Wildfire Impacts on Power Industry Steel Structures, Part 2

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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 addressed transmission and distribution structures and materials, gases, and corrosive substances generated in wildfires, and high-temperature wildfire effects on bare structural steel mechanical properties.[1] Part 2 addresses 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 monitoring.

Effects of Wildfires on Hot-Dip Galvanized Steel

Unlike paints and organic coatings used to protect steel structures, galvanized coatings are zinc-based metallic coatings applied to structural steel using a variety of processes. The performance of these zinc-based coatings when subjected to fires depends on several factors, not the least of which is the characteristics of the galvanized coating arising from the process by which it is applied.[2] Pure zinc has a melting point of 419.5 °C (787 °F). Therefore, a coating consisting primarily of pure eta phase zinc is expected to start melting once this temperature is reached on the metal surface. Most galvanized steel products produced by a continuous galvanizing process (sheet, coil, and some tube) have a coating that is largely pure eta phase zinc.

Hot dip galvanized coatings are for transmission and distribution applications, applied by immersing batches of fabricated structural steel in a bath of molten zinc, and are made up of zinc-iron intermetallic alloy crystals with a thin layer of pure zinc on the surface. These zinc-iron intermetallic alloys constitute between 50% to 100% of the coating, depending upon steel chemistry and processing techniques. These zinc-iron intermetallic alloys are not only much harder than pure zinc, being about four to five times harder, but they also have a much higher melting point ranging from 530 °C to 780 °C (986 °F to 1,436 °F). The inner zinc-iron intermetallic layers are therefore more stable than the outer zinc-rich eta layer during exposure to high temperature wildfire conditions.

Loss of galvanizing without loss of strength may occur at lower temperatures and not be obvious, since such a pole/tower would still be standing. It would, however, be subject to accelerated corrosion and weakening over time. As an approximation, the bare steel will corrode in an atmospheric environment one to two orders of magnitude faster than the galvanized steel. To inspect for melted zinc galvanizing, a close-up visual examination would be required, preferably under moderate magnification. When the zinc melts, liquid droplets form, followed by the collection and formation of small pools of zinc. In addition, the surface of the liquid zinc metal could oxidize. Areas to be examined must be free of dust and ash.

Peeling of Outer Free Zinc Layer Above 200 °C (390 °F)

Although not often considered, excessive heating of hot dip galvanized coating caused by wildfires and other heat sources may induce peeling of the outer free zinc layer, which is caused by metallurgical changes that create a series of closely spaced voids at the free zinc/zinc-iron alloy interface.[3] These voids are produced by the diffusion of zinc from the outer free zinc layer into the inner zinc-iron alloy layer. When these voids expand and form a gap, it causes the outer free zinc layer to physically separate from the underlying zinc-iron alloy layers. This solid-state physical process is known in metallurgy and materials science as the Kirkendall effect. At or below the industry-recommended limiting service temperature of 200 °C, the coating resists zinc layer peeling.

However, the remaining zinc-iron alloy layers may still provide a level of corrosion protection for an indeterminate duration. Exactly how long depends on the time/temperature conditions and the rate the deterioration process is influenced by coating thickness, the relative thickness of outer zinc and iron-zinc alloy, and by the uniformity of the individual layers. At exposure temperatures ranging from 200 °C to 250 °C (480 °F), the zinc-iron alloy layers may continue to protect the steel from corrosion. Exposure temperatures above 250 °C will accelerate peeling, and continued exposure can result in the zinc-iron alloy layers cracking and separating from the steel. Figure 1 presents cross section microscopic evidence of this peeling phenomenon.

