alteration. Proceedings, International Federation for Information Processing (IFIP), 9th Working Conference on Reliability and Optimization of Structural Systems, pp. 167-174, Ann Arbor, MI, September 2000.

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Rau CA, Eiselstein LE, Rau SA, Harris DO, Sire R, Dedhia D, McMinn A. Probabilistic assessment of crack initiation and growth in shrunk-on disks. Proceedings, Life Prediction of Corrodible Structures International Conference, National Association of Corrosion Engineers International, p. 51/1, Cambridge, UK, September 1991.

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1989.

Eiselstein LE, Caligiuri RD. Application of laminated metallic armors to heavy hybrid armor systems. Proceedings, 4th TACOM Armor Coordinating Conference for Light Combat Vehicles, Monterey, CA, March 1988.

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Eiselstein LE, Ruano OA, Sherby OD. Structural characterization of rapidly solidified white cast iron powders. Journal of Materials Science 1983; 483-492.

Eiselstein LE, Ruano OA, Sherby OD, Wadsworth J. Microstructural and mechanical properties of rapidly-solidified white cast iron powders. Proceedings, 3rd Conference on Rapid Solidification Processing, National Bureau of Standards, Mehrabian R (ed), Gaithersburg, MD, pp. 246-251, December 1983.

Eiselstein LE, Syrett BC, Wing SS, Caligiuri RD. The accelerated corrosion of copper-nickel alloys in sulfide polluted seawater. Paper No. 59, Corrosion/82, Annual Meeting of the National Association of Corrosion Engineers, Houston, TX, March 1982.

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Corlett N, Eiselstein LE, Budiansky N. Chapter 29. Types of Corrosion in Liquids: Crevice Corrosion in Shreir's Corrosion. Vol. 2, Editor: T. Richardson, Elsevier, 2010, pp. 753-771.

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Lemberg J, Gibbs J, Birringer R, James B, Eiselstein L. Fire cracking of leaded and lead-free brasses for use in water, oil and gas applications. MS&T 2014, Pittsburgh, PA, October 12-16, 2014.

Huet R, Eiselstein LE. Lessons learned from explosion in ammonium nitrate neutralizer. Symposium on Chemistry, Process Design, and Safety in the Nitration Industry, Spring ACS Meeting, San Diego, CA, March 25-29, 2012.

FDA, Cardiovascular metallic implants: Corrosion, surface characterization, and nickel leaching, March 8, Erica Takai: Moderator, CDRH, FDA: FDA White Oak Conference Center, Silver Spring, Maryland, 2012.

Guyer E, Eiselstein LE. Getting it right the first time: Accelerated testing of active implantable medical devices. Exponent Webinar, October 16, 2008.

Eiselstein LE, Steffey D, Nissan A, Corlett N, Dugnani R, Kus E, Stewart S. Acceptance criterion for the corrosion resistance of medical devices: A statistical study of the pitting susceptibility of Nitinol, accounting for the in-vivo environment. International Conference on Shape Memory and Superelastic Technologies, Stresa, Italy, 2008.

Corlett N, Eiselstein LE, Steffey D, Nissan A, Dugnani R, Kus E, Stewart S. Effect of long-term immersion on the localized corrosion resistance of Nitinol wire under aerated conditions. ASM International Conference on Shape Memory and Superelastic Technologies. International Conference on Shape Memory and Superelastic Technologies, Stresa, Italy, 2008.

Eiselstein LE. Material degradation issues in the implantable medical industry. Meeting of the San Francisco Bay Area Section of the Electrochemical Society, Menlo Park, CA, February 25, 2008.

Eiselstein LE, Steffey D, Nissan A, Corlett N. Toward an acceptance criterion for the corrosion resistance of medical devices: A statistical study of the pitting susceptibility of Nitinol. Proceedings, ASM International Conference on Shape Memory and Superelastic Technologies, Tsukuba City, Japan, 2007.

Nissan A, Corlett N, Eiselstein LE, Steffey D. Effect of long-term immersion on the pitting corrosion resistance of Nitinol. Proceedings, ASM International Conference on Shape Memory and Superelastic Technologies. Tsukuba City, Japan, 2007.

Eiselstein LE, James B. Medical device failure analysis. Keynote Session VI - Failure Analysis (Fracture, Fatigue, Corrosion, and Materials Degradation), Materials, Medicine, and Nanotechnology Summit, ASM International, Cleveland, OH, October 20-25, 2006.

Eiselstein, LE, James B. Keynote lecture - medical device failures. 2nd International Congress on Engineering Failure Analysis, Toronto, Canada, September 12-15, 2006.

Eiselstein, LE. Medical device failures. Medical Device Seminar: Leaders and Visionaries, Stanford University, Stanford, CA, October 25, 1999.

Eiselstein, LE. Material considerations for biomedical devices. Golden Gate Materials and Welding Technologies Conference, San Francisco, CA, February 26-28, 1997.

Caligiuri RD, Eiselstein LE. Development of metallic laminate composites for heavy armor. Defense Advanced Research Projects Agency/Army/Marine Corps Armor/Anti-Armor Joint Program Office Information Exchange, Los Alamos National Laboratory, Los Alamos, NM, March 1990.

Caligiuri RD, Andrew SP, Eiselstein LE. A review of high strain rate properties and penetration mechanisms of depleted uranium and tungsten alloys. Army Research Development and Engineering Command/Army Research Office Workshop on Metallurgical Aspects of Deformation/Failure Mechanisms in "The Terminal Ballistics of Heavy Metal Kinetic Energy Penetrators," Picatinny Arsenal, Dover, NJ, April 1990.

Reports

Eiselstein LE. Declaration of Lawrence Eiselstein in Support of Motion for Summary Judgment. Fireman's Fund Insurance Company, Plaintiff, v Columbia Mechanical Contractors, Inc., Defendants, Exponent Report to William B. Waterman, October 2005 (Rule 26B Report).

Eiselstein L, Belanger J, Buehler C, Reza A, Ogle R, Adan M. Investigation of the explosion at Ultem Monomer production plant. Exponent Failure Analysis Associates, December 2003.

Eiselstein LE. Support of Plaintiff Microlife Intellectual Property GmbH's Opposition to Defendant

Actherm, Inc.'s Motion for Summary Judgment of Non-Infringement of U.S. Patent No. 6,419,388, Microlife Intellectual Property GmbH Plaintiff and Counter defendant, v Actherm Inc. Defendant and Counterclaimant. Civil Action No. C 03-1117 (SBA) in U.S. District Court for Northern District of California, Oakland Division, September 2003 (Rule 26B Report).

Eiselstein LE. Supplemental Declaration of Lawrence E. Eiselstein, Marchon Eyewear, Inc. and Rothandberg, Inc., Plaintiffs, v Global Optical Resources, Inc., Defendant, Exponent Report to Frommer Lawrence & Haug LLP, June 2003 (Rule 26B Report).

Eiselstein LE. Stern tube corrosion and cathodic protection. Exponent Report to United States Coast Guard, Lockport, LA, May 2003.

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Eiselstein LE, Giddings V, Kennedy R, Mahnovski S, Medhekar S. Zelickson Patent Valuation. Enteric Medical Technologies and Boston Scientific, Exponent Report, August 2002.

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Eiselstein LE. Stress Corrosion Cracking of CAP Wire. Exponent Report to Rogers, Joseph, O'Donnell & Quinn, July 2000.

Eiselstein LE. Support of COM/Energy's Memorandum of Law on Harvard's Purported Damages in President and Fellows of Harvard College, Plaintiff v COM/Energy Steam Company. Report to Riemer & Braunstein, April 2000 (Rule 26B Report).

Eiselstein LE and Moncarz P. Hayden-Rhodes Aqueduct Siphon Rebuttal Report. Exponent Report to Rogers, Joseph, O'Donnell & Quinn, March 2000.

Paduano D and Eiselstein LE. CS Integrated v. Vilter Manufacturing Exponent report to McCutchen, Doyle, Brown & Enersen, May 2000 (Rule 26B Report).

Eiselstein LE. Rebuttal Report (Subject to Protective Order). Cordis Corporation, Plaintiff v Advanced Cardiovascular Systems, Inc., Medtronic AVE, Inc., Boston Scientific Corporation, and Scimed Life Systems, Inc. Defendants and Medtronic AVE, Inc. Plaintiff, v Cordis Corporation, Johnson & Johnson,

and Expandable Grafts Partnership, Defendants. United States District Court for the District of Delaware, February 2000 (Rule 26B Report).

