Wildfire Impacts on Power Industry Steel Structures: Part 1

Mehrooz Zamanzadeh, George T. Bayer, Peyman Taheri, Anil Kumar Chikkam, and Clinton Char, *Matergenics, Inc., Pittsburgh, Pennsylvania, USA*

This technical article, in two parts, addresses the adverse impacts of wildfires on power industry steel structures, with an emphasis on the degradation of structural material mechanical properties and protective coating properties due to the high-temperature exposure. Part 1 addresses transmission and distribution structures and materials, gases, and corrosive substances generated in wildfires, and high-temperature wildfire effects on bare structural steel mechanical properties. Part 2 will address high-temperature wildfire effects on galvanized steel coating layers, thermal degradation of organic coatings, concrete mechanical properties, and condition assessment of wildfire exposed structures by nondestructive techniques, including remote temperature and corrosion potential monitoring.

A wildfire, bushfire, wildland fire or field fire is an unplanned, unwanted, and usually uncontrolled event in an area of combustible vegetation. Climate change is credited for a dramatic increase in wildfire events, along with flawed forestry/ecosystem management policies, including overpopulation, agriculture, and poor staffing/resource allocation. By December 18, 2020, there had been about 57,000 wildfires in the United States, compared with 50,477 in 2019, according to the National Interagency Fire Center.[1] More than 10.3 million acres were burned in the United States in 2020, compared with 4.7 million acres in 2019. Five of the top 20 largest California wildfires occurred in 2020. Due to the extreme drought conditions in the West, the predictions are for increasingly worse fire events. The extreme temperatures of these wildfires can cause a reduction in structural strength and even melt zinc-based galvanized coatings on steel. This can lead to accelerated corrosion, or even the collapse of lattice towers at some later time. Figure 1 is a photograph of one such wildfire after it passed a power transmission structure.

Many locations in the United States and worldwide, such as Australia and India,[2] are subject to wildfires due to dry conditions during parts of the year, in conjunction with poor land management and maintenance practices, such as failure to maintain rights-of-way, inadequate fire breaks, and ground clearing operations. Conditions immediately leading up to and during the fire combine to create a highly combustible fuel load. These conditions include:

- Heavy grass covering due to a wet spring.
- An unusually dry fall.
- Decreased humidity (23% dropping to 10%).
- Unusually dry fuel (5% 1,000-h moisture level).

FIGURE 1 Wildfire having passed a power transmission structure.

- Hot, dry, sustained and gusting high winds (25 to 35 mph).

On average, the flame heights of a wildfire can reach approximately two to three times the height of the material being burned and can reach temperatures of 800 °C (1,472 °F) or more. Under extreme conditions, flame heights of 50 m or more and flame temperatures exceeding 1,200 °C (2,192 °F) could be realized. Flame front movement is fast at 6 to 14 mi (9.7 to 22.5 km) per h, depending on locations. Under those conditions, it was found that a structure is exposed to the high heat of the flame front for a period of between 60 to 120 s.

Wildfires and Transmission and Distribution Structures

Steel structures used in overhead transmission and distribution (T&D) lines (excluding substations) can be divided into two generic groups:

- Lattice towers including masts in portal and H-frame structures, as shown in Figure 2.
- Poles and other type of structures with tubular design.

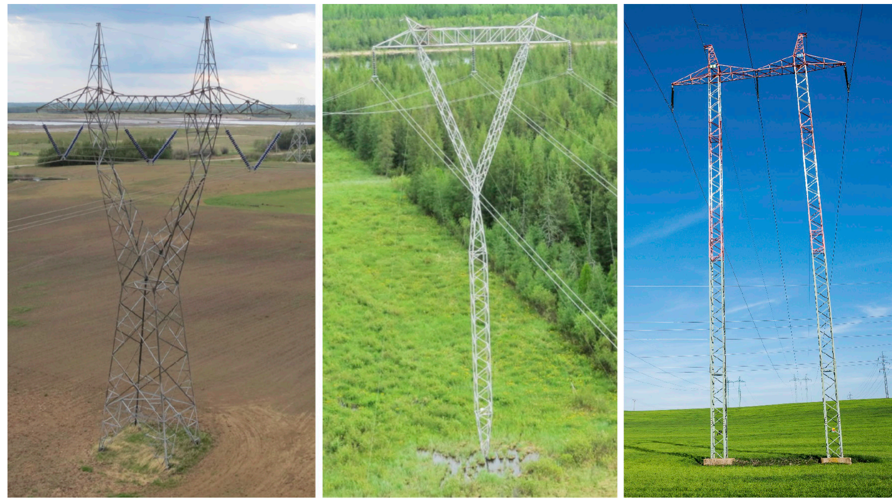

FIGURE 2 (Left) lattice structure; (middle) portal structure; (right) H-frame structure.[3]

- Both may be with or without guy-wire cable anchors.