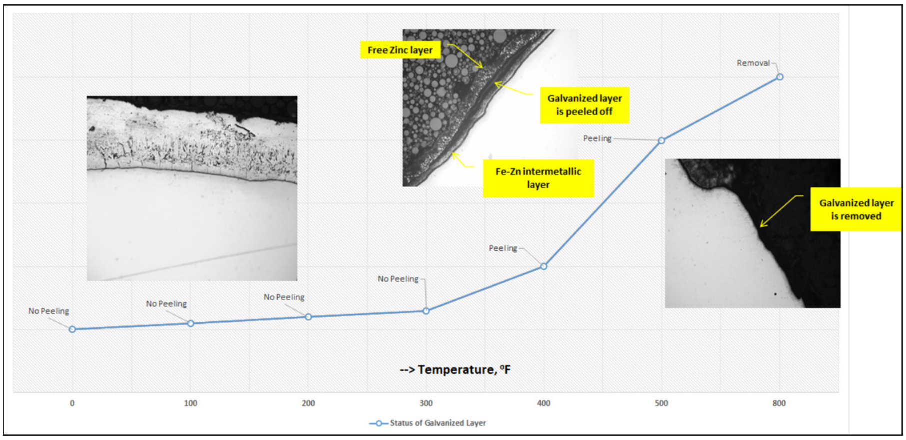

FIGURE 1 Cross-section microscopic evidence of the peeling phenomenon.

Some investigators have found that the peeling effect is greatly reduced when the galvanized coating contained very low levels of lead, less than 0.001%.[4] These investigators also found that brief temperature excursions up to 300 °C (572 °F) can be handled with no coating problems.

Galvanized Coating Exposures Above 538 °C (1,000 °F)

Although temperatures in fires can easily exceed 538 °C, they do not often last for durations that might compromise the integrity of a hot-dip galvanized steel structure.[4] Therefore, the potential for coating damage exists. However, prior experience has typically found minimal fire damage on galvanized structural steel parts exposed to fires. Fire exposure usually results in some orange- and/or rust-color staining, with a layer of black carbon dust, while the underlying galvanizing is intact.

Typical bushfire conditions may expose steel structures to air temperatures of 800 °C (1,472 °F) for periods of up to 120 seconds.[5] Depending on section thickness of the steel, the actual steel surface temperatures do not exceed 350 °C (662 °F) for a Level II bushfire event.

Wildfires and Thermal Degradation of Organic Coatings

Organic coatings and paints that may be burned or charred due to wildfire exposure will require replacement. The resin content of a fully cured organic (paint) coating is essentially a polymer with a complex combination of chemical bonds crosslinking together the organic monomers into two- and three-dimensional chains.

Thermal Degradation

If the heat applied is of sufficient intensity, such as would be experienced in a wildfire, the molecular vibrations increase in an organic coating or paint to such a degree that bonds could break. When this occurs, free radicals form and react with the polymer resin. Several chemical and physical phenomena may take place, as follows.[6]

- A decrease in molecular weight of the polymer chains comprising the resin of the coating
- A reduction of mechanical properties such as tensile strength, modulus of elasticity, and toughness
- Potential introduction or formation of reactive polar organic functional groups, or free radicals. These reactive polar functional groups may cause changes in compatibility and in the electrical and optical behavior of the polymer.
- Introduction of light-absorbing organic functional groups. These organic functional groups can cause discoloration and internal cyclization of the chains, resulting in hard-

TABLE 1 MAXIMUM SERVICE TEMPERATURE OF CONVENTIONAL COATING SYSTEMS[7]

Coating System	Maximum Service Temperature, °C (°F)
Epoxy phenolic coatings	204 °C (400 °F)
Epoxy novolac coatings	177 °C (350 °F)
Pure silicone coatings (tailored)	204 – 649 °C (400 – 1,200 °F)
Modified silicone acrylic coatings	177 – 204 °C (350 – 400 °F)
Modified silicone alkyd coatings	107 °C (225 °F)
Multi-polymeric matrix coatings(A)	400 °C (752 °F)

(A)Single or multi-component inert, inorganic, and composed of resin combinations. They may contain aluminum and micaceous iron oxide flake or titanium.

ening and a decrease in toughness of the coating.