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Eiselstein LE and Haussmann G. Investigation of the October 23, 1995 Chemical Release at Gaylord Chemical, Bogalusa, Louisiana. Exponent Report, September 1998.

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Project Experience

General Failure Analysis

Power Plant Steam Explosion — Investigated a steam explosion at a fossil fueled power plant that killed four plant personnel. One of the plants main steam lines had been severed as a result of a large primary air draft fan failure that was used to blow crushed coal into the boiler. Fractography, fracture mechanics, material testing, and metallurgy were used to help investigate the cause of this accident. Pieces of the fan were put back together to identify the origin. The failure was traced to a weld crack. These results were presented to the plant personnel concerned about plant safety.

Railroad — Determined the cause of a rail axle failure that resulted in a train derailment. A combination of corrosion, fatigue, and inadequate non-destructive inspection (NDE) and repair was found to be the cause.

Automotive — Examined fatigue and corrosion induced cracks in automotive stabilization bars.

Power Steam Turbine Experience — Investigated the corrosion mechanisms associated with stress corrosion cracking (SCC) of steam rotor materials for EPRI (Electric Power Research Institute). This research included measurements of initiation and growth of SCC cracking in low pressure steam turbine disks. In another project, I performed a probabilistic based risk analysis of LP steam turbine disk cracking for a large number of units operating at a mid-west power plant.

New York City Williamsburg Suspension Bridge — Investigated the atmospheric corrosion damage that had occurred over the 80-year life (now over 100 years old) to the Williamsburg Suspension Bridge main suspension cables. This bridge was opened to traffic in 1903 and the four main support cables are composed of 7,696 high carbon patented steel wire. These wires were ungalvanized but given a protective organic coating when installed. Wire samples were removed from the cables and evaluated for corrosion damage and mechanical properties. Mechanical properties had been degraded. Accelerated corrosion tests were used to estimate the current rate of corrosion.

Atmospheric Corrosion of Copper Coated Stainless-Steel Architectural Material — Investigated the nature of corrosion failures that was occurring on copper coated stainless-steel sheet that was being used as roofing, gutters and siding on homes and businesses. In some cases, the atmospheric corrosion of the electroplated stainless-steel sheet had corroded sufficiently to expose the underlying stainless steel. In other cases, the stainless-steel sheet had undergone pitting to such an extent to allow water to leak through. Atmospheric corrosion rates that can be expected for copper in various environments such as marine or coastal, urban, and rural areas were reviewed. The potential for galvanically assisted pitting of the stainless steel was also investigated. The acidic condensation from chimneys and flues was found to rapidly strip off the copper plating.

LM2500 Gas Turbine Failure — Investigated the reason for the failure of a LM2500 turbine. Turbine bolting manufactured from Inconel 718 that had been plated with silver for anti-galling (low friction) had failed while the unit was at full power. Issues were turbine operating temperature, creep-fatigue, and hot corrosion (sulfur and chloride).

Steam Turbine Rotor Straightening — Investigated the reasons for the warpage (bowing) of HP/IP rotors

manufactured from Ni-Cr-Mo-V steel. The effect of turning gear failure, creep during time at temperature while stationary, the effect of thermal gradient induced thermal stresses (from rubbing or loss of turning gear) on plastic and creep deformation, and the resulting residual stresses induced by these permanent deformations were considered along with the effectiveness of proposed straightening methods.

Fertilizer Plant Explosion — Investigate the December 13, 1994 massive explosions that leveled portions of a Port Neal, Iowa, ammonium nitrate plant owned by Terra Industries. Four plant workers were killed, eighteen others suffered serious injury, and damage to the plant and surrounding community was estimated in the hundreds of millions of dollars. Reviewed the events surrounding the accident, analyzed the plant's process data for reliability, and conducted extensive research regarding ammonium nitrate properties and decomposition mechanisms. Also completed analytical modeling and experimental testing to resolve the conflicting accident theories and inspected and performed metallurgical analysis of various artifacts from the explosion site. The investigation revealed that the detonations occurred due to unsafe plant operations, including poor maintenance and inadequate employee training. Specifically, plant operators allowed the ammonium nitrate within their 18,000-gallon-capacity neutralizer vessel to become contaminated and highly acidic. Operators then injected superheated steam directly into the neutralizer vessel, precipitating a runaway chemical reaction.

Inconel 718 Fuel Nozzle Cracking — A commercial airliner experienced an in-flight engine fire and shutdown in Paris that was linked to the failure of the superalloy Inconel 718 forged fuel spray nozzle used in certain Rolls Royce engines installed on Airbus and Boeing aircraft. This led to the worldwide replacement of thousands of fuel spray nozzles on hundreds of aircraft. We investigated the nature of the aircraft fuel nozzle cracking, the forging procedures (forgability limits, forging temperature), ingot size, and inspection and manufacturing techniques used to make these nozzles.

Ammonium Perchlorate Plant Explosion — Investigated the cause of a series of explosions that destroyed a solid rocket oxidizer plant (ammonium perchlorate manufacturing facility) in Henderson NV. The largest of five individual explosions at PEPCON was equivalent to 1.5 million pounds of TNT, and another explosion was equivalent to 500,000 pounds of TNT. Assessed the role that ERW weld defects in a 16-inch high pressure natural gas pipeline that traversed the plant and was damaged by the explosions may have played in the incident.

Oil Well Perforation Gun Explosion — Investigated a perforation gun explosion at the Halliburton Industries assembly plant in Kenai, Alaska that killed one employee and seriously injured five others. Perforation guns are used in oil well completion to perforate the oil well casings to allow oil to flow into the well. A perforation gun consists of numerous explosive shaped charges aligned within a pipe. The explosion occurred and workers were injured during the shop assembly of the perforation gun. Exponent's forensic investigation involved detailed examination of the remaining fragments, combined with mapping of the fragment locations after the explosion, to determine the sequence of events that led to the explosion. The evidence indicated that an employee accidentally ignited the shaped charges or the detonation cord within the gun.

Drill String Failures — Investigated the cause of several drill string failures. These failures involved complete separation of the string at the threaded coupling, rather than the more commonly observed washout failures that occur in the main pipe segment. These failures occurred at various depths and total drilling hours. Testing and finite element analysis was performed to determine if these failures were a result of stress corrosion cracking (SCC) or from fatigue from stresses in the shoulder of the coupling.

Galvanization of Steel Structural Steel Beam Cracking — Investigate reported incidents of cracked galvanized structural beams found in buildings over the last few years. Although cracking of steel beams in galvanizing baths is not a new phenomenon, there is a concern that the rate of cracking, although still small, has increased since 2000. The observed cracking is due to a mechanism known as liquid metal assisted cracking (LMAC) LMAC is a form of liquid metal embrittlement (LME). LMAC is a result of the simultaneous application of a high stress, a potentially deleterious environment (the galvanizing alloy) and a susceptible material (the steel) used for the structural beam. Several variables can affect LMAC, which

makes predicting how and when it will occur challenging. Selecting an appropriate nondestructive testing (NDT) technique for inspection of beams containing LMAC cracks requires careful consideration as they can be filled or covered with the zinc (Zn) galvanizing alloy. This makes visual and dye penetrant testing impossible. It may be possible to use a modified magnetic particle testing technique, or even ultrasonic testing (UT) or eddy-current testing (ECT), to detect such cracks.

Natural Gas Fitting Failure and Explosion — Investigated a natural gas explosion that occurred in a mobile clinic. Examined a broken copper natural gas fitting on the clinics heater to determine the cause of failure. The failure was found to be a result of fatigue and not stress corrosion cracking.

Refinery Pipe Rupture and Fire — a metallurgical evaluation into the cause of the rupture of an elevated temperature steel pipe in a petrochemical refinery was performed. The pipe had been in crude oil distillation service for many years. The pipe was found to have thinned and ruptured as a result of sulfidation corrosion (also known as sulfidic) corrosion. Rates of sulfidation corrosion as a function of various variables were reviewed including McConomy and modified McConomy curves.

Refrigerator Compressor Failures — Excessive field failures were observed a few years after introduction of a new type of refrigerator compressors. The investigation included engineering analysis of wear in the compressor parts as well as statistical analysis to determine the factors associated with field failures.

Membrane permeation cartridges — Investigated the performance of vapor permeating membranes for ethanol purification (dehydration) for fuel grade ethanol. This included a thorough review of plant operating conditions as well as establishing a mathematical model of the cartridges to deduce the membrane permeability from the cartridge operating parameters. The membrane had a high tolerance to high water contents, the distillation stage did not need to go up to the azeotrope (92%), which enables the process to be more energy efficient when compared to other dehydration methods. In addition, the dehydration process is continuous rather than a batch one as there is with zeolite-based fuel grade ethanol dehydration processes.