Other structures, like guyed towers and monopoles, have similar structural characteristics and vulnerability to wildfires as their counterparts in electric utilities.

Transmission and Distribution Structures and Materials

A variety of structural designs exist in each category that result in a wide range of structural features specific to different applications and service environments.

Despite design variations, all T&D structures are composed of two sections:

- Aboveground section, which supports the overhead conductor at a safe height from ground level.
- Below-ground section, referred to as the structure foundation, which supports the aboveground section.

Foundations are designed to stabilize the structure in the service environment (usually soil or concrete) and provide support and a path to ground to carry the dynamic and static forces imposed on the structure. During their service life, both above and below-ground portions of T&D structures are exposed to a variety of natural calamities and environmental conditions; thus, aging and material degradation are inevitable because of environmental and mechanical stresses.

Corrosion is the most common aging process that affects the integrity of any metallic structure, if it is not properly monitored, leading to a partial or complete mechanical failure of the structure. Corrosion occurs at both above and below-ground portions of T&D structures; however, in most cases, the rate of below-ground corrosion is much higher than aboveground (atmospheric) corrosion. AMPP's Standards Committee 11 for Electric Power has sponsored and published industry guidance for evaluating and managing these concerns, including:

- AMPP SP0215/IEEE Std. 1839, AMPP/IEEE "Joint Standard Practice for Below-Grade Corrosion Control of Transmission, Distribution, and Substation Structures by Coating Repair Systems."[4]
- AMPP SP0315/IEEE Std. 1835, "AMPP/IEEE Joint Standard Practice for Atmospheric (Above Grade) Corrosion Control of Existing Electric Transmission, Distribution, and Substation Structures by Coating Systems."[5]
- AMPP SP0415/IEEE Std. 1895, "AMPP/IEEE Joint Standard Practice for Below-Grade Inspection and Assessment of Corrosion on Steel Transmission, Distribution, and Substation Structures.[6]

TABLE 1 IMPACTS ON STRUCTURAL STEEL OF CRITICAL TEMPERATURES

Temperature	Structural Impact
> 200 °C or 392 °F	Decrease in modulus of elasticity
> 400 °C or 752 °F	Decrease in yield strength, and zinc will begin to melt
> 600 °C or 1,112 °F	50% loss in strength, and oxidation will occur

Due to their high strength-to-weight ratios and relatively low cost, ferrous-based alloys (i.e., steels) are the favored materials in construction of T&D structures. The three types of steels that are typically used include:

- Carbon steel, special alloys which generally are referred to as structural quality steel, specified by standards such as ASTM A572, "Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel"[7] or CSA G40.20/G40.21, "General requirements for rolled or welded structural quality steel/structural quality steel."[8]
- Galvanized steel—more details about galvanized steel will be provided in Part 2.
- Weathering steel—a special class of high-strength, low-alloy structural steels that is intended for atmospheric exposure without coating application. Different compositions for commercial weathering steel alloys are provided in ASTM A242, ASTM A588, and CSA G40.21. Please refer to the CEATI report *Assessment, Prevention and Remediation of Corrosion in Weathering Steel Transmission Line Poles*[9] for more details about weathering steel.
- Steel cables—aluminum conductor steel reinforced are mostly used in high-voltage transmission lines.

It is important to mention that each of these steel types exhibits different corrosion behaviors in outdoor conditions.

Transmission lines are vulnerable to both direct heat exposure and deposition of airborne combustion products (ashes), which are transported from remote fires containing corrosive contaminants. The lattice structures are assembled from constructional steel components that may be painted steel, weathering steel, hot-dip galvanized, or painted galvanized steel. Wildfire exposed transmission and distribution structures may experience degradation at low, mid, or high elevation; on overhead hardware; and on insulators.