Where absorbed heat energy is high enough, as in an elevated temperature exposure, bonds can break, and free radicals can form. This leads to the concept and definition of a maximum service temperature for a specific coating. When the fully cured organic coating is exposed above its maximum service temperature, such as may be experienced in a wildfire, bond-breaking and free-radical formation will occur from the absorbed heat energy. Maximum service temperatures of some conventional coating system types are provided in Table 1.[7]

A possible technique to mitigate extensive damage to a coated steel structure exposed to a wildfire would be to replace conventional organic coatings with a type of coating known as an intumescent coating.[7] Intumescent coatings offer a mainstream solution to protect load-bearing structural steel systems exposed to fire and excessive heat. When heated, intumescent coatings swell, forming a low-density and low-thermal-conductivity foam-like char. This foamed char prevents temperature increases of the steel that can cause structural instability and progressive failure.

Effects of Wildfires on Concrete

Concrete exposed to high temperatures such as fires has a complex behavior due to the differences in coefficient of thermal expansion of the concrete constituents.[9] The proportioning of concrete mixtures to achieve high strength and durability requirements in service has led to the production of dense mixtures with lower water to cementitious material ratios. The mechanical properties of high-strength concrete at elevated temperatures are different than those of conventional concrete, particularly regarding strength loss in the intermediate temperature range 100 °C to 400 °C (212 °F to 752 °F) and with the occurrence of explosive spalling in high-strength concrete. The foundation engineer should consider this strength loss in design and code specifications. Explosive spalling during a fire may lead to the direct heat exposure of steel reinforcement, causing a loss of structural capacity.[10] There will be significant differences in fire performance between high-strength and normal-strength concrete. Several factors may affect the fire resistance of concrete. These factors include concrete strength, moisture content, concrete density, steel reinforcement design, and aggregate type.[11]

FIGURE 2 A tower leg foundation after exposure to a wildfire. Note spalling of the concrete foundation.

Figure 2 is a photograph of a tower leg foundation that has been exposed to a wildfire. Note that the high temperature of the wildfire has caused spalling of the concrete. If left unmitigated, this could lead to further foundation degradation when exposed to various environmental conditions.

The properties of the concrete are determined by the type of coarse aggregate used in the mixture. The following three types of aggregates are used in construction, and their high-temperature compressive strength and modulus of elasticity properties are presented in Table 2.[9]

Modulus of elasticity is a measure of the stress–strain relationship and is an important parameter in the evaluation of the deformation response of concrete under working loads. The load-deformation behavior of concrete is in fact nonlinear, though generally in practice an elastic modulus is adopted for convenience.

It is also important to point out that the thermal properties of specific heat and thermal conductivity are also affected by the type of aggregate. Under fire exposure conditions, the thermal conductivity affects the rate of temperature increase of the material. Lightweight aggregate types have lower thermal conductivity when compared to carbonate and siliceous aggregate types. Nevertheless, all three aggregate types will experience up to a 50% reduction in thermal conductivity at 649 °C (1,200 °F).[9] Concrete foundations and structures exposed to wildfires should be reviewed by a registered professional structural engineer.

TABLE 2 EFFECT OF HIGH TEMPERATURE ON CONCRETE PROPERTIES[9]

Aggregate Type	Compressive Strength	Modulus of Elasticity
Carbonate (limestone, dolomite)	Maintain strength up to 649 °C (1,200 °F)	Reduction up to 50% at 427 °C (800 °F)
Siliceous (granite and sandstone)	Reduction up to 50% at 649 °C	Reduction up to 50% at 427 °C
Lightweight (natural or manufactured)	Maintain strength up to 649 °C	Reduction up to 40% at 427 °C

Concrete failure mechanisms during a fire event include loss of bending or tensile strength, loss of bond strength, loss of shear or torsional, loss of compressive strength, and concrete spalling.[12] The design of concrete structural elements should consider their separating and load-bearing functions without failure for a required period of time under a given fire scenario. Fire resistance design of concrete structures should ensure sufficient overall dimensions of a structural element section to keep heat transfer through the element within an acceptable limit. There should also be a concrete cover over reinforcement sufficient to keep the reinforcement temperature below critical values for a sufficient duration for the required fire resistance.