Home High Efficiency Furnace — Examined the corrosion damage to the enameled steel heat exchanger used in a condensing home furnace. X-ray photoelectron spectroscopy (XPS also known as ESCA) was used to characterize the pitting damage.

Armor/Anti-Armor — Worked on various armor and anti-armor projects. Designed, manufactured, and ballistically tested these armor systems (metallic laminates and ceramics) against a variety of threats from small caliber to shaped charges and kinetic energy penetrators. Manufacturing techniques included roll bonding, superplastic solid-state pressure induced diffusion bonding, electron beam welding, hot isostatic pressing (hipping) and other techniques. Hardness, metallography and grain size analysis of tantalum shape charge liner materials.

Shaving Cream Can Corrosion — Investigated "rust free" exploding shaving cream cans. This incident resulted in a product recall. The pressurized "rust free" (i.e. aluminum not steel) shaving cream cans were filled with shaving cream foam with an isobutene propellant. The pH of one of the two shaving cream formulations was of a sufficiently high pH to result in corrosion penetration of the uncoated aluminum can inner surface.

Wastewater Treatment — A major regional county sanitation district experienced a leak in their sulfur dioxide evaporator within 72 hours after placing a 90-ton railcar on-line. The wastewater processed at the plant goes through a series of treatment steps before it is released to the environment. These include primary and secondary treatment, chlorination and de-chlorination. Sulfur dioxide (SO_2) is used to neutralize residual chlorine (de-chlorination). The corrosion induced SO_2 release was attributed to the much higher than specified moisture of the SO_2 in the rail car.

Sanitation District Methane Gas Storage — Investigation of corrosion on the inside of methane gas storage spheres. The corrosion investigation looked at issues of atmospheric corrosion and the effect of

the presence of condensation and carbon dioxide in the methane.

Dechlorination Facility Corrosion — This was the investigation of a through-wall penetration of the steel carbon dioxide line (CO_2) used for dichlorination/dechloramination prior to filling a lake reservoir with excess treated water. The effect of soil chemistry and stray current were investigated as potential causes for the leak.

Digester Facility Coating — Steel tanks used for anaerobic digestion of waste had been painted and the coating was failing at and above the water line. Issue was to determine if the coating failed as a result of thermo-chemical degradation or as a result of being improperly applied.

Boiler Steam Explosion — Soon after commissioning a boiler at a smelter plant severe corrosion was discovered in the bottom section. To reduce the corrosion/erosion rates of the SA-192 steel tubes it was decided to weld overlaid these tubes with Inconel 626. About two years later, there was a steam explosion in the boiler. Laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS) was used to identify the weld and tube chemistry.

Food and Beverage

Pear Can Corrosion — Approximately 8 million cans of cooked fruit were produced over a two to three-month time period, 5.8 million cans were produced on one production line. Three months later when cans were being removed from the pallets for labeling and shipping to customers, noticeable and extensive rusting was noted. We investigated the cause of the rusting and determined whether the rusting would continue and eventually cause leakage. Several factors that may have contributed to the rusting included:

- Stray current from the cooker resulting in rapid corrosion of the cans;
- Too much chlorine added to the water used to wash and cool the cans; or
- The cans may have been too wet (or too cool) when they came out of the cooler, and therefore did not dry immediately, thereby allowing corrosion to occur.

Carbonated Beverage Can Corrosion — Several cargo shipping containers containing carbonated beverages cans (soda) were found to have leaked during oversea transport to market. The majority of these soda cans were found to be empty as a result of corrosion induced leaks. Typically, there is no protective coating on the can outer surface. When one can leaked it resulted in a chain-reaction of leaking cans as the first leaking can wetted the cardboard containers with low pH carbonated cola. The unprotected can bottoms then rapidly corroded and leaked, wetting more cardboard and therefore causing more cans to leak.

Food Contamination — Investigated claim of mercury contamination frozen food product and identified source of metallic objects found in fruit juice.

Welds and Welded Connections

Steel Moment Frame Weldment Failures — Investigated the causes of failed steel moment frame welds after the Northridge Earthquake in Los Angeles, CA. Investigation included metallurgical examinations of failed welds removed from buildings, chemical analysis of weld material, and analysis of the potential for hydrogen induced weldment cracking.

Engineering Significance of local brittle zones (LBZ) in U.S. Navy ships- HSLA-80 is the name used to designate ASTM A710 Grade A Class 3 steel that has been modified to a military specification that, along with other requirements, specifies a minimum yield strength of 550 MPa. The Navy's certification of HSLA- 80 for use in surface ship hull construction occurred in February 1984 and provided shipbuilders with their first new steel since the mid-1950s. This steel has been used as a replacement for martensiticHY-80 steel in the construction of U.S. Navy ships beginning with cruisers of the Ticonderoga class. The low carbon content ofHSLA-80 makes it much less sensitive to hydrogen-assisted HAZ

cracking, and therefore it can be welded without the expensive preheat and process controls required for HY-80. During the certification process, the Navy conducted an intensive testing program to characterize HSLA-80 base plate and weldment properties. In this project, the engineering significance of local brittle zones in multi-pass, HSLA-80 steel weldments that might be subjected to large strains (such as the straining that occurs during explosive bulge testing): was evaluated using probabilistic fracture mechanics. The heat affected zone of HSLA-80 was modeled as containing only two distinct types of material along the fusion line, local brittle zones, and the gaps between them. The local brittle zones have a lower toughness than gap material, and both have toughness properties that are lower than those of the base plate. The model calculated the failure probability of weldments as they are plastically strained to various levels by simulating the growth of preexisting crack-like weld defects that are distributed along the fusion line and within the weld metal. Failure was considered to occur if weld defects link up and grow through the entire plate thickness. The model incorporates the statistical variation of the toughness for the base metal, weld metal, local brittle zones, and gap materials to model the tearing resistance along the fracture path. The probabilistic fracture mechanics modeling of typical HSLA~80 weldments indicates that the distribution and toughness of local brittle zones and gaps have a small effect on the failure probability at large plastic strains typical of explosive bulge tests. The calculated failure probabilities agree with a limited number of actual explosive bulge tests. At the large strain levels considered; the simulations showed that the failure probabilities are nearly equal to the existence probability of welding defects.

Stainless Steel Piping Welds — Investigated the corrosion damage to stainless steel piping and welds in a semiconductor equipment manufacturing facility that had a hydrochloric acid (HCl) spill. The heat affected zone of the welded stainless-steel piping was inspected for pitting and stress corrosion cracking. Methods for cleaning and passivating the stainless-steel piping in place were evaluated.

Residual Stress in Space Satellite Fuel System — Investigated the effect of residual stress in an electron beam (EB) welded component used in a satellite fuel system. The failures appeared to be the result of low-cycle fatigue.

ERW Weld Corrosion Attack — The electrical resistance weld in steel piping used to pipe water to and from the cooling tower in an HVAC system was analyzed to determine if it was defective.

Ceramic-to-Metal Seal Braze — An exploding bridge wire detonator used in the aerospace industry was analyzed for reliability. The thermal stresses resulting from the difference in thermal expansion coefficient between the low expansion alloys used (Kovar and Invar), alumina, and the brazing alloy were analyzed.

Failure Analysis of EB and Laser Welded Inconel 718 Nickel-Hydrogen Battery — Some batteries used for an aerospace application developed a leak while in service after various charge/discharge cycles which cyclically pressurize and depressurize the battery. The manufacturing methods and materials used to manufacture nickel hydrogen battery were reviewed. Micro-fissuring grain boundaries during welding, niobium enrichment, delta phase precipitation, deep drawing and heat treatment variations, hydrogen assisted crack growth, caustic SCC, and other factors were considered as a potential cause for leaks.

Cracking of Nickel 200 Spot Welds on Cathodes in a Clorox Chlor-Alkali Plant — Examined some Nickel 200 spot welds that were found cracked in the cathode portion of chlor-alkali production cells at a chlorine production facility and determined the nature of this cracking. The nickel was exposed to 32-wt% caustic at 90 °C. These cracks occurred in the heat-affected zone of the welds and therefore were not associated with defects in the weld metal, such as solidification porosity or hot tearing. The cracking was intergranular with little, if any, indication of ductile rupture. The location of the intergranular cracking in the heat affected zone of the spot welds may indicate that this cracking is associated with precipitation of a carbon film (or graphite), or segregation of sulfur, antimony, tin or some other known embrittling trace element in the Nickel 200, at the grain boundaries during cooling. It is also at or near the maximum stress location. This cracking is most consistent with hydrogen embrittlement cracking driven by hydrogen charging at the cathode, potentially exacerbated by mechanical embrittlement from graphite precipitation or metalloid segregation in the grain boundaries.