Contamination Issues

In the phenomenon known as flash over, the line voltage flashes over an electrically conductive film (due to moisture entrapment) of surface contamination that impacts the function/effectiveness of insulators and other components, causing a line outage or relay operation. In most cases, several arcing periods may precede an actual flashover that results in an outage event. Most flashover outages are unpredictable and take several hours to remediate.

Insulator contamination and corrosion products on transmission and distribution structures could potentially be a cause of wildfires due to arcing and flash over in proximity to combustible materials. Salts and other electrically conducting airborne contaminants such as dust and industrial emissions, as well as soot from previous wildfires and existing wildfires nearby, could build up on transmission and distribution system equipment, increasing the potential for conductivity and flash over at the insulators.

Coastal utilities may experience salt contamination when salt fog condenses, or wave aspirated aerosol salt crystals settle on electrical equipment. The insulator pollution builds up gradually but does not decrease the insulation strength when the insulators are dry. But when the polluted insulators become wet, a conductive layer forms on the contaminated insulator surface, initiating a flash over.

Non-soluble aerosol deposition information is required to estimate the atmospheric site pollution for insulators and conductors according to the IEC TS 60815-1 standard.[10] The main parameters considered in this category are particulate matter and dust deposition. Distinct from conventional soil mapping but important as well, the development of a geographical information system (GIS) map layer for site pollution severity (SPS) can be used for evaluating the risk of arcing across insulators, initiating wildfires, and increasing asset integrity risk for regional infrastructure. Key parameters to be mapped to track/trend arcing risk by SPS include:

- Previous wildfire exposures map (direct, direct less than 30 s, downwind, etc.).
- Time of wetness map.
- Sulfur dioxide (SO_2) deposition rate map.
- Airborne chloride (Cl–) deposition rate map.
- Oxidized nitrogen (NO_X) deposition rate map.
- Wind speed and direction map.
- Atmospheric corrosion map (combined map).
- Fine particulate matter $PM_{2.5}$ deposition map.
- Dust deposition map.
- Atmospheric contamination GIS map (combined map).

Gases and Corrosive Substances Generated in Wildfires

Wildfires are major sources of trace gases and aerosol. It is believed that these emissions significantly influence the chemical composition of the atmosphere and the earth's climate on both regional and global scales.[11] Over the past century, wildfires have accounted for 20 to 25% of global carbon emissions. The gaseous pollutants generated by wildfires include greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and photochemically reactive compounds such as carbon monoxide (CO), volatile organic compounds, sulfur oxides (SO_x), and nitrogen oxides (NO_x). Most important to the issue of structural materials corrosion are the fine and coarse particulate matter, or soot, generated by wildfires. Figure 1 presents a photograph of a wildfire with apparently heavy soot content.

Wildfires produce soot containing chlorides and other water-soluble corrosive ions such as sulfates. The wind and buoyant flames (buoyant plumes) carry the potentially corrosive soot and facilitate soot depositions on high-elevation members including the conductor and line hardware. After the passage of a wildfire, if the structures are not analyzed for contaminants and subsequently cleaned free of them, this will cause accelerated corrosion of galvanized and weathering steel structures for the remainder of their service life or until removed. Field testing of steel structures for contamination after a wildfire is suggested.

Additionally, the soil at the footing of structures may become more corrosive due to contamination by the soot and ashes of organic matter. For example, deposition of the corrosive soot may change soil resistivity in a sandy noncorrosive soil from 200,000 to 300,000 Ω-cm to less than 1,000 Ω-cm, which is considerably more corrosive. Chloride levels in the soil may change from 10 to 20 parts per million (ppm) to greater than 1,000 ppm. The same situation is true for the other water-soluble corrosive ions.

Asset integrity programs that proactively consider surface chemistry and soil chemistry before, during, and after wildfires will provide the most accurate forecast of asset risk/network reliability for susceptible infrastructure in high-consequence markets. The rate of removal of soot contamination from the local soil environment after wildfires would be an important topic for further research.