Condition Assessment After Wildfire Exposure by Non-Destructive Techniques

After fire exposure, structures should be assessed into one of three categories.[13] On-site hardness measurements will confirm if the members exhibit softening, embrittlement, hardening, or loss of ductility.

- **Category 1**–Straight members that appear to be unaffected by the fire, including those that have slight distortions that are not easily visually observable. These members are typically unaffected by the fire or require minor repairs.
- **Category 2**–Members that are noticeably deformed but that could be heat-straightened, if economically justified.
- **Category 3**–Members that are so severely deformed that repair would be economically unfeasible when compared to the cost of replacement.

These categories do not address embrittlement or loss of ductility during fast cooling by extinguishing liquids, galvanized steel, and corrosion risks.

The following non-destructive techniques and condition assessments can be used to determine strength reductions or galvanizing damage due to wildfires.

- Dimensional check
- Zinc coating thickness at visually affected areas
- Wall thickness measurements at visually affected areas
- On-site nondestructive hardness measurements
- On-site nondestructive corrosion potential measurements
- On-site nondestructive metallographic analysis
- On-site nondestructive compressive strength hammer impact measurements of concrete and petrographic analysis

For information purposes only, Table 3 presents nondestructive testing (NDT) sample reads and associated risks prior to and after exposure to a wildfire

If any of the above values are reached, exceeded, or approached, the asset owner is advised to consider the structure's service, loading, and impacts for loss of function to determine any corrective actions, contingency plans, and other integrity program actions.

Temperature and Corrosion Potential Monitoring

Wildfire temperature and corrosion potential monitoring is the best way to determine the temperatures to which a structure has been exposed and for what durations. Based on this data, decisions can be made as to the level of investigation that will be required to determine the steel properties and stability of the structures. From this, remediation actions can be implemented. These actions could include repair, replacement, or no action. There is a critical need to install sensors to ascertain any temperature and corrosion risks.

A wildfire temperature sensor should be able to transmit by satellite the temperature and corrosion potential in real time prior to, during, and after a wildfire. This will provide important information and identify specific towers that have been exposed to wildfire and quantify the risk by transmitting exposure temperature, time of exposure, and corrosion potential. Figure 3

TABLE 3 SAMPLE NDT READS AND ASSOCIATED RISKS PRIOR TO AND AFTER EXPOSURE TO WILDFIRE

Test	Readings
Corrosion Resistance Loss	−0.80 V (acceptable) vs. −0.40 V (not acceptable)
Concrete Strength Loss	28 MPa/4,000 psi (acceptable) vs. 3.4 KPa/500 psi (not acceptable)
Metallography	Pearlite (acceptable) vs. Martensitic Structure (not acceptable)
Hardness and Strength	90 HV (acceptable) vs. 70 HV (not acceptable)