Pipelines, Piping, and Plumbing

Hot Water Recirculation Systems — Investigated the reasons for copper plumbing (piping) leaks in a housing development. The failure investigation indicated the reason was too high a flow rate of the water in the hot water recirculation system that caused erosion-corrosion of the copper piping that was comprised of both hard and soft copper lines.

Pitting of Copper Tubing in Computer Room Air Handlers (HVAC) System — Investigated the cause of through wall pitting of aluminum finned copper tubing used in a large data center's air handler (i.e. computer room air handler - CRAHs) chilled water system. This system containing, both steel and copper piping in the computer room, had been originally run with a nitrite-based water chemistry with the addition of tolyl-triazole (TT) as the copper corrosion inhibitor. These units had been in operation for about 5 months when the first leaks were reportedly. These leaks are clearly the result of internal corrosion, but the corrosion that is occurring in the coils was not reflected in the copper and iron corrosion coupons that were exposed to the chilled water. This was likely a result of the position of these specimens in the system where there is never any stagnant flow. Corrosion test coupons generally give only uniform corrosion rates whereas the damage observed in the copper coils is pitting. Such pitting could be missed if only the uniform corrosion rates are considered without a detailed examination of the corrosion coupons looking for the formation of small pits. The copper coils leaked as a result of internal pitting corrosion as a result of microbiological influenced corrosion (MIC) of the copper. Some algae were found in the chilled water. In addition, the presence of MIC was supported by the corrosion morphology (isolated pits under deposits) and DNA/RNA testing indicating the presence of denitrifying and nitrifying bacteria. The use of nitrite in an open loop system that can allow oxygen ingress that will convert the nitrite to nitrate may have provided a food source for the nitrifying-denitrifying bacteria. In addition, the lack of a biocide would allow MIC to occur. The very thin wall of the copper tubes makes them very susceptible to corrosion induced leaks.

Crude Oil Pipeline Release — Investigated, performed a failure analysis, and provided testimony regarding the adequacy of the corrosion protection (coating and cathodic protection) of a 20-inch diameter crude oil line that leaked. The leak was found to have occurred on the bottom side of the pipe elbow. The corrosion that caused the crude oil release was a result of anaerobic microbiologically induced corrosion (MIC). This type of corrosion can be very rapid and can occur even if the pipe is being appropriately cathodically protected, that is maintained at a pipe-to-soil potential below -850 mV vs. Cu/CuSO4. There was no evidence that this line was improperly cathodically protected or that the leak was a result of stray current from either high-voltage electrical transmission lines overhead, the railroad nearby, or other potential sources. Exponent performed an experiment that allowed the amount of oil released to be calculated given certain assumptions regarding the temperature and pressure history at the elbow, oil viscosities, and time at which the elbow was penetrated.

Corrosion investigation of piping, tanks, and joints at gasoline stations — Investigated the condition of metal product (gasoline) piping (primarily galvanized pipe), joints and unions at gas stations and evaluated the corrosion, if any, observed.

Casing and Coupling Gas Well — Investigated issues regarding the design, manufacture, and assembly oil country tubular goods for use in oil and gas wells in Texas. Plated 5-1/2" P110 steel connectors were bucked onto the casings (about 45,000 feet of API Grade P-110 seamless casing) and were in several wells in Texas. The production strings installed in the wells were subjected to high pressure hydraulic fracturing ("fracking") technique to put the wells into production. After the casing had been run into the well using normal running procedures, had been cemented and during the early stages of the hydraulic fracturing of the wells, some of the connections failed (cracked) at pressures below design specification resulting in a loss of the wells. I reviewed evidence regarding the allegations that the coupling/connectors were improperly designed, manufactured from substandard steel, improperly heat treated, were not bucked on properly (i.e. excessive torque), were coated improperly leading to hydrogen charging, or subjected to a sufficiently acidic environment during the hydraulic fracture from the fracking fluid to result in hydrogen assisted cracking, or a sufficiently "sour" environment (i.e. sufficient hydrogen sulfide to result

in sulfide stress cracking.

Natural Gas Pipeline Rupture and Explosion — Investigated the cause of a 36-inch natural gas transmission pipeline rupture that occurred in Carlsbad, NM. This investigation including evaluation of the effects of internal corrosion and assessed the extent to which water ingress into the transmission line from third party producers and the pipeline configuration may have contributed to the observed internal corrosion.

Natural Gas Pipeline Permit to Increase Operating Pressure — Performed a technical evaluation of a petition to modify an existing special PHMSA permit to allow a gas transmission company to increase the maximum allowable operating pressure (MAOP) in this section of its pipeline. This modification would allow the company to undertake fewer excavations and repairs at areas where surveys indicate damage to the pipeline coating. Analysis of alternating-current voltage gradient (ACVG) indications of coating damage could have been a result of either third-party excavations at various locations along the pipeline or corrosion. Factors such as external SCC and denting or gouging (as determined by in line inspection (ILI) and external corrosion direct assessment ECDA)) were considered.

Painted Steel Pipe Aqueduct — Investigated the condition of 10 miles of painted above ground steel piping with approximately half inch thick wall that had become submerged as a result of a flooding event. Pipe diameter varied from 65-inches to 87-inches. Some flood induced abrasion damage to the paint was noted on some of the pipelines. Biological growth was also observed on the paint on the undersides of the pipelines. There was little to no significant corrosion damage to the steel pipeline. Various alternatives were considered regarding how to bring the pipeline coatings to pre-flood conditions.

Evaluation of Corrosion on Stainless Steel: Carbon steel and stainless-steel piping and fittings were submerged for several days in flood waters. These pipes and fittings were to be used in the construction of a liquified natural gas facility. These components were inspected and subjected to wipe sampling for the presence of chlorides and sulfates and swab sampling for the presence of microbes that could cause microbiological influenced corrosion (MIC). The microbiological testing was performed using a DNA method that does not involve culturing. Samples, including positive and negative test controls, were analyzed for slime formers. As some slime formers are associated with MIC of carbon steel and stainless steel, but the primary microbial groups associated with MIC are the iron-depositing bacteria (IDB), sulfate-reducing bacteria (SRB), sulfuric-acid-producing bacteria (APB), and nitrifying bacteria.

Underground Corrosion of Cast Iron Water Main — Investigated and testified on the reasons for a cast iron water main failure. The reasons were graphitic corrosion and lack of cathodic protection. (CP)

City Water Main Failures — Investigated several instances of water main failures. In one instance, as described in the following, the reasons for repeated water main failures in a municipal water distribution system was investigated. The system consisted of a network of 6-inch, 8-inch and 10-inch diameter cast iron pipes. A section of 10-inch diameter pipe ruptured several times and the Department of Public Works (DPW) took the section of water main out of service until repairs or replacement could be completed. The DPW reported that this water main system had been repaired five times over the last two decades. Our investigation was to identify the cause of recent breaks and to help the city identify what remaining portions of the water main within the area could remain in service without significant risk of imminent rupture. We determined these pipe sections were gray cast iron with a mortar coating on the interior surface and no coating on the exterior surface. There was no cathodic protection on this pipeline as determined by the pipe-to-soil potential measurements. The most recent pipe rupture showed signs of extensive graphitic corrosion. Graphitic corrosion occurs in gray cast iron where the graphite flakes (inherent to gray cast iron) act as a cathode, thereby accelerating anodic dissolution of nearby iron. This leaves behind the graphite network which maintains the structural shape of the pipe but lowers the burst strength of the pipe. Graphitic corrosion had completely penetrated the 0.375-inch wall of the pipe over an extensive area. Once the extent of graphitic corrosion has affected a enough area and depth of the pipe wall, the internal pressure of the pipe is enough to cause rupture of the area of graphitic corrosion. Soils with a corrosion rate that could penetrate a 0.375-inch-thick cast iron pipe wall in twenty years (the

approximate pipe age) would be classified as moderately to severely corrosive on the basis of reported graphitic corrosion rates. None of the non-ruptured pipe sections examined showed signs of through-wall corrosion. The rough coincidence of a former stream channel and highly corroded pipe suggested that elevated groundwater levels were the most significant factor affecting corrosion rates along this portion of the water main system. However, localized areas of saturated soil may exist in other areas from existing leaks in the pipe, leakage from the artificial stream/pond systems, irrigation, and low areas lacking adequate surface drainage were not ruled out as reasons for the external corrosion.