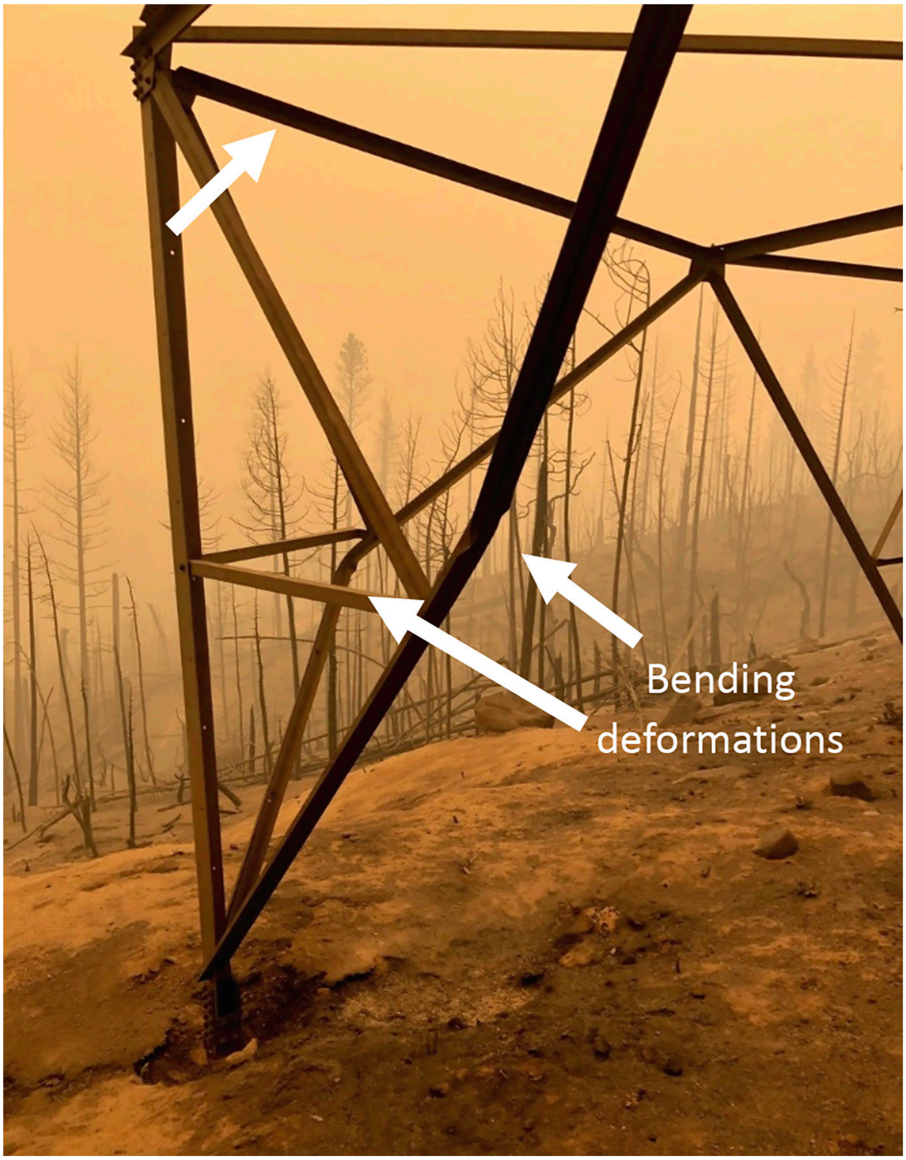

FIGURE 3 Deformation of two diagonal steel braces and one instance of a bolted joint pulling away from vertical structural member (upper left). The other arrows point to the inflection points of the deformed diagonals.

Effects of Wildfires on Structural Steel

The mechanical properties of steel are temperature-dependent. Mechanical properties such as tensile strength, yield strength, ductility, hardness, and toughness could be negatively affected when exposed to the heat of a wildfire. A reduction in these properties could reduce the strength capacity of the structure to a level below a minimum factor of safety, particularly if the structure was previously weakened by corrosion, mechanical damage, or severe loading events. Physical properties such as thermal conductivity, electrical conductivity, and the coefficient of thermal expansion could also be affected by exposure to a wildfire. In addition, permanent changes in the microstructure of the steel could take place. These are all important factors in considering the effects of wildfires on structural steel.[12-13] Figure 3 illustrates the effect of mechanical deformation on a transmission structure caused by wildfire heating.