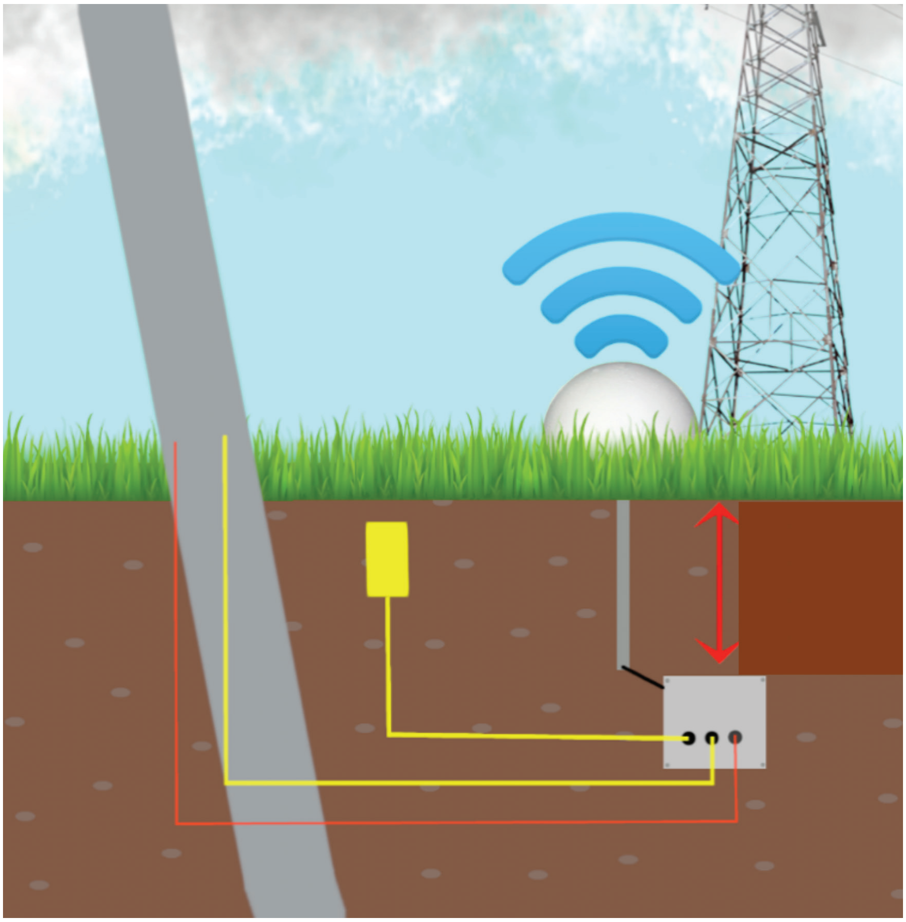

FIGURE 3 Wildfire temperature sensor system configuration for transmission and distribution structures including buried controller unit (gray), temperature sensors (yellow), corrosion sensors (red), and a helical satellite antenna with heat-resistant dome (at ground level).

presents one such wildfire temperature sensor system configuration known as EnviroZense,[†] which is a wireless, heat-resistant temperature and corrosion monitoring sensor that is contained in an electrical enclosure underground at the project site. The unit is simple to install and comprises corrosion and temperature sensors–one to monitor the wildfire temperatures and the second to monitor the corrosion activity of the bare steel structure below ground. The monitoring unit is configured to collect data routinely, at specific time intervals. The data are wirelessly transmitted by a satellite module for analysis and warns the project owner of abnormal temperature rises before more serious structural problems occur. The web view allows one to monitor the temperature and corrosion potential data from each structure in real time. Critical temperatures and corrosion potentials will be highlighted for quick identification, so one knows which structures need attention. The web view can also graph data for a quick and easy way to analyze how long the structures have been exposed to elevated temperatures or corrosive environments.

Summary and Conclusions

The key points concerning adverse effects of wildfires on power industry steel structures are summarized below.

- The mechanical properties of galvanized steel towers/poles are temperature-dependent. With increasing temperature, the yield strength (>400 °C = 752 °F) and the modulus of elasticity (>200 °C = 392 °F) would decrease.
- If the wildfire temperature is above 600 °C (1,112 °F), time allowing almost 50% of the strength will be lost and load capacity of such member towers will decline dramatically.
- In most cases, the loss of mechanical properties cannot be determined or quantified by visual examination. This may have important implications for high-voltage structures and in high-consequence areas. Fast cooling (quenching) of wildfire-exposed towers by extinguishing liquids and chemicals may result in formation of martensite and embrittlement (loss of ductility) that cannot be detected by visual examination and may have serious consequences upon impacts.
- Sensors transmitting real-time wildfire temperature and corrosion potential will provide specific information on the mechanical integrity and corrosion risk to towers during and after a wildfire. Use of temperature sensors that can monitor temperature greater than 371 to 760 °C (700 to 1,400 °F) are required.
- Life-limiting mechanisms: corrosion, fatigue, and embrittlement should be considered in condition assessment and inspection of transmission and distribution structures exposed to wildfires and fire extinguishing liquids.

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