External Underground Corrosion of Copper Laterals — Investigate the reasons for through wall corrosion of copper laterals in a new housing development. Cathodic protection was recommended.

External Underground Corrosion of HVAC Supply/Return Water Piping — Investigate the reasons for through-wall corrosion of steel HVAC supply and return underground water piping to office building. Stray current effects were evaluated. Isolation and cathodic protection were suggested as a remediation method.

PEX Plumbing System Failures — Leaks in many homes utilizing a cross linked polyethylene (PEX) plumbing. The majority of leaks occurred on the hot water supply line. The PEX plumbing joint is composed of PEX piping, a brass elbow or tee, and stainless steel crimp bands. The stainless steel bands are used to clamp PEX tubing to brass fittings. Some of these clamps had failed resulting in a leaking joint. Scale or deposits were found on the inside and outside of the incident brass fittings. Analysis of the corrosion deposits was done with energy dispersive spectroscopy (EDS) in a scanning electron microscope (SEM). The deposits were composed mainly of zinc, oxygen, and aluminum with traces of carbon, lead, iron, and nickel. SEM examination of the fractured stainless steel crimp bands indicated it failed from intergranular stress corrosion cracking (SCC). EDS analysis revealed chlorine present on the band near the fracture surface. The SCC of the stainless steel clamp appears to be the result of moisture and contaminants leaking through the wall of the dezincified brass.

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Polybutylene Potable Water Pipe Failure — A landslide occurred on a steep hillside. A leak in polybutylene potable water fitting on supply main may have been the reason the landslide occurred after a long dry spell. Polybutylene (PB) pipe has a high susceptibility to chemical degradation, and a low resistance to cracking. The rate at which antioxidant are leached from the pipe interior, water chemistry, and the stress in the PB pipe at the rigid coupling, factors in environmental stress cracking (ESC) were considered. Fractography of the PB pipe fracture surface was performed to determine if the pipe failed as a result of ESC and thereby a cause of the landslide or from ductile overload and thereby a result of the landslide.

Ethylene Steam Pyrolysis Furnace — I have investigated two ethylene plant incidents. Both incidents resulted in damage to the high temperature tubes that are used to convert the ethane to ethylene. Both incidents resulted from a sudden and unplanned shutdown of an ethylene steam cracker plant from a loss of electrical power. This rapid shutdown caused immediate and potentially latent damage to the expensive nickel-chromium-iron (Ni-Cr-Fe) centrifugal case furnace tubes (cast HP or HK alloys or Incoloy 800H) .Ethylene is obtained by flowing hydrocarbons (e.g. ethane) and steam inside tubes heated

in a furnace; the reaction produces light alkenes (including ethylene) and hydrogen. The furnace is heated by gas burners; the tube temperature in service is about 1000 °C (1800 °F). At these temperatures the tube metal experiences several damage mechanisms that eventually result in tube failure and replacement. A byproduct of the reaction is the formation of a layer of coke (carbon) on the inner surface of the tube. This layer is detrimental for several reasons; it acts as a thermal insulation barrier between the tube and the cooler gas inside the tube, thus increasing the tube metal temperature. If the coke buildup severely restricts the flow of gas inside the tube or completely plugs it, the entire tube will overheat because it will no longer be cooled by the gas flow on the inside. As a result, the coke layer must be removed periodically by flowing only steam in the tubes, or steam and some air. This burns off the coke. The change between carburizing and decarburizing conditions at the tube inner surface contributes to surface damage. Decoking accelerates the tube degradation. The various damage modes and operating conditions leading to tube failures were investigated and include:

- Carburization during normal operation where carbon diffuses into the metal Operating with thick coke
- Deposits will increase tube temperature, accelerating carburization and shortening tube life
- Oxidation and wear of the inside surface. Oxidation may occur during decoking cycles, eroding and consuming the metal matrix.
- Overheating and melting of the tubes if the coke deposits are too thick or if a tube becomes partially or completely plugged.
- Sulfidation: Hydrocarbon mixtures frequently contain some level of sulfur. Although sulfur may be used to the control of coking rates, iron- and nickel-based alloys are susceptible to accelerated high temperature degradation when exposed to sulfur compounds, as a result of the low melting temperature of various metal sulfides. For example, nickel sulfide (Ni_3S_2) melts at 635 °C.
- Creep, which is a phenomenon where metal under stress at high temperature will slowly deform and eventually crack.
- Thermal fatigue, due to cyclic stresses.
- Metal embrittlement due to formation of intermetallic phases or sigma phases.

Central Arizona Project (CAP) Pipe Failure — Investigated the reason for pre-stressing wire failures that occurred on the pipe used in the Central Arizona Project (CAP). CAP is a waterway transporting water from the Colorado River to central and southern Arizona. At the time of construction, it was the longest single water transportation project ever authorized by the United States Congress; it combines an intricate system of canals, tunnels, pipelines and pumping stations. Where CAP crosses seven major riverbeds and washes, 6.4 m (21-foot) diameter inverted siphons are used. Six of these seven siphons, ranging in length from one quarter mile to almost two miles in length, were constructed from what was at the time, the largest precast prestressed concrete pipe ever manufactured, that is, pipe with an internal diameter of 6.4 m (252 inches), a wall thickness of 0.54 m (21 inches), and a length of 6.9 m (22.6 feet). Individual prestressed concrete pipe (PCP) sections weighted as much as 225 tons. The prestressing wire was high-strength patented steel wire (ASTM A648 Class III) and up to 35 km (22 miles) of wire was used to prestress each pipe segment. This prestressing placed the wire at approximately 75% of the wire's minimum ultimate tensile strength (UTS). The wire was then covered by a thin layer of mortar. The pipe sections were not coated or cathodically protected. Wire fractures and splits were the main symptoms of wire distress in the CAP pipes. While the mortar initially contained relatively low concentrations of chloride, evaporation led to a chloride concentration build-up to levels supporting SCC. Water sources included ground water and pipe joint leakage, both of which can contain chloride. Evaporation of the water, as it "wicked" up around the pipes through the mortar, deposited the chloride within the upper half of the siphon pipes, eventually concentrating it to levels exceeding the values necessary to initiate. Chloride levels in the wet/dry transition zone of the siphons appear to have been high enough to cause SCC without any significant carbonation of the mortar or the core. These conditions would not have occurred in the absence of a frequent or continuous evaporation process, a direct result of the CAP geographic location and the size of the pipe, as well as the arid area soil characteristics.

Brass Plumbing Failure — Several brass elbows from two different commercial installations had failed. The cracking on the female end was examined with optical microscopy and the fractures surfaces with

SEM/EDS. Ion chromatography of debris, corrosion product, and solder flux found on piping and fittings was examined for contaminates that may be responsible for SCC. The evidence pointed to fitting failures from over tightening.

Inconel 625 Piping and Fittings — 6-inch diameter Inconel 625 (N06625) seamless pipes and fittings were supplied to a middle east project an oil extraction and conditioning facility. The crude was sour and contained very high concentrations of hydrogen sulfide (H2S). The piping was to be supplied in the cold-worked and annealed condition in accordance with ASTM B444. Through mechanical testing, metallography, and NDE ultrasonic testing. It was determined that the majority of the piping and fittings did not comply with the technical specifications.

Copper plumbing leaks: Leaks in copper piping was a result of pitting corrosion on the inner surface of the pipe as a result of the supplied water chemistry. There was no indication of general corrosion, erosion-corrosion (also known as flow-induced corrosion), mechanical damage, defective piping, or solder flux induced corrosion.

Intellectual Property Litigation

Nitinol Patent Infringement — Provided expert testimony in an intellectual property litigation involving whether multiple companies were infringing a patent involving superelasticity and shape memory properties of nitinol (NiTi). This effort included reviewing the patent, reviewing the court rulings, and testing exemplar materials to determine their shape memory and superelastic properties.

Stent Patent — Testified in an intellectual property dispute regarding whether a stent being manufactured and sold infringed on a stent patent. The issues involved both manufacturing methods as well as design issues.

Wafer Cleaning Patent Infringement — Review a new wafer cleaning apparatus to determine if there might be infringement of existing patents.

Mitral Valve Repair Patent — Reviewed a patent and a venture capital funded company's proposed mitral valve repair device to see if there would be infringement.

Gastroesophageal Reflux Disease (GERD) Patent — Developed a probabilistic economic model to estimate the present value of a GERD patent.