Temperature and Mechanical Properties of Steel

With increased temperature as experienced in a wildfire, the yield strength (>400 °C, 752 °F) and the modulus of elasticity (>200 °C, 392 °F) would decrease. If the temperature is above 600 °C (1,112 °F), bainite phase forms, and almost 50% of the

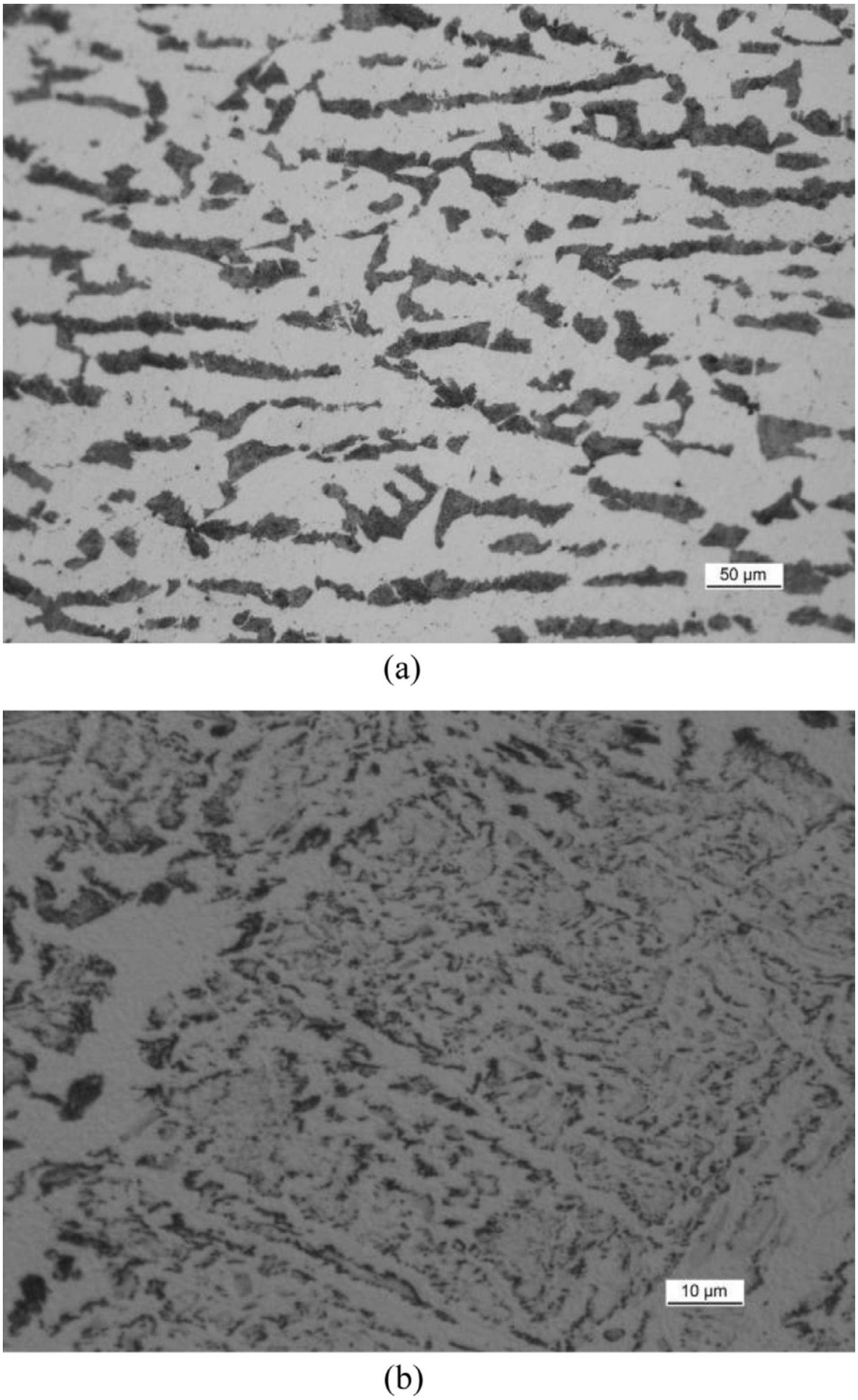

FIGURE 4 Cross-section photomicrographs of pearlite (a) vs. bainite (b); bainite being indicative of high-temperature exposure.

strength will be lost. Table 1 summarizes these critical temperatures and their impacts.

