Thermal Sciences

PG&E Briones Pipe Span Addendum

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Contents

Executive Summary

Exponent, Inc. (Exponent) was retained to investigate two exposed pipe spans on Line 191-1 near Mile Point 28.21 in Briones Regional Park, Lafayette, California. An Exponent report dated October 16, 2019, included a stress analysis of the exposed segments; an analysis of the potential impact from wildland fires, falling trees, and seismic activity; and a review of the local geology and potential erosion to understand the intended construction of the spans. In this addendum, further technical analysis of the exposed pipe spans is presented, with particular focus on potential thermal impacts of a wildland fire on the spans. Factors beyond the scope of the original analysis are presented here, including the effect of vegetation clearance distance on the anticipated maximum temperature, the effect of gas flow on the pipe temperature, the effect of temperature on internal gas pressure, and the potential effects of the coal tar coating on maximum predicted temperature. Since the Buckeye Ranch Trail span is longer than the Girl Scout Camp span, the Buckeye Ranch Trail span represents a more severe condition for the temperature estimates in this study. Conclusions based on heat transfer calculations drawn with respect to the Buckeye Ranch Trail span will be conservative when applied to the Girl Scout span.

Conclusions

Based on our investigation, we have come to the following conclusions:

1. Under wildland fire conditions,[1] average pipe temperatures may reach $600°F$, resulting in a decrease in the material strength, and a yield safety factor per ASME B31.8 of less than 1.0. However, a safety factor of less than 1.0 does not indicate catastrophic failure, only that the elastic limit has been reached and plastic deformation may occur in the form of pipe bending.

2. A three-dimensional finite element analysis (FEA) computer simulation has shown that the Buckeye Ranch Trail span will retain sufficient structural capacity in wildland fire conditions (i.e., will not be at risk of collapse under their own weight), as shown by a comparison of the maximum predicted plastic deformation (1.1% true strain) relative to the expected ductility of the Grade B vintage steel (11.3 to 19.9% true strain). Unlike the previous work (Exponent report dated October 16, 2019), which calculated safety factors relative to the maximum allowable stress according to ASME B31.8, the current FEA incorporates a simulated geometric configuration and allows for an understanding of the structural behavior beyond the elastic limit and the actual geometry of the span.

[1] Frankman et al. “Measurements of Convective and Radiative Heating in Wildland Fires.” *International Journal of Wildland Fire*, 2012.

3. Under wildland fire conditions, conduction within the pipe walls will dissipate the heat quickly and will maintain the pipe temperature near the $600°F$ value despite peak wildland fire temperatures potentially exceeding $1500°F$.[2] [3]

4. Removal of large trees within 40 feet, and brush (under six feet high) within 20 feet are likely to maintain calculated safety factors relative to ASME B31.8 above 1.0 for both spans under the no-residual-stress case.

5. Gas flow within Line 191-1 at the span locations will not result in substantial cooling under wildland fire conditions. Flow rates from both typical summer and winter days were analyzed, and neither was found to result in substantial cooling of the pipe.

6. The internal gas pressure will not increase substantially as a result of heating of the pipe under wildland fire conditions, even if the nearest mainline valves are closed, due to the large volume of contained gas as compared to the relatively short length of the exposed sections.

7. Based on precise lab experiments and recreation testing, the coal tar enamel coating is expected to ignite under wildland fire conditions; however, it is not expected to increase the temperature of the pipe. Furthermore, testing showed that fire did not propagate along the length of the pipe, away from the heat source.

Recommendations

Based on the results of our analysis:

1. Exponent recommends that PG&E consider adopting a modified vegetation encroachment management practice for these exposed spans at Buckeye Ranch Trail and Girl Scout Camp on Line 191-1, in which:
    a. Within a 20-foot radius from the pipe, only surface fuels such as grasses are permitted.
    b. Within a 40-foot radius from the pipe, only brush that is less than 6 feet 6 inches high is permitted.
    c. Outside a 40-foot radius, vegetation is permitted.

Note that this Executive Summary does not contain all of Exponent's technical evaluations, analyses, conclusions, and recommendations. Hence, the main body of this report is at all times the controlling document.

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[2] Penny, Greg and Richardson, Steven. "Modelling of the Radiant Heat Flux and Rate of Spread of Wildfire within the Urban Environment." *Fire*, 2019.

[3] Dennison et al. Wildfire Temperature and Land Cover Modelling using Hyperspectral Data. Remote Sensing of Environment. 2006

Heat Transfer Calculations

The initial Exponent reported dated October 16, 2019, concluded that the temperature of the exposed pipe in the case of a wildland fire would be near 600º F. The following provides additional detail regarding the basis for this conclusion. Furthermore, the assumption of a constant pipe temperature, which results in a difference between the maximum temperature of a wildland fire, and the maximum temperature in the pipe, is justified.

Heating of an object in a wildland fire is caused by two modes of heat transfer, convection and radiation. Convection heat transfer is caused by air and other gases that are heated by the fire, pass over the object, thereby heating it. Increasing gas temperature and velocity increase the total heat transfer to the object. In the case of the exposed pipe span in a wildfire, the air velocity over the pipe is induced naturally due to buoyancy of the air heated by the fire. Radiation heat transfer is the direct emission of energy from a higher temperature body that is absorbed by a cooler body. In contrast to convective heat transfer, radiation does not require a physical medium (i.e., hot air passing over the pipe), but rather transmits heat directly through the space between the objects. Increasing the temperature of the high temperature body increases the magnitude of heat transfer. In the case of the exposed pipe spans in a wildland fire condition, the hot gases and trees in the fire transmit energy directly to the colder pipe.

Frankman et al. (2012) performed heat flux measurements 0.5 meters (1.64 feet) off the ground in wildfires with varying density and types of vegetation. They defined three types of wildfire conditions dependent on the sizes of the vegetation: **surface fires** in which only ground fuels (grasses, dead leaves, needles, and small brush) are consumed; **brush fires** in which medium-sized vegetation including brushes and shrubs are consumed; and, finally, **crown fires** in which the canopy of large fully developed trees are consumed. In all cases, heat flux from radiation and convection was measured, and the radiation term was found to be the dominant factor providing consistently high heat flux. Convection provided a fluctuating intermittent heat flux including occasional negative heat flux (cooling) when cold air near the ground was pulled up into the burning area.

Surface fires generated peak radiative heat fluxes of $\leq 115 kW/m^2$with flame lengths of $\leq 1.6\ m\ (5.25\ ft)$. Brush fires with flame lengths of $\leq 2.4\ m\ (7.87\ ft)$ reached peak heat fluxes of up to $132 kW/m^2$. Finally, fully-involved crown fires with flame lengths as large as 30 meters (98 feet) were measured to generate peak heat fluxes of up to $300 kW/m^2$[4]. Figure 1 shows vegetation for all three fire types (ground, surface, and crown) from Frankman et al. (2012).

As discussed in the Exponent October 2019 report, the pipe temperature can be computed to first order by performing a simple lumped capacitance heat transfer model. The lumped capacitance model treats the entire pipe as one body at a spatially uniform temperature with a bulk thermal mass (pipe mass multiplied by material heat capacity) that increases temperature as

[4] Frankman et al. “Measurements of Convective and Radiative Heating in Wildland Fires.” *International Journal of Wildland Fire*, 2012.

heat is added. Under the lumped capacitance