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Engineering & Scientific Consulting

Larry 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. He 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.

Dr. Eiselstein's 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), hydrogen embrittlement issues and indentation hardness and fracture toughness of ceramics and single crystals.

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 failure modes and effect analysis (FMEA) 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, and 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 Univ, 1974

International Nickel Company Scholarship, Virginia Tech

Townsend Fellowship, Stanford University

Wire Foundation Competition Prize

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

Licenses and Certifications

Professional Engineer Metallurgical, California, #1779

Professional Engineer Corrosion, California, #1067

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 H, Underwood RJ, Baykal D, Eiselstein LE, Torelli DA, Klein GR, Lee GC, and Kurtz SM. "Is there material loss at the conical junctions of modular components for total knee arthroplasty?," The Journal of Arthroplasty, 2019. DOI: 10.1016/j.arth.2019.05.030

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Fasching A, Kuş E, James B, Bhargava Y, Eiselstein L. The effects of heat treatment, surface condition and strain on nickel-leaching rates and corrosion performance in nitinol wires. Materials and Processes

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Nissan A, Corlett N, Eiselstein LE, Steffey D. Effect of long-term immersion on the pitting corrosion resistance of nitinol. Proceedings, SMST-2007 ASM International Conference on Shape Memory and Superelastic Technologies, Tsukuba City, Japan, December 2-4, 2007.

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.

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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
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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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Caligiuri RD, Eiselstein LE, Fox MJ. Low temperature sensitization of Type 304 stainless steel pipe weld heat affected zones. Proceedings, Specialists Meeting on Subcritical Crack Growth, Freiburg, West Germany, May 1981; NUREG/CP-0044, US Nuclear Regulatory Commission, pp. 199-228, May 1983.

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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.

Presentations

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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. Declaration of Lawrence E. Eiselstein, regarding underground corrosion of ARCO station piping, Report to O'Melveny & Myers LLP, September 2001 (Rule 26B Report).

Eiselstein LE. FSI International v Particle Measuring Systems, Exponent Report to Robins, Kaplan, Miller & Ciresi, August 2001 (Rule 26B Report).

Eiselstein LE. Rebuttal Expert Report, Varian Associates, Inc. v General Electric. Exponent Report to Farella Brawn & Martel, March 2001 (Rule 26B Report).

Eiselstein LE. Trident Weld Consumables Rebuttal Report. Exponent Report to Castro and Worthge, LLP, March 2001 (Rule 26B Report).

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).

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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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Reza A, Eiselstein LE, Huet R, Belanger J. Investigation of the April 1994 Halliburton perforation gun explosion in Kenai, Alaska. Failure Analysis Associates Report to DeLisio Moran Geraghty & Zobel and Lane Powell Spears Lubersky, January 1998.

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Project Experience

General Failure Analysis and Prevention

Power Plant Steam Explosion—Investigated a steam explosion at a fossil-fueled power plant that killed four plant personnel. One of the plant's main steam lines had been severed after the failure of a large primary air draft fan that had been 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 freight train rail car axle failure that resulted in a train derailment. A combination of corrosion, fatigue, and inadequate nondestructive examination (NDE) and repair was found to be the cause.

Structural Fasteners—Analysis of the metallurgy, corrosion, pull-out strength, and fracture of steel shot pins used to fasten framing of single-family homes to their foundation. Power-actuated fasteners (PAFs) are nail-like pins used to attach materials to concrete, masonry, or steel base materials by a system that uses either explosive powder, gas combustion, or compressed air to embed the fastener in structural elements. The general term is "shot pin." Measured and analyzed pull-out strength and analyzed how it may have been affected by atmospheric corrosion.

Automotive—Examined fatigue and corrosion induced cracks in automotive stabilization bars. Investigated the cracks found in salt belt states regarding recalled axles, reviewed durability testing used to evaluate axle fatigue resistance during driving, and assessment of fleet-wide implications.

Guardrail Corrosion—Evaluated and assessed the corrosion of a galvanized guardrail. My investigation included metallographic and chemical analysis of exemplar units, chemical analysis of staining agent, and soil analysis upon which it was stored.

Brake Assembly—Evaluated corrosion of the internal component of the brake assembly, including possible galvanic coupling between a zinc piston and a steel spring.

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 (LP) steam turbine disks. Another project involved performing a probabilistic-based risk analysis of LP steam turbine disk cracking for units operating at a power plant in the Midwest.

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 not galvanized but were 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. The electroplated stainless steel sheet had corroded sufficiently (due to atmospheric corrosion) 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.

Geothermal Power Plant—Operation of a geothermal power plant located in a marine environment was interrupted by a volcanic eruption. Provided help evaluating atmospheric corrosion damage claims to the surface of equipment (air-cooled condensers, switchgear, transformers, motors, generators, turbines, pumps, and other equipment) as the result of volcanic gases and marine atmospheric exposure during the plant forced shutdown. Performed site inspections and analyzed other site inspection reports, plant status reports, repair invoices, vendor reports on damage repairs, and maintenance records to qualitatively rank the amount of damage that resulted from the eruption.

LM2500 Gas Turbine Failure—Investigated the reason for the failure of an 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 deformation 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.

Failure of Forged Alloy 718 Disks—Forged Inconel 718 (Alloy 718) disks had been ordered from a forging supplier. These forgings were machined into disks for testing a new design for a turboshaft jet engine. The disks failed during testing, destroying the test stand placing the development program behind schedule. The root cause of the failure was that, although the disk had been ordered in an age-hardened condition, it had not received this heat treatment.

Fertilizer Plant Explosion—Investigated massive explosions that leveled portions of a Port Neal, Iowa, ammonium nitrate plant owned by Terra Industries. Four plant workers were killed, 18 others suffered significant injury, and damage to the plant and surrounding community was estimated in the hundreds of millions of dollars. Reviewed and analyzed the plant's process data and conducted extensive research regarding ammonium nitrate properties and decomposition mechanisms. Also completed analytical modeling and experimental testing to analyze various accident theories and inspected and performed metallurgical analysis of various artifacts from the explosion site. Plant operators allowed the ammonium nitrate in the neutralizer vessel to become contaminated and highly acidic. When superheated steam was injected into the neutralizer vessel, a runaway chemical reaction occurred.