Please note that martensite can form due to rapid cooling from water by aerial water drops, fire hoses, and extinguishers.

Figure 4 illustrates the metallurgical microstructures of pearlite (top photomicrograph [a]) and bainite (bottom photomicrograph [b]); bainite being indicative of high-temperature exposure.

If the temperature does not exceed 600 °C and there is no prolonged exposure, the mechanical properties return to their initial values after cooling down. If steel is exposed to temperatures above 600 °C for approximately 20 to 30 min, oxidation will appear on the surface, as well as pitting and a loss of cross-sectional thickness.

Above 715 °C (1,320 °F), steel experiences a crystalline phase transformation. If the steel is then quenched or cooled rapidly, a phase known as martensite can form. Untempered, or relatively untempered, martensite is brittle and prone to cracking when subject to mechanical stress. This will reduce the ductility of the steel, which will reduce its impact resistance. There are certain areas of structural vulnerability that should be considered very carefully, such as bolting, flange plates, and any other structural components that are subject to residual manufacturing stresses.

The collection of carbon soot and ash can increase the corrosion rate of the metallic members that they settle upon.

Thus, while a structure may appear to have survived a wildfire unscathed, the potential loss of mechanical strength and ductility could reduce the strength of the structure to levels below its required factor of safety. This could lead to catastrophic failure in the future. To mitigate this possibility, a detailed investigation on the structural steel should be performed to determine if the steel has been negatively affected by exposure to a wildfire and whether the structure's serviceability is in question due to the event, any preexisting conditions (e.g., corrosion/cross-section loss), and its anticipated service requirements.

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MEHROOZ ZAMANZADEH is the senior technical director at Matergenics, Inc., Pittsburgh, Pennsylvania, USA, email: zee@matergenics.com. He is a NACE-certified Corrosion. Cathodic Protection, Coating, and Materials Selection Design Specialist with over 30 years of experience in corrosion risk assessment and corrosion mitigation in the electric, water/wastewater, oil, and gas Industries. He has a Ph.D., is a NACE Fellow and ASM Fellow, holds 65 patents, and has authored 67 technical publications. He has been a member of NACE (now AMPP) for 30 years.

GEORGE T. BAYER is the coating department manager at Matergenics, Inc., email: george.bayer@matergenics.com. He has almost 30 years of combined experience in metallic and nonmetallic materials, organic and metallurgical coatings, aqueous and high-temperature corrosion, and materials characterization. Dr. Bayer holds five U.S. patents and has authored over 35 technical papers. He is a member of ASM International and the American Chemical Society. He has an M.S. degree in chemistry/metallurgical engineering and a Ph.D. in public policy & administration.

Peyman Taheri is the director of engineering at Matergenics, Inc., email: peyman@matergenics.com. He has more than seven years of experience in corrosion inspection and risk mitigation in power and telecommunication utility structures with a focus on field surveys and risk quantification. He is an expert in computational cathodic protection systems design for complex geometries and GIS-based corrosion mapping. He has a Ph.D., is a professional engineer, and is a member of AMPP.

ANIL KUMAR CHIKKAM is the lead—Metallurgy & Corrosion Laboratory at Matergenics, Inc., email: anil.chikkam@matergenics.com. He has over 13 years of experience providing solution engineering to problems related to corrosion failures, corrosion fatigue failures, design failures, elevated temperature failures, fatigue failures, hydrogen damage failures, stress corrosion cracking, heat treating-related failures, liquid erosion failures, wear failures, weldments, and more. He is a member of AWS, API, IEEE, AMPP, AWWA, TMS, ASNT, PMAI, IIM, and IEI-India. He has an M.S. degree in metallurgy and materials technology, is certified to NACE CP2, and is a contributor to AMPP technical committees.

CLINTON CHAR is a senior structural engineer at Matergenics, Inc. He has 30+ years of experience in utility transmission and distribution structures. He is a member of several ASCE committees and has authored 20+ technical papers. He has a BSCE and MSCE. MP