Digital Thermometer Patent — Performed inspections using microfocus x-ray radiography that demonstrated infringement on a patent.

Hazardous Chemical Releases

Ammonia Release — An injury resulted when a worker was overcome by ammonia that had been released from failed tubing that was part of the refrigeration system at a large frozen foods warehouse facility. This effort involved a microscopic examination of the failed part with scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) and a comparison with exemplar products. Issues considered were silver brazing, joint strength, vibration-induced fatigue, and whether a manufacturing defect was present.

Chlorine Release from Rail Car — Two trains collided, and a pressure tank car loaded with liquefied chlorine was punctured, releasing a vaporized cloud of chlorine gas about 700 feet in radius prior to drifting away from the site. Three died as a result of this incident. I was asked to investigate the extent of corrosion or other environmentally induced damage, if any, done to property that was being transported on one of the two trains. This investigation included a through visual inspection and wipe sampling of all the consumer product products being transported.

Chlorine Release from Chlor-Alkali Plant — Investigated the root cause failure of a large chlorine release that occurred at a liquid chlorine production facility located in Henderson, NV. This release required the evacuation of areas surrounding the plant. This investigation reviewed the various plant processes, including the primary chlorine liquefier. Efforts included detailed metallurgical examination of corroded components, use of computational fluid dynamics to model the flow of liquid chlorine, and corrosion experiments in brine contaminated chlorine. Experiments and computational fluid mechanics were used to evaluate the erosion-corrosion where chilled brine entered the liquid chlorine stream at a hole that had developed in the primary liquefier. The corrosion rate of steel in liquid chlorine/brine mixtures at high flow velocities was measured to determine how fast this mixture would corrode through the rundown elbow, causing the chlorine release.

Toxic Effects of Tungsten Alloys — Tungsten based alloys have been gaining in usage as munitions since they are considered an environmentally friendlier alternative for lead and depleted uranium-based materials. For larger caliber munitions (>30 mm), a two-phase material called tungsten heavy alloy (WHA), is used that consists of pure tungsten bound together with a lower melting temperature metal alloy binder. The binder alloy is typically composed of nickel and either iron or cobalt (sometimes both). For smaller caliber munitions tungsten carbide (WC) particles are bound together or "cemented" by a ductile binder phase of cobalt or other alloys. These materials are variously known as hardmetals, cemented carbide, or cermets and are used in armor piercing round. When WHA and hardmetal munitions are used there is the possibility that fragments (shrapnel) may be present in-vivo for long periods of time. Recently, an unexpected adverse toxicological response to some of these was discovered during laboratory animal testing. Preliminary work suggested that galvanic interactions between the tungsten particles and the surrounding metal matrix binder phase in these materials may be responsible for this behavior. In order to develop a better understanding of the corrosion behavior of these materials in vivo, a set of in vitro laboratory experiments was conducted to assess corrosion in these materials three ways: through galvanic testing of selected material pairs, through long-term immersion metallic ion release testing of WHA and other materials, and through characterization of these materials using ASTM F 2129- a standardized testing procedure for assessing localized corrosion in medical implants (ASTM F 2129-08 2008). All of the experiments were conducted in a simulated physiological environment, i.e. pH 7.4 phosphate buffered saline (PBS) solution at 37°C.

Chlorine Release from Train Collision — A train collided with a stationary train, which contained a liquefied chlorine rail car that was punctured. The resulting chlorine cloud killed several people and resulted in corrosion damage to the factory that was located at the site. The extent of corrosion damage to various plant equipment, structures, and electronics was evaluated through the use of wipe sampling, SEM/EDS, and atmospheric corrosion coupons.

Iodine Release from Drug Manufacturing Laboratory — A glass container stored in a laboratory refrigerator that contained an organic iodine compound came into contact with the plastic lining of the refrigerator, and then leaked onto the floor. It is likely that this compound decomposed into iodine and hydrogen iodine which caused extensive atmospheric corrosion damage to stainless steel and other equipment and facilities throughout the lab.

Corrosion Induced Nitrogen Tetroxide Release from Rail Car — Investigated the circumstances leading up to the failure of a carbon steel railcar which was transporting approximately 110,000 pounds of nitrogen tetroxide (N_2O_4), also known as dinitrogen tetroxide or nitrogen peroxide. Upon receipt, the end user found that the nitrogen tetroxide was contaminated with water. After partially draining the railcar (the plant personnel believed they had completely emptied the tank car contents) the contents were further diluted with water until the tank rupture occurred. The jacket head was blown 350 feet from the railcar, the inner tank liner ruptured and the railcar was propelled 35 feet in the opposite direction and derailed. A large reddish-brown cloud was released as a result of this rupture. The interior and exterior of the railcar was inspected along with components removed from the railcar including the vapor dome, dip tubes, and other components. A series of laboratory tests were conducted in Exponent's corrosion/chemistry laboratory to recreate conditions inside the railcar prior to its rupture. A chemical corrosion reaction between nitric acid and carbon steel inside railcar caused a dramatic and localized reduction in the wall

thickness. This substantially decreased the pressure required for rupture. The gaseous products of this reaction overcame the limited ability of the scrubber to reduce the internal pressure in the railcar, which built up the point where the pressure relief valve opened briefly and then partially closed. Nitric acid corrosion of the carbon steel railcar shell resulted in continued wall thinning and gas generation inside the tank car, ultimately causing the tank car end to fail.

Silane Release — Investigated the cause of cracking and leakage of a silane-producing chemical reactor vessel. Metallographic, corrosion, and mechanical property testing were performed on the Incoloy 800H hydrogenation reactor vessel material. ASTM G28 sensitization was performed on the vessel material. Both silicon tetrachloride and trichlorosilane were produced in this vessel. Cracks were located in both the weld and heat affected zones (HAZ). Intergranular carbides were present in both the base and HAZ material. The failure was likely the result of sensitization induced intergranular stress corrosion cracking.

Sodium Hydroxide Release — Investigate the stress corrosion cracking that occurred to steel and Nickel 200 used in a multiple-effect evaporator for sodium hydroxide. Both the first effect and 2nd effect vessels had experienced some levels of cracking.

Hydrogen Sulfide Release — Assessed the occurrence and cause of sulfide-induced stress corrosion cracking in small bore process piping welds that led to releases of hydrogen sulfide (H2S) gas into the environment at an upstream oil and gas processing facility.

Electronic and Electrical Equipment and Consumer Goods

BGA Fatigue Failure — Investigated the reasons for the failure of an electronic consumer product. This investigation involved thermal management, ball grid array solder joints, low cycle fatigue, and under fill issues. Accelerate life testing, statistical analysis of field failure data, modeling of creep-fatigue and intermetallic compound formation, and finite element analysis (FEA) were used to help understand the reason for the BGA cracking.

Lead Free Solder — Examined the effect of various board finishes, such as organic solder preservative (OSP), hot air solder leveling (HASL), electroless-nickel immersion gold (ENIG), and Immersion Silver (ImAg) on lead free (SAC) solder ball grid array (BGA) mounted device reliability.

Oxidation Rates — Evaluation of liquid metal oxidation rates for gallium-indium-tin solders (Ga/In/Sn) and the effect of relative humidity

Backup Alarm on Earthmoving Equipment — A fatality occurred when a grader backed up over an employee at a construction site. The backup alarm on the grader was not operating when inspected after the accident, because one of the wires had been cut. The cut wire was examined to determine the nature and timing of the cut. This investigation determined it was not cut with wire cutters. Examination of the cut wire with SEM/EDS could not reliably determine whether the cut had been made near the time of the accident or several years earlier.

Limit Switch Failure — Investigated a limit switch that reportedly failed to turn off and disengage the control circuit for an electric motor on a hoist on board a US Navy ship, resulting in a serious injury. The accident limit switch and exemplar switches were examined and tested electrically and mechanically. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were used to investigate the atmospheric marine corrosion that had developed on the various materials of construction, 6000 series aluminum, copper, and steel. The primary cause of failure was that the wrong type of limit switch was specified and installed, however even if the appropriate limit switch had been used, the accident still may have occurred since the tab was incorrectly placed on the lever and the accumulation of corrosion debris from the marine atmospheric corrosion may have prevented correct operation.