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. Investigated the nature of the aircraft fuel nozzle cracking, the forging procedures (forgeability 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, Nevada. 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-diameter high-pressure natural gas pipeline that traversed the plant and was damaged by the explosions may have played in the incident.

Remaining Life Assessment of Space System Thruster Valves—Examined and analyzed 304 stainless steel thruster valves that were inadvertently cleaned in a halogenated hydrocarbon solvent (freon) after test firing with monomethylhydrazine (MMH-CH_3NHNH_2). The stems of the thruster valves had been cold worked during fabrication. Both pits and stress corrosion cracks (SCC) were observed using metallography and SEM, Surface residual stresses were determined through X-ray diffraction (XRD) methods. The effect of stress intensity (KI) on crack growth rate, chloride concentration, oxygen concentration, and temperature, on SCC resistant regions for 304, 316L, and duplex stainless steels 2304, 2205 and 2207 were evaluated.

Materials Study for Generator—Provided recommendations for appropriate accelerated corrosion and wear testing for materials to be used in a portable combustion powered electrical generator. Tribology, high-temperature oxidation, acid dewpoint corrosion, metal dusting/carburization, and other effects were considered. Materials considered included precipitation hardenable stainless steels (17-4PH and 17-7PH), Nitronic 60, Duplex 2507, and graphite.

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 clinic's heater to determine the cause of failure. The failure was found to be a result of fatigue and not stress corrosion cracking.

Refrigerator Compressor Failures—Excessive field failures were observed years after the introduction of a new type of refrigerator compressors. The investigation included wear rate modeling, metallurgical issues concerning M2 high speed tool steel, cast iron, nitriding, lubrication, and total acid number (TAN). Engineering analysis of wear in the compressor parts as well as statistical analysis was performed 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.

High-Efficiency Home 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.

Furnace Fuel Filter Issues—I analyzed environmental remediation matters regarding leaking fuel filters used in home heating furnaces. The fuel was supplied from an aboveground fuel oil tank with a line out the bottom that fed the fuel into the furnace in the basement after going through a fuel filter. Fuel filters that are not changed out as frequently as recommended can collect moisture in the bottom of the filter; given enough time, this can result in through-wall corrosion leading to fuel oil leaking into the basement. Investigated issues of galvanization, coating, compliance with manufacturer's recommendations, and the rate of microbiologically influenced corrosion (MIC).

Oxidation and Carburization—Evaluated the rate of oxidation and carburization (metal dusting) at high-temperatures for various high-temperature alloys subjected to extended exposure times and thermal cycling. Looked at the effects of spallation, chromia evaporation, and penetration depths to develop degradation rate model.

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, and hot isostatic pressing (hipping). 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 its sulfur dioxide evaporator within 72 hours after placing a 90-ton rail car on-line. The wastewater processed at the plant goes through a series of treatment steps before it is released to the environment. Steps include primary and secondary treatment, chlorination, and de-chlorination. Sulfur dioxide (SO2) is used to neutralize residual chlorine (de-chlorination). The corrosion induced SO2 release was attributed to the much higher than specified moisture of the SO2 in the rail car.

Sanitation District Methane Gas Storage—Investigated 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—Investigated through-wall penetration of the steel carbon dioxide line (CO2) 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.

Anaerobic Digester—Investigated corrosion control issues in an anaerobic digester. This “dry” fermentation anaerobic digestion was used to produce biogas consisting of up to 65% methane and compost. The biogas is utilized to produce compressed natural gas (CNG). Ammonia and volatile organic compounds (VOCs) and odor-producing compounds are removed from the air, and thermophilic anaerobic conditions are established after the aerobic microbes consume the available oxygen. During the anaerobic digestion, gases such as methane, CO2, hydrogen sulfide (H2S), or ammonia are produced. Microbially induced corrosion (MIC) conditions were considered, such as the acid-forming bacteria associated with methane-forming bacteria. For instance, acetate-forming (acetogenic) bacteria grows in a symbiotic relationship with methane-forming bacteria as well as the effects of sulfate-reducing bacteria (SRBs), which can produce hydrogen sulfate that can be further oxidized to sulfuric acid. The fermentation of volatile organic acid (RCOOH) resulting in the production of methane and the reduction of carbon dioxide to produce methane was also considered.

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. The issue was to determine if the coating failed because of thermo-chemical degradation or because of having been improperly applied.

Power Plant Steel roofing and siding panel coating on new construction at a power plant was blistering, peeling, and cracking, and the steel underneath was exposed after a brief time in service. Investigated the root cause of the coating failure.

Boiler Steam Explosion—Soon after commissioning a boiler at a lead and zinc 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 625. 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. I evaluated the mechanical properties of E7018, ER70S-2, and ER70S-6 weld electrode materials to help determine if thermally-induced stresses or thermal-fatigue could induce crack propagation at the interface between the Inconel and steel, and if this effect played a part in the explosion. I also reviewed the effect of molten salts on the high temperature corrosion/erosion conditions in the boiler.

Corrosion Study—Performed life assessment for solder pile. Considered the underground corrosion rate for the steel members, considering the variation in corrosion rate, presence, or absence of coating and cathodic protection (impressed current or sacrificial anodes), galvanization, and drainage conditions.

Performed a failure analysis of an industrial accident involving the rapid uncoiling large diameter superalloy steel coil after the steel strapping failed resulting in the fatality of the forklift driver.

Friction, Wear, Fretting-Corrosion, Tribocorrosion)

These projects involving friction, wear (tribology), and tribocorrosion (erosion-corrosion, corrosive wear, fretting-corrosion, mechanically assisted crevice corrosion) have included:

- Sliding wear of metal-on-metal and ceramic-on-metal wear of hip implants
- Tapered modular junctions used in hip implants.
- Wear mechanism map consideration for metal-on-metal wear of metal suspension hooks.
- Fretting wear and fatigue analysis of woven stents
- Wear and material selection considerations involving rotating or rolling-piston compressors for refrigeration equipment,
- Sliding friction between steel and refractory bricks

Oil and Gas

There have been various projects in the oil and gas industry, including various aspects from upstream (hydraulic fracturing and perforation guns) to downstream (piping, refinery, underground storage tanks, and gasoline fuel tanks in automobiles). The following are examples of this project experience.

Oil Well Perforation Gun Explosion—Investigated a perforation gun explosion at the Halliburton Industries assembly plant in Kenai, Alaska, which 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 up to 171 explosive shaped charges aligned within a drill 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 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—Investigated reported incidents of cracked galvanized structural beams found in buildings. The cracking was from liquid metal assisted cracking (LMAC), a form of liquid metal embrittlement (LME). Predicting how and when LMAC will occur is challenging. Selecting appropriate nondestructive testing (NDT) for inspection requires careful consideration as the cracks can be filled or covered with the zinc (Zn) galvanizing alloy making visual and dye penetrant testing impossible. Modified magnetic particle, ultrasonic testing (UT), and eddy-current testing (ECT) techniques were suggested to detect such cracks.

Refinery Pipe Rupture and Fire—Performed a metallurgical evaluation into the cause of the rupture of an elevated temperature steel pipe in a petrochemical refinery. The pipe had been in crude oil distillation

service for years. The pipe was found to have thinned and ruptured because 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.

Refinery Ducting—Determined the degree of graphitization on samples of carbon steel and condition of stainless steels taken from steel ducting from a refinery that had been in high-temperature service (790°F) for 30 years. The Grade 70 carbon steel sample exhibited a ferrite/pearlite microstructure with a small amount of transformed graphite, consistent with the extended exposure at elevated temperature. No internal cracking or significant deviation from the expected microstructure was observed. The 304 stainless steel exhibited sensitized microstructure with carbide precipitates at the grain boundaries. A minor grain boundary attack was observed on the stainless steel inlets.

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. Five-and-a-half-inch P110 steel connectors were bucked onto the casings (about 45,000 feet of seamless casing) and were in wells in Texas. The production strings were subjected to high-pressure hydraulic fracturing (“fracking”). During the initial stages of the hydraulic fracturing of the wells, connections cracked at pressures below design specification, resulting in a loss of the wells. Reviewed evidence regarding the allegations that the coupling/connectors were improperly designed, manufactured from substandard steel, improperly heat treated, were subjected to excessive torque, were coated improperly leading to hydrogen charging, subjected to an acidic environment during the hydraulic fracture from the fracking fluid, and exposure to “sour” environment (hydrogen sulfide) resulting hydrogen cracking or sulfide stress cracking.

Inconel 625 Piping and Fittings—Six-inch-diameter Inconel 625 (N06625 or Alloy 625) seamless pipes and fittings were supplied to a Middle East project for an oil extraction and conditioning facility. The crude was sour and contained 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 piping and fittings did not comply with the technical specifications.

Corrosion Behavior of Steel Tubulars Used in Sour-Gas-Rich Oil Fields—Measured the corrosion rate of steel (A387 and A516) in highly saline (salt saturated) hot brines (100°C) that were in equilibrium with very high pressure hydrogen sulfide (20 atmospheres) and carbon dioxide (5 atmospheres), as a function of flow velocity up to 10 m/s. This work helps to understand the life of steel tubing used in deep oil and gas wells that are subjected to these corrosive conditions, i.e., elevated temperatures, high flow rates, high salt concentration brines, and corrosive dissolved gases such as H2S and CO2.

Oil Rig Accident in Texas—A worker fell through the grate hatch door into a mud pit and sustained burns. Exponent’s analysis indicated that there had been post-manufacturing modifications to the mud pit latches and grating that insufficiently supported the grating and resulted in the grating and the employee falling into the mud pit.

Investigated corrosion related issues with the production of concentrated calcium chloride, sodium chloride, and magnesium hydroxide from brines. Evaluated the corrosion to titanium alloy heat exchanger tubes and Inconel 625 tube sheets in the evaporator section. Also evaluated corrosion under insulation (CUI) concerns.

Food and Beverage

Pear Can Corrosion—Approximately 8 million cans of cooked fruit were produced over a two- to three-month 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. Investigated the cause of the rusting and determined whether the rusting would continue and eventually cause leakage. The 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—Cargo shipping containers containing carbonated beverage (soda) cans were found to have leaked during oversea transport to market. These soda cans were found to be empty because of corrosion-induced leaks. Typically, there is no protective coating on the outer surface of the cans. 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 thereby causing more cans to leak.

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

Coating Defects in Cans—Analyzed the extent and degree of coating defects in cans used for jalapeños, green chiles, and enchilada sauce.

Leaking Beverage Cans—Performed a root cause analysis to understand why sparkling beverage cans from three products were leaking. Analysis included optical microscopy, scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and Fourier transform infrared spectroscopy (FTIR). Electrochemical analysis of the coating was also used. Both electrochemical impedance spectroscopy (EIS) and linear polarization resistance (LPR) were used in this analysis.

Reviewed various issues in the construction of a tartaric acid manufacturing plant. The newly constructed tartaric acid plant used the remains of grape crushing to obtain tartaric acid. Materials of construction such as the use of 316 or 317 stainless steel, material spillage on the concrete and non-stainless steel plant components, and the life span of the equipment were the issues considered along with plant start up delays.

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, California. 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.

Analyzed the cause of collapse of an aluminum gantry crane that injured personnel. The failure path was through the weld metal used to join the top plate to the top of the tube leg as well as through one of the two gusset plate welds. Through the failure analysis investigation, I analyzed the welding records, welding practice, and reviewed the design considerations.

Engineering Significance of Local Brittle Zones (LBZs) in U.S. Navy Ships—The Navy’s certification of HSLA-80 (ASTM A710) for use in ship hull construction occurred in 1984. It provided shipbuilders with their first new steel since the mid-1950s. This steel has been used in the construction of Navy ships, beginning with cruisers of the Ticonderoga class. The low-carbon content of HSLA-80 makes it much less sensitive to hydrogen-assisted heat-affected zone (HAZ) cracking, and therefore it can be welded without the expensive preheat and process controls required for HY-80. The Navy conducted an intensive testing program to characterize HSLA-80 base plate and weldment properties and found the presence of LBZs in the multi-pass weldments and wanted to better understand how this may affect the weldment when subjected to large strains such as those that occur during explosive bulge testing. This was evaluated using probabilistic fracture mechanics. The model calculated the failure probability of weldments as they are strained, simulating the growth of preexisting crack-like weld defects. The model incorporates the

variation of the toughness for the base metal, weld metal, and LBZs to model the tearing resistance along the fracture path. This modeling indicated that the distribution and toughness of LBZs only have a small effect. The calculated failure probabilities agree with a limited number of actual explosive bulge tests.