Bus Transfer Criteria for Power Generating Stations — Computer simulation and mechanical analysis was used to see the effect of the ANSI C50.41-1982 criteria for bus transfer on electrical power

generating equipment damage. Some methods of bus transfer result in all external sources of power being removed from auxiliary busses for a short period of time. Electric motor driven equipment will decelerate when all external power sources are removed. The rates of deceleration depend on the inertia of the drives and the synchronizing power. Data on motor-driven equipment, including pumps, fans, compressors, and pulverizers, and where possible their motors, was collected from various manufacturers. Single machine simulations showed that high-inertia fan drives were found to have limitations when transferred at or near the criteria limit. Multimachine simulations indicate that drives can be subjected to more transfer without concern for crack initiation due to torsional fatigue. In most cases, and particularly for high-inertia fan drives, the limiting component of the shaft system is the motor shaft keyway.

Handheld Consumer Electronic Manufacturing Issue — Discoloration was observed on a polished stainless-steel part that was being developed for a handheld consumer electronic device. It was found that a lead-free solder was used to attach a bracket and that the residual flux containing chloride had attacked the stainless-steel substrate.

Thermal Contact Resistance — Methods to reduce thermal contact resistance with thermal greases, phase change materials, soldering and other methods.

Smoke Detector — Investigated a badly damaged smoke detector. Performed microfocus x-ray radiography to look for the presences of any manufacturing defect.

Stray Current — Various projects involving whether stray current from above ground and below ground electrical utilities had affected the corrosion of above ground or underground steel and copper piping.

Output multiplexers (OMUX) — Investigated the low-cycle fatigue life of a copper OMUX component used in communications satellite. Performed a finite element analysis (FEA) and used these results to evaluate the fatigue life via the Coffin-Manson fatigue relationship between cyclic plastic strain and the number of cycles.to predict low cycle fatigue life.

Marine, Maritime, and Shipping Failure Analysis

Examined the cause of metallurgical defects and cracks found in large scale gearing on offshore drilling platforms (jack up rigs). The jack up systems have many gearboxes on each of the three legs of the platform. The pinion, a large forged quenched and tempered steel shaft with gear teeth that engage the teeth of a rack affixed to each leg to move the hull up or down. In addition, the gear box contained many cast planetary gears and torque plates. The pinions were not properly heat-treated and/or did not have enough hardenability to achieve the required mechanical properties. The case planetary gear components contained excessive aluminum nitride and suffered from aluminum nitride embrittlement. Stress analysis by Finite Element Analysis (FEA) and fracture mechanics were performed to show the material and heat treatment were not suitable and responsible for the failures in the shipyard.

Stern Tube Corrosion — Investigated the reasons for a series of stern tube failures on 87-foot boats in a seawater environment. Issues involved the materials selected and inadequate cathodic protection.

Evaluation of seawater pump failure — Investigated two seawater pumps used in a HVAC system. Crevice and deep pitting corrosion was observed in cast duplex stainless steel that occurred in as little as one year of service.

Ship Propulsion Boiler Bolt Failures — Socket head bolts holding the surface blowdown valve bonnet to the valve body failed on a ship operated by the Military Sealift Command (MSC). I investigated the boiler water chemistries that had been used over the years. The first boiler water chemistry used was a coordinated phosphate program. This was changed to a continuous chelate treatment comprised of EDTA-hydrazine-phosphate. The boiler water treatment was then changed to a catalyzed hydrazine, disodium phosphate, and sodium hydroxide treatment. Fractography of the bolt fracture surfaces clearly

showed that the fracture surface was almost entirely intergranular indicating caustic stress corrosion cracking was the reason for the failure. This failure mode was consistent with some of the prior water chemistries used (particularly the ones with high Na/PO_4 ratios) since when they concentrate can cause concentrated sodium hydroxide solutions to develop.

U.S. Coast Guard Cutter Hull Penetration — A 110-foot patrol boat steel hull is protected by epoxy and anti-fouling paint and an impressed-current cathodic protection (CP) system. Nonetheless, a corrosion hole occurred about eight inches below the waterline. The cathodic protection system was found to be in general working order but the paint in this location had been damaged.

Shipping Container Cargo Crane — Analyzed the reason for cracking observed on a newly build container handling gantry crane. This crane had recently been placed into service at one of the west coast ports. Cracks developed in the box beam structural elements. Investigate the design, methods of manufacture, and operating history to determine the reason for the cracking.

Fracture of Navy Ship Welds — The Navy's certification of HSLA-80 (ASTM A710 Grade A Class 3) for use in surface ship hull construction occurred in February 1984 and provided shipbuilders with their first new steel since the mid-1950s. This steel has been used as a replacement for martensitic HY-80 steel in the construction of U.S. Navy ships beginning with cruisers of the Ticonderoga class and the low carbon content of HSLA-80 makes it much less sensitive to hydrogen-assisted HAZ cracking, and therefore it is able to be welded without the expensive preheat and process controls required for HY-80 Research conducted at David Taylor Research Center (DTRC) on HSLA 80 base plate and HAZ microstructures and mechanical properties after the certification-program had been completed showed that the fracture properties of certain small grain-coarsened regions of the HAZ were much lower than those of the base plate material and raised the issue of whether these locally brittle zones could significantly increase the probability of fracture of welded plates. A probabilistic fracture mechanics (PFM) analysis was performed to quantify the influence of LBZs on the reliability of weldments in HSLA80 considering the considerable variability in LBZ location, size, and toughness and the wide variability in frequency and size of as-manufactured welding flaws.

Pretensioned Monel K-500 Propeller Bolts — Powerheads are used by the marine industry to install pretensioned Monel alloy K-500 ship propeller bolts. The Powerhead is manufactured from high strength steel. The LaQue Center for Corrosion Technology corrosion-fatigue tested the Powerhead and bolts in natural seawater. Both the Monel bolts and steel Powerheads were cathodically protected with zinc anodes during the corrosion-fatigue. The Powerhead and bolts were fatigue-cycled till fracture. Our investigation was to determine the location of the fracture origin and the mode of failure.

Identification of Debris on Ship Hull — I investigated debris that was found on an un-painted area of a ship hull docked in brackish water to determine if it was of a microbiological origin. Optical and scanning electron microscopy was used, along with EDS, to help characterize this material. No evidence was found that indicated a microbiological origin. The most likely origin of the debris was from the cathodic protection system that resulted in the formation of a calcareous deposit at this location.

Fire and Fire Prevention Investigations

Electric Power Line Arcing — Investigated the arc marks on an aluminum conductor from a high voltage transmission line that had broken and fallen along a road. The origin of a forest fire that destroyed many homes was near a tree where the downed line was found. The arc marks were found to be consistent with arcing between the tree limbs and the high voltage line.

Investigation of PCB Fire: Investigated an electrical failure that involved rapid thermal damage to the printed circuit board assembly (PCBA) for a medical device that was used in an operating room. Our analysis was to understand the cause and origin of the failure, the potential risk to patients and medical professionals of such failures, suggestions for redesigns to minimize future failures, and evaluation of the fire and smoke inhalation hazards that may be associated with the electrical failure.

Investigation the fire and explosion in a mobile veterinarian clinic. Cause and origin was associated with a copper fitting fatigue failure associated with the propane tank.

Arc Damage from Lightening: Investigated the cause of a mercaptan ground water contamination and soil remediation litigation. A stainless steel mercaptan line, used to inject the odorant to natural gas prior to distribution, was found to be leaking. The leak location on the stainless-steel line, which ran underground, was found to be within a foot or less of a power pole's ground rod. near a power line's grounding rod. A microstructural investigation of the hole was conducted to determine if the hole was a result of stray current or a lightning strike.

Investigated the cause and origin of a propane explosion and house fire. Investigated the propane piping and fittings for the cause and origin of their fractures.

Dr. Eiselstein has extensive experience in conducting failure analysis investigations regarding fire protection systems: Some examples are as follows:

- Investigation of leaks in a copper fire sprinkler piping. Corrosion was occurring on the wet side. Investigated allegations that the lubricant used to drill holes or the flux at solder joints was responsible for the leaks.
- Investigated leaks on fire protection system (FPS). There was corrosion in the inner surface of the steel lines. The issues investigated involved microbiological influenced corrosion (MIC), defective electrical resistance welds (ERW), grooving corrosion and corrosion tubercles.
- Investigated the failure of a cast iron elbow in a fire sprinkler system in a food warehouse. Failure was determined to be the result of high pressures formed from an ice plug.
- Failure and flooding from large diameter fire protection water supply line supplying fire protection water to a large warehouse. Investigation of the fracture surface and graphitic corrosion indicated failure was associated with initial installation defect.
- Investigated the cause and origin of leaking in a fire protection system in Hawaii. Issues considered were atmospheric marine corrosion and pipe dope used to seal cut thread in steel pipe.
- Investigated the cause and origin of leaking in a fire protection system in Hawaii. Issues considered were atmospheric marine corrosion and pipe dope used to seal cut thread in steel pipe.

Medical Device Investigations

Corrosion Evaluation for Various Implantable Medical Devices — Evaluated a wide range of medical devices and materials, for a wide variety of medical device manufacturers. These efforts have included evaluating the medical device's corrosion resistance and surface finish using long-term potential monitoring, ASTM F3306 Standard Test method for Ion Release Evaluation of Medical Implants (nickel ion release); ASTM F 2129 standard test method for conducting cyclic potentiodynamic polarization measurements to determine the corrosion susceptibility of small implant devices, ASTM F3044 standard test method for evaluating the potential for galvanic corrosion for medical implants, Transformation temperature determination by differential scanning calorimetry (DSC) in accordance with ASTM F2004 the standard test method for transformation temperature of nickel-titanium alloys (nitinol) by thermal analysis (for instance A_f temperature determination), nickel ion release (leaching) rates, Auger electron spectroscopy, x-ray photoelectron spectroscopy (XPS) in order to evaluate the chemical composition as a function of depth into the passive/protective oxide layer, and other techniques. Devices and types of corrosion effects evaluated include:

- Passivated stainless-steel stents with and without radiopaque markers such as platinum, tantalum, and gold markers.
- Implantable neurostimulator and leads - dissolution rate of platinum.
- Electropolished nitinol (NiTi) coronary stents with and without radiopaque markers.
- Platinum Iridium coils

- Tungsten dissolution metal release in vivo
- Cobalt-chromium (CoCr), Elgiloy, Phynox MP35N, stainless steel, and nitinol stents that are overlapped for fretting and galvanic corrosion
- Nitinol (NiTi) with various organic and inorganic coatings
- Potential for crevice corrosion from markers or delaminated coatings
- Metallic components of mitral and aortic heart valves, both mechanical and tissue.
- Annuloplasty rings
- Vena Cava Filters
- Various implantable chronic obstructive pulmonary disease (COPD) devices
- Various implantable devices to mitigate sleep apnea
- Evaluation of corrosion-fatigue strength of various implantable devices
- Fretting Fatigue Evaluations
- Evaluated the metal ion release (primarily nickel ion release from nitinol) from a variety of implantable medical devices. But have also reported metal ion leaching from cardiovascular, neural, gynecological and orthopedic devices and tools manufactured from nitinol, cobalt-chromium alloys, tungsten, MP35N, etc.
- Metal-on-Metal (MoM) Hip Implants: Investigated issues associated with the release of wear debris from MoM and modular tapered junctions used in total hip arthroplasty/replacements (THA/THR)

Electronic Failure in Implantable Device — Performed a failure analysis, and suggested methods to prevent further such failures, for an electronic medical device that failed during clinical trials. The issue involved stress corrosion cracking of glass and laser sealing.

Accelerated Life Testing for Active Implantable Medical Devices — Helped a medical device manufacturer design a suite of HASL and accelerated life tests to assure reliability of a new design for an electrically active implantable medical device (AIMD). This effort involved considering potential failure modes and suggesting tests to determine acceleration factors for the accelerated life tests (ALTs). Mechanical (fatigue, shock, etc.), electrical, and chemical tests were considered.

Implantable Batteries — Various projects involving the testing and manufacture of different types of lithium batteries used for biomedical applications. Destructive and non-destructive failure analysis of primary lithium-silver vanadium oxide (Li-SVO) ICD batteries that exhibited less than expected life including x-ray computer tomography (CT), open circuit voltage (OCV), complex impedance, and swelling measurements.

Leaking Medical Devices — Hermetic Sealing Issues — Helped various implantable medical device manufactures (cardiovascular and neurological) determine the reason for moisture ingress. Helium (He) leak checking, dye penetrant testing, metallography, SEM, microfocus x-ray radiography, x-ray microtomography (micro-CT), and residual gas analysis (RGA) and accelerated life testing have been utilized to solve these problems.

Tracheobronchial Stent Failure — A tracheobronchial stent fractured while implanted. Investigated design and manufacturing issues regarding this stent. The adequacy of accelerated life testing for mechanical fatigue (effect of coughing) and corrosion resistance and submissions to the FDA were reviewed as were product quality management documents. This stent was manufactured from cobalt-chromium-nickel-molybdenum wire. Allegations of improper heat treatment were considered and dismissed based on micro-hardness measurements. It was determined that this stent had failed as a result of fatigue and the device was found to be free from material or manufacturing defects.

Electronic Control Module for a Medical Procedure — A printed circuit board assembly (PCBA) used in a medical procedure experienced a rapid thermal damage due to an electrical failure. Our analysis was to

understand the cause and origin of the failure, the potential risk to patients and medical professionals from fire and smoke inhalation hazards and provide recommendations to minimize future failures.

Pedicle screw failure — A patient underwent surgical decompression and fusion that used a pedicle screw system (i.e. a pedicle screw, rod, and locking nut). There was a revision to the original surgery that required the replacement of all locking nuts. Several weeks after the replacement of all locking nuts the lower most pedicle screw came off the rod. I investigated the reasons for this failure

Instrumentation and Data Analysis for In-vivo Loading — Instrumented an implantable medical device (mitral annuloplasty repair device) to collect in-vivo biomechanical loading data on a heart repair device for fatigue life analysis of the device.

Failure Analysis of Vena Cava Filter — A vena cava filter failed to deploy correctly and was successfully retrieved surgically. Reviewed medical device and manufacturing records as well as photographs of the retrieved device within order to determine if a manufacturing defect was responsible for of improper deployment.

Failure Analysis of Pacemaker Leads — Investigate the reasons for pacemaker lead failures. Issues included corrosion-fatigue, fretting, how polymer materials were used, manufacturing changes, effects of residual stress, and in-vivo loading of the leads.

Failure of Periarticular Screws — Examined the periarticular system including tibial plates and two broken screws with a stereomicroscope and scanning electron microscope (SEM). The subject periarticular screws fractured due to low cycle fatigue crack initiation and growth. The fatigue fracture of the subject screws was due to cyclic in-vivo loads that exceeded those for which they were designed.

Safety and Hazard Analysis for Various Medical Devices — I have performed safety and hazard analysis such as failure modes and effects analyses (FMEAs) for various medical devices including fertility control devices, brain stem implants, needle incineration devices, plastic surgery devices, septal defect closure device, hearing aid, and a drug inhaler.

Stress and Fatigue Analysis of Various Implantable Medical Devices — I have performed stress and fatigue analysis of various implantable medical devices. Stress analysis has included estimating the loading conditions from biomechanical and medical literature reviews, measuring the in-vivo loads, modeling device and tissue interactions with finite element analysis (FEA). The calculated stresses, or strains, are then compared to fatigue life data generated from accelerated life testing in physiological solutions such as phosphate buffered saline (PBS), bile, Hanks, and Ringers. Devices analyzed include anastomosis fasteners, stents (coronary, iliac, carotid, biliary), abdominal aortic aneurysm (AAA) stent grafts, heart valves, septal defect closure device, vena cava filters, bifurcated stents, COPD devices, trans-jugular intrahepatic portosystemic shunt (TIPS). The effect of mean stress is accounted for by the modified Goodman, Gerber, Soderberg, Haigh type of analysis. These results are generally used for PMA submissions to the FDA.

Great Toe implant Failure Analysis — Examined the issues regarding the development metallosis in a Ti-6Al-4V great toe joint implant. Device design, manufacture specifications, and quality control during manufacture were examined.

Failure of Electrical Circuit in Defibrillator — Helped a defibrillator manufacturer understand the reasons for a small number of circuit failures that were observed during manufacture.

Intra-aortic Balloon Pump Failure — Examined the reasons for the failure of the balloon used in an intra-aortic balloon pump. The balloon had developed a leak after many days of use. Fatigue, abrasion, and appropriate instructions for use were evaluated.

Laser Cutting of Stents — Evaluated two different laser-cutting processes to cut stents from Nitinol tubing.

Metallography and scanning electron microscopy (SEM) were used to characterize the laser cut surfaces.

Broke Dental Needles — Evaluated several dental needle failures. Needles generally work reliably but occasionally fine gauge needles will break in use. Needle breakage in the oral cavity after local anesthesia is a common complication with possible serious complications. In the majority of cases needle fracture happened during inferior alveolar nerve block. It is generally considered to occur as a result of improper technique or the use of too thin a needle. Analysis of the fracture surface of the needle can provide evidence for the presence or absence of material or manufacturing defects.