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. Evaluated methods for cleaning and passivating the stainless steel piping in place.

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 were the result of low-cycle fatigue.

ERW Weld Corrosion Attack—The electrical resistance weld (ERW) 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. Small cracks that form because of thermal stresses during cooling from the brazing temperature could result in vacuum leak path. 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, and design and manufacturing changes were suggested for this brazed/pin ceramic assembly.

Failure Analysis of EB and Laser-Welded Inconel 718 (Alloy 718) Nickel-Hydrogen Battery—Batteries used for an aerospace application developed a leak while in service after various charge/ discharge cycles that 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 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 (HAZ) 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 HAZ 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 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.

Post-Tensioning Strands—Investigated the failure of post-tensioning strands used in different projects. For example, Exponent performed a metallurgical failure analysis investigation on two post-tensioning strands that failed in service on a bridge tendon in Tampa, Florida. The failed strands were identified during the bridge’s first annual inspection. The investigation included optical microscopy, scanning electron microscopy (SEM), metallographic examination, microhardness, and chemical analysis. The investigation determined that the strands fractured due to environmentally assisted cracking (EAC) because of water ingress into the tendon combined with a lack of protective wax coating on areas of the strands that failed. The EAC fractured strands exhibited microstructures, microhardness, and chemical composition consistent with high-strength steel wire typical of post-tensioning wires. There was no evidence of gross corrosion that would have reduced the wire cross-sectional area to the point that wires

would break under normal post-tensioning loads. Corrosion product in the environmentally assisted cracks indicated that the EAC had occurred months earlier prior to discovery.

Underground Storage Tanks (USTs), Pipelines, Piping, and Plumbing

Leaking Underground Fuel Storage Tanks—I have had projects regarding this issue. Investigations included corrosion analysis to determine the time that the leaks started, analysis of the risk of corrosion thinning and weld defects being underestimated from various inspection methods, and the effect of cathodic protection and coatings on increasing useful life.

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 the cause was erosion-corrosion of the copper piping, which consisted 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 the chilled water system of a large data center's air handler (i.e., computer room air handler, or CRAH). This system, containing both steel and copper piping in the computer room, had originally been 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 five months when the first leaks were reported. The copper coils leaked because of internal pitting corrosion from microbiologically influenced corrosion (MIC) of the copper. 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.

Internal Corrosion of Copper Piping Used to Supply Potable Water leading to the formation of "blue water"—These projects dealt with this issue, including the "Blue Water Problem" that occurred in the early 1990s in the Danville and San Ramon Valley area of California. Issues considered include stray current, solder flux, water flow rates, time of stagnation, soft versus hard, copper piping and the inner surface condition (Campbell carbon film theory), MIC, water chemistry including scaling index, dissolved oxygen, and residual chlorine effects. Projects also included cases of pitting-induced leaks in potable copper piping. In one instance, after 30 years of few water leak reports, there was a sudden onset and frequency of pinhole leaks. It was expected that the localized corrosion on the inner surface of the copper piping was a result of a recent change in the water chemistry of the supplied water as there was no indication of erosion-corrosion, defective piping, or solder flux induced corrosion.

Crude Oil Pipeline Release—Investigated and 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 MIC. This type of corrosion can be very rapid and can occur even if the pipe is being appropriately cathodically protected—i.e., maintained at a pipe-to-soil potential below –850 mV versus 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, that was observed.

Natural Gas Pipeline Rupture and Explosion—Investigated the cause of a 36-inch natural gas transmission pipeline rupture that occurred in Carlsbad, New Mexico. This investigation included evaluation of the effects of internal corrosion and assessment of 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 to 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 aboveground steel piping with approximately half inch-thick wall that had become submerged because of a flooding event. Pipe diameter varied from 65 inches to 87 inches. Flood-induced abrasion damage to the paint was noted on 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 days in flood waters. These pipes and fittings were to be used in the construction of a liquefied natural gas (LNG) 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 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 slime formers can be associated with MIC of carbon steel and stainless steel, 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 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 were investigated. The system consisted of a network of 6-inch-, 8-inch-, and 10-inch-diameter cast iron pipes. Various sections of 10-inch-diameter pipe ruptured after a previous repair. 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 main water system had been repaired five times during the past two decades. Our investigation was to identify the cause of recent breaks and to help the city identify portions of the water main within the area that could remain in service without significant risk of imminent rupture. Those pipe sections were gray cast iron with a mortar coating on the interior surface and no coating on the exterior surface. There was no CP on this pipeline as determined by the pipe-to-soil potential measurements. The most recent pipe rupture showed signs of extensive graphitic corrosion.

Corrosion of Cast Iron Vent and Sewer Lines: Investigated the corrosion deterioration of vent and sewer lines on multiple projects involving stagnation, microbiological generation of hydrogen sulfide (sewer gas) going into vent lines in condos and apartment complexes.

External Underground Corrosion of Copper Laterals—Investigated the reasons for through-wall corrosion of copper laterals in a new housing development. CP was recommended.

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

PEX Plumbing System Failures—Leaks in homes utilizing cross-linked polyethylene (PEX) plumbing. Most 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. 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 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.

Brass Valves and Fittings—There were projects involving SCC, intergranular attack (IGA), fire cracking, and dezincification (dealloying) of brass valves and fittings manufactured from brass for water, oil, and gas plumbing service (WOG). Analyzed red brass, yellow brass, and low lead (Pb) or lead-free brass components. Issues included water chemistry effects, alloy chemistry, microstructure, hardness, residual and installation stresses, temperature of operation, ISO, and NSF dezincification standards as well as ammonia vapor testing for SCC resistance per ASTM B858 testing.

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

Ethylene Steam Pyrolysis Furnace—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 damage to the expensive nickel-chromium-iron (Ni-Cr-Fe) centrifugal case furnace tubes (cast HP or HK alloys or Incoloy 800H). Ethylene is produced by hydrocarbons (e.g., ethane) and steam reacting inside tubes heated in a furnace. The tube temperature is about 1000°C (1800°F). At these temperatures, the tube metal experiences damage mechanisms that eventually result in tube failure and replacement. The various damage modes, and operating conditions, leading to tube failures, were investigated and included:

• Carburization during normal operation.

• Deposits that increase tube temperature, accelerating carburization.

• Oxidation and wear of the inside surface during decoking cycles.

• 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. Iron- and nickel-based alloys are susceptible to accelerated high-temperature degradation when exposed to sulfur compounds, because 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 in which metal under stress at elevated 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 prestressing wire failures that occurred on the pipe used in the CAP. CAP is a waterway that transports water from the Colorado River to central and southern Arizona. At the time of construction, it was the longest single water transportation project authorized in the United States. 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 pressure pipe (PCP or PCCP) ever manufactured—i.e., 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 PCP sections weighed 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. 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 low concentrations of chloride, evaporation led to a chloride concentration build-up to levels supporting SCC. Chloride levels in the wet/dry transition zone of the siphons were high enough to cause SCC without any significant carbonation of the mortar or the core.

Water Transmission Pipeline Leaks—Horizontal directional drilling (HDD) was used in the construction of a water transmission pipeline project. An 1,800-foot length 31-inch-diameter, half inch-thick spiral-welded steel pipe was pulled through the 1,800-foot-long HDD drilled hole at a river crossing. No leaks were found after installation. However, after about four years of service, this pipeline was found to be leaking. Investigated issues regarding the pipe coating, weld defects in the spiral welds, the corrosion rates, the pipe bend radius during the HDD operation, and resulting strains at the pipe welds.

Brass Plumbing Failure—Brass elbows from two different commercial installations had failed. The cracking on the female end was examined with optical microscopy, and the fracture surfaces were examined 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 overtightening.

Copper Plumbing Leaks—Leaks in copper piping were a result of pitting corrosion on the inner surface of the pipe caused by 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.

Connector Hose Leaks—Investigated the reasons for leaks in plumbing in both stainless steel and copper corrugated flexible connector hoses where the connectors were attached to the elbow joint. The leaks were initiated on the inside surface where the corrugated tube was attached to the elbow joint. There was no evidence of obvious signs of corrosion, pitting, SCC, or fatigue. X-ray imaging and metallography was used to locate and target the leak locations. Significant porosity inside the solder/braze joints, from the time of manufacture, appeared to have interconnected over years of operational service. This interconnection of porosity was a combination of fatigue and corrosion that slowly opened a leak path between the porosity.

Flexible PVC Hose Leak—Investigated a leaking flexible hose manufactured from PVC tube with rigid PVC helix. It was used in a data center and was operating with a propylene glycol and water mixture at 28 psi at 136°F at the time of the leak. It had been operating within its pressure and temperature limits for a couple of hours prior to failure. There was no evidence of embrittlement or environmental stress cracking

the PVC or stiffening helix. Three short cracks were found only at the rigid PVC stiffening helix component at one location in the hose and all were aligned co-linear along the tube's longitudinal axis. The leak was caused by local deformation on one side of the tube, damaged by another tube laying on the hose that fractured the rigid helix stiffening ring but not compromising the hose pressure integrity. When placed into elevated temperature and pressure service, creep rupture resulted in crack propagation through this cracked and weakened region.

Powder Metallurgy

There have been projects involving powder metallurgy. These projects included developing unique microstructures and properties using various methods of consolidation such as high-temperature high-pressure (HT-HP) sintering, hot isostatic pressing (HIP), and other processing techniques to make monolithic and composite structures. The following are examples of this project experience.

- Superplastic densification of ultrahigh carbon steel powder compacts
- Rapid solidification processing of metal alloy powders
- Mechanical alloying for development of high temperature superalloys and other applications
- Near net shape processing of heavy metal chemical energy warhead liners
- Development of remarkably high strength and ductile white cast iron by stabilizing the carbides against transforming to graphite and heat treating
- Characterization of superplasticity in white cast iron
- Explosive compaction of Nd-Fe-B ferromagnetic powders

Intellectual Property (IP) Litigation

There have been various projects in the IP area involving patent infringement and validity, trade secrets, and inter partes review (IPR). The following are examples of this project experience.

Nitinol Patent Infringement—Provided expert testimony in an IP 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 IP 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—Reviewed a new wafer cleaning apparatus to determine if there might be infringement of existing patents. The apparatus used the Maragoni effect (mass transfer along an interface between two phases due to a gradient of the surface tension) as part of the cleaning process.

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.

Lead Alloys for Anodes—Trade secret litigation regarding improper use, disclosure of confidential information, and trade secrets regarding lead (Pb) alloys used for anodes in the electrowinning/ electroplating of copper and lead recycling.

Use of Coiled Steel Tubing—Patent regarding manufacturing coiled steel tubing use in the oil and gas industry. Specific issues included the microstructure of the base material, heat-affected zone (HAZ), and weld metal and the various techniques that can be used to evaluate them. Of particular interest were martensite, tempered martensite, and bainite microstructures.

Hydraulic Fracturing Method—Patent regarding a method of hydraulic fracturing involving, among other things, a well service pump, fluid end body, salinity (salt concentration) of hydraulic fluid, corrosion-resistant steel, a minimum fatigue limit, maximum working pressure, and tensile stress. Addressed both validity and infringement.

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 X-ray spectroscopy (EDS) and a comparison with plumbing. 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 people died in 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 thorough 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, Nevada. 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 in which 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.

Inconel 600 and Inconel X750 check valve springs being used in railroad liquid chlorine tank cars failed and leaked chlorine. The was stress corrosion cracking (SCC) and not fatigue cracking as the cracking did not originate from pits or wire drawing marks that were occasionally found.

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. WHA consists of pure tungsten bound together with a lower melting temperature metal alloy binder. The alloy binder 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 hard metals, cemented carbide, or cermets, and are used in armor-piercing rounds. When WHA and hard metal munitions are used, there is the possibility that fragments (shrapnel) may be present in vivo for years. Recently, an unexpected adverse toxicological response to these munition fragments 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. 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 in 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 the experiments were conducted in a simulated physiological environment (phosphate-buffered saline (PBS) solution at 37°C and a pH of 7.4).

Chlorine Release from Train Collision—A train collided with a stationary train that carried a liquefied chlorine rail car, which was punctured in the collision. The resulting chlorine cloud killed nine 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 using wipe sampling, SEM/EDS, and atmospheric corrosion coupons.

Investigated the potential for indoor atmospheric corrosion damage to brass and bronze artwork in a home that was fumigated for termites using methyl bromide.

Evaluated the extent of indoor air quality in the interior of trailers that were being used to store agricultural products that had been fumigated with magnesium phosphide (Mg_3P_2) (sometimes known as “Fumi-Cel”) for pest control. Scanning electron microscopy/energy dispersive X-ray spectroscopy (SEM/EDS) and FTIR were used in this investigation. The corrosion was primarily to the galvanized steel components The higher-than-expected corrosion on the trailers is likely due to some combination of unacceptably high relative humidity or time-of-wetness (TOW), residual cleaning products, and potentially atmospheric contaminants from the fumigant and organic acids from the product being stored in the trailers.

Iodine Release from Drug Manufacturing Laboratory—A glass container stored in a laboratory refrigerator that contained an organic iodine compound met 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 (N_2O_4) Release from Rail Car—Investigated the circumstances leading up to the failure of a carbon steel rail car that was transporting approximately 110,000 pounds of N_2O_4. Upon receipt, the contents were found to be contaminated with water. The contents were diluted with water until the tank rupture occurred. The jacket head was blown 350 feet from the rail car, the inner tank liner was ruptured, and the rail car was propelled 35 feet and derailed. A large red-brown cloud was released because of this rupture. The interior and exterior of the rail car was inspected along with components removed from the rail car. A series of laboratory tests were conducted in Exponent’s corrosion/chemistry laboratory to recreate conditions inside the rail car prior to its rupture. A chemical corrosion reaction between nitric acid and carbon steel inside the rail car caused a dramatic and localized reduction in the wall thickness. This decreased the pressure required for rupture. Nitric acid corrosion of the carbon steel rail car shell resulted in continued wall thinning, very rapid gas generation, rapidly increasing the pressure inside the tank car, causing the tank car end to rupture and accelerate the rail car.

At the Fairchild Site, in 1959, Dr. Robert Noyce invented the first integrated circuit that could be produced commercially. The Site contained a 14,600 square foot building on a 0.55 acre plot that had been constructed in 1957. Fairchild used minute amounts of chlorinated solvents such as trichloroethylene (TCE) and acids during 1957 to 1962. Fairchild’s industrial wastes and wastewater were discharged through the building’s northern sanitary sewer. The above ground PVC piping draining into the cast iron wastewater lines which, in turn, drain into the vitrified clay pipe (VCP) at the curb. I provided technical assistance in connection with claims for cost recovery and allocation in Federal District Court. Specifically, I investigated historical activities at the site and their relation to the alleged corrosion of the sanitary sewer lateral pipe and assessed whether there is evidence that the northern sewer lateral would have leaked during Fairchild’s occupancy.

Silane Release—Investigated the cause of cracking and leakage of a silane-producing chemical reactor vessel after 13 years of service. This reactor vessel processes superheated hydrogen and silicon

tetrachloride in a fluidized bed of metallurgical grade silicon operating at 1,000°F and 300 psi. This produces an effluent of approximately 80% silicon tetrachloride and 20% trichlorosilane. 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. Cracks were in both the weld and the heat-affected zones (HAZ). Intergranular carbides were present in both the base and the HAZ material. The failure was the result of sensitization-induced intergranular stress corrosion cracking (SCC).

Sodium Hydroxide Release—Investigated the SCC that occurred to steel and Nickel 200 used in a multiple-effect evaporator for sodium hydroxide. Both the first-effect and second-effect vessels had experienced various levels of cracking.

Hydrogen Sulfide Release—Assessed the occurrence and cause of sulfide-induced SCC 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.

Thorium-Containing Dust Particles—Evaluated issues surrounding a glioblastoma brain tumor cluster alleged to have been the result of either exposure to X-ray radiation or small levels of dust containing thorium. Provided critical review of the characterization of the few small dust particles that were found to contain thorium and their source.

Lead (Pb) Release—Investigated the mechanism and release rate of lead (Pb) to the environment under atmospheric, underground, and aqueous environments.

Electronic and Electrical Equipment and Consumer Goods

Ball Grid Array (BGA) Fatigue Failure—Investigated the reasons for the failure of an electronic consumer product. This investigation involved thermal management, BGA solder joints, low cycle fatigue, and underfill issues. Accelerated 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 the reliability of lead-free (SAC) solder BGA-mounted devices.

Oxidation Rates—Evaluated 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 years earlier.

Limit Switch Failure—Investigated a limit switch that failed to turn off and disengage the control circuit for an electric motor on a hoist on board a U.S. Navy ship, resulting in a severe 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 debris from the marine atmospheric corrosion may have prevented correct operation.

Hydrostatic extrusion of high strength electrical conductor wire, including the effects of iron-aluminum precipitates on pinning sub-grain boundaries for stronger transmission and distribution electrical lines.

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. Methods of bus transfer result in all external sources of power being removed from auxiliary buses for a short period. 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, were 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.

Photoelectric Sensor/Emitter Failure—Performed a root cause analysis of a photoelectric sensor/emitter used in exercise equipment. Visual inspection, optical microscopy, and SEM/EDS were used on these sealed devices to determine the root cause of failure. No leak path for moisture ingress was found at the transmitter and receiver windows, and moisture entered along the power cord.

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

Smoke Detector—Investigated a severely damaged smoke detector. Performed microfocus X-ray radiography to look for the presence 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.

Stray Current from Telecom Cables—Investigated external pitting corrosion observed on the copper lateral water supply to private homes. Determined that the cause was stray current from telecommunication cables.

Output Multiplexers (OMUX) Investigated the low-cycle fatigue life of a copper OMUX component used in communications satellites. 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.

Transformer Explosion—International arbitration in Singapore regarding the cause of an explosion of a 500 kV generator step-up transformer (GSUT) at a complex of coal-fired power plants. Issue involved corrosion design and maintenance issues that allowed moisture ingress into the high-voltage bushings. The transformer was in a hot tropical marine environment with atmospheric corrosion potentially exacerbated by sulfur emissions (SO2, SO3) and crevice corrosion forming at gasket.

Marine, Maritime, and Shipping Failure Analysis

Metallurgical Issues on Offshore Drilling Platforms—Examined the cause of metallurgical defects and cracks found in large-scale gearing on offshore drilling platforms (jack-up rigs). Presented the findings to the International Center of Dispute Resolution (ICDR) in Houston. The jack-up systems have gearboxes on each of the three legs of the platform. The pinion is 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 gearbox contained planetary gears and torque plates manufactured by casting. The pinions were not properly heat-treated and/or did not have enough hardenability to achieve the required mechanical properties. The 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 that the material and heat treatment were not suitable and were 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 an 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. The boiler water chemistries that had been used over the years were investigated. The first boiler water chemistry used was a coordinated phosphate program. This was changed to a continuous chelate treatment consisting 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 that caustic stress corrosion cracking was the reason for the failure. This failure mode was consistent with the prior water chemistries used (particularly the ones with high Na/PO4 ratios) since, when concentrated, they can cause concentrated sodium hydroxide solutions to develop.

U.S. Coast Guard Cutter Hull Penetration—A 110-foot patrol boat steel hull was 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 CP 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. Investigated the design, methods of manufacture, and operating history to determine the reason for the cracking.

Fracture of Navy Ship Welds—A probabilistic fracture mechanics (PFM) analysis was performed on U.S. Navy vessel weldments, as described more fully in the section on Welds and Welded Connections.

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. Exponent investigated to determine the location of the fracture origin and the mode of failure.

Identification of Debris on Ship Hull. Evaluated protective coating systems for U.S. Coast Guard steel ships, including coating performance in marine environments and interaction with corrosion-control practices.

Investigated debris that was found on an unpainted area of a ship hull docked in brackish water to determine if it was of a microbiological origin. Optical and scanning electron microscopy (SEM) were used, along with energy-dispersive spectroscopy (EDS), to help characterize this material. No evidence was found that indicated a microbiological origin. The origin of the debris was from the CP system that resulted in the formation of a calcareous deposit at this location.

Evaluated the rate that Pb (lead) is released from lead-clad power and telecommunication cables into an aqueous environment. i.e., a freshwater lake. Reviewed and described the theory of passivation and statistical analysis of the concentration of Pb in water.

Investigated coating and paint failures on steel, concrete, and pipelines, including cracking, loss of adhesion, delamination, and corrosion beneath coatings.

Evaluated epoxy coating cracking and delamination related to surface preparation, coating thickness, and application conditions in institutional concrete and steel structures.

Investigated large-diameter water pipelines involving internal lining failures and corrosion of underlying steel.

Investigated long-term degradation of historic organic protective coatings on high-carbon steel suspension bridge wires, including corrosion damage and mechanical property loss after decades of exposure.

Evaluated the effect of painted over mill scale on the abrasive blasting production rate due to mill scale staining.

Fire and Fire Prevention Investigations

Electric arc mark investigations: Investigated fires that were suspected to have initiated as the result of arcing from electric power lines One incident occurred where an aluminum conductor from a high-voltage transmission line broke and fell along a road. The origin of the fire was near a tree where the downed line was found. The arc marks were found to be consistent with arcing between the tree limb and the high-voltage line. Other arcing-initiated fires occurred because of fatigue fractures or fretting/wear-induced failures.

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. Exponent’s analysis aimed to understand the cause and origin of the failure and the potential risk of such failures to patients and medical professionals, to offer suggestions for redesigns to minimize future failures, and to evaluate fire and smoke inhalation hazards that may be associated with the electrical failure.

Veterinarian Clinic Fire and Explosion—Investigated a fire and explosion in a mobile veterinarian clinic. Cause and origin were associated with a copper fitting fatigue failure associated with the propane tank.

Arc Damage from Lightning—Investigated the cause of a mercaptan groundwater contamination and soil remediation litigation. A stainless steel mercaptan line, used to inject the odorant into 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 near the grounding rod of a power line. A microstructural investigation of the hole was conducted to determine if the hole was a result of stray-current or a lightning strike.

Propane Explosion and House Fire—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.

Fire Protection Systems (FPSs) Failure analysis investigations regarding FPSs include the following:

• Investigated leaks in a copper fire sprinkler piping. Aqueous corrosion was occurring on the wetted side. Investigated allegations that the lubricant used to drill holes or the flux at solder joints was responsible for the leaks.

• Investigated leaks on an FPS. There was corrosion on the inner surface of the steel lines. The issues investigated involved microbiologically 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 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 leaks in an FPS 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 FPSs in California. Issues considered were ERW weld defects in seam-welded steel pipe and frequent refilling with fresh water due to operational issues.

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 F2129 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 Standard Test Method for Transformation Temperature of Nickel-Titanium Alloys by Thermal Analysis (for instance Af temperature determination), nickel-ion release (leaching) rates, Auger electron spectroscopy, and 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 included:

- Passivated stainless steel stents with and without radiopaque markers such as platinum, tantalum, and gold markers.
- Implantable neurostimulator and leads and dissolution rate of platinum.
- Evaluated the need for galvanic corrosion testing of medical devices that contain dissimilar metals.
- Electropolished nitinol (NiTi) coronary stents with and without radiopaque markers.
- Platinum iridium coils.
- Accelerated life testing of retinal implants.
- Brain stem stimulation for hearing
- Sputtered iridium oxide films (SIROF) for neural stimulation electrodes
- Analysis of polymer membrane degradation mechanism for endometrial ablation and suggestions to improve reliability.
- Measured the rate of tungsten dissolution (metal release) in PBS to evaluate its dissolution rate in vivo.
- Cobalt-chromium (CoCr), Elgiloy, Phynox MP35N, stainless steel, and nitinol stents that are overlapped for fretting/wear and galvanic corrosion testing and analysis.
- 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.
- Inferior vena cava (IVC) 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.
- Analysis of the effect of shelf life on the mechanical properties of nitinol.
- Fretting fatigue evaluations.
- Evaluation of the metal ion release (primarily nickel ion release from nitinol and stainless steel) from a variety of implantable medical devices. Measured metal ion leaching (metal dissolution rate) from cardiovascular, neural, gynecological, and orthopedic devices and tools manufactured from nitinol, cobalt-chromium alloys, tungsten, MP35N, etc., using ASTM F3306 Standard Test Method for Ion Release Evaluation of Medical Implants.
- Fatigue failure of a CoCrMo (ASTM F1537) modular neck used in total hip arthroplasty (THA).
- Permanent sterilization/contraception device placed in fallopian tube.
- Hip implant Ti6Al4V (ASTM F136) femoral neck fatigue fractures.
- Osteointegration of acetabular cup manufactured from beaded CoCrMo (ASTM F75).
- Metal-on-metal (MoM) hip implants: Investigated tribology issues associated with the release of wear debris from MoM and modular tapered junctions used in total hip arthroplasty/replacements (THA/THR).

Evaluated the effect of metallic surface area on the breakdown potential of a Nitinol (NiTi) wire frame for a surgical vascular graft. The results were like those that Duane Steffey, and I found and reported in 2008. Our more recent investigation, as well as the area effect we reported in 2012 that the breakdown potential (determined by ASTM F2129) showed larger surface areas have the effect of lowering the breakdown potentials (Eiselstein, Steffey et al. 2008). Since 2008, this effect has been quantified recently by Sena et al. in 2020 (Sena, Sivan et al. 2020). The Sena et al. paper indicated, even for an order of magnitude increase in surface area. the change in the average breakdown potential is small whereas the variance in breakdown is large making it unlikely that the 8% larger surface area effect will be statistically significant.

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.

Water chemistry issues regarding disinfection with bleach: Analyzed aqueous water chemistry and equilibrium issues, such as pH, concentration and dilution of bleach on the concentration of hypochlorite. The bleach and peroxide were being used in the disinfection of medical equipment in a hospital.

Examined an endovascular prothesis that had been removed from a patient. The explant contained broken attach hooks at both the superior and inferior attachment end. Scanning electron microscopy (SEM) was used to examine the fracture surfaces, and the failures were found to have originated at tool marks because of fatigue with no indication that material defects, such as inclusions, voids or porosity played a part in the failure.

Spinal Fusion Stimulator: Investigated an implantable device that applied current to enhance spinal fusion by means of a bone growth stimulator. We set up an in vitro system to experimentally evaluate the propensity for hydrogen embrittlement/h (HE)/hydrogen Induced Cracking (HIC) on the implanted

hardware manufactured from high strength Ti-6Al-4V and Cobalt-Chromium (CoCr) alloys. Hydrogen levels in the materials were then measured, and instances of cracking were observed.

Lung Tissue—Performed an examination of lung tissue with SEM and EDS to determine the size, shape, and composition of particles that were present, if any. Particles in the tissue were found to have come from various metal alloys as well as silica particles. Most particles were less than 5 microns in size. This was done to see if the particles, if found, could be related to patients' work history.

Accelerated Life Testing for Active Implantable Medical Devices—Helped a medical device manufacturer design a suite of HASL and accelerated life tests (ALTs) to assure reliability of an innovative 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 ALTs. Mechanical (fatigue and shock.), electrical, and chemical tests were considered.

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

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

Spinal Rod Failure—Investigated the reason for the failure of the Harrington rod used in the correction of Scheuermann kyphosis. The spinal rod failed because of fatigue. The transconnector had migrated to the end of one of the Harrington rods. The fractured rod, pedicle screws, transconnector, and hooks were examined.

Pedicle Screw and Locking Nut: I testified on an injury that occurred to a patient that had undergone surgical decompression and fusion using a pedicle screw and locking nut. The screws and rods became loose and additional surgery was required. The issue involved the thread profile and alleged improper testing.

Flexible Reaming System Failure—A patient was undergoing an open reduction internal fixation (ORIF) of a femur fracture. While undergoing the multiple reaming steps to enable the insertion of the intramedullary nail, the reamer head came loose. The allegation was that the flexible reaming system was defective, allowing the reaming head to detach. The surgeon was unable to retrieve the head during this procedure. The patient declined to have the surgeon remove it and had it removed weeks later by another surgeon after the patient developed an infection. Based on examination of the flexible reaming rod and reaming head, nothing was found wrong with the design or manufacture. There was testimony that the root cause of this failure was that the surgeon had not used the flexible reaming rod during the last reaming operation. The presence of the reaming rod was required for locking the reaming head to the rod, thereby allowing it to detach.

Stainless Steel Bone Plate Failure—Investigated an explanted 316 stainless steel tubular bone plate with seven locking holes that had fractured in situ. The fracture occurred at the middle hole, and fatigue striations were found on the fracture surface. No material or manufacturing defects were found.

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 because 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 rapid thermal damage due to an electrical failure. Exponent's analysis aimed to understand the cause and origin of the failure, to identify the potential risk to patients and medical professionals from fire and smoke inhalation hazards, and to 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. 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.

Trocar Injury Investigation—Evaluated the issues surrounding the reasons for a safety trocar injury.

Retained Objects Post-Surgery—I performed investigations regarding the identification of material found in patients after specific surgeries. One instance involved a guidewire that had been left in the patient after the placement of porta-catheter (port-a-cath).

Failure Analysis of Vena Cava Filter—An inferior vena cava (IVC) 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 improper deployment.

Analyzed a Left Ventricular Assist Device (LVAD) that experienced an intermittent loss of pumping.

Failure Analysis of Pacemaker Leads—Investigated 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—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—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' (HBSS) salt solution, and Ringer's solution. 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, and trans-jugular intrahepatic portosystemic shunt (TIPS). The effect of mean

stress is accounted for by the modified Goodman, Gerber, Soderberg, and Haigh type of analysis. These results are 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, manufacturing specifications, and quality control during manufacturing was examined.

Failure of Electrical Circuit in Defibrillator—Helped a defibrillator manufacturer understand the reasons for 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 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 SEM were used to characterize the laser-cut surfaces.

Broken Dental Needles—Evaluated dental needle failures. In cases studied, needle fractures happened during inferior alveolar nerve block. It is considered to occur because of improper technique or because the needle was too thin. Analysis of the fracture surface of the needle can provide evidence for the presence or absence of material or manufacturing defects.

Examined Components for Possible Corrosion—Used optical microscopy, SEM, EDS, and FTIR to characterize the condition of the stainless steel and nitinol components of a medical device after they were used in animal testing for more than 36 hours. Spots of reddish-orange deposits were found to be consistent with blood and not corrosion product. No obvious pitting or other corrosion was observed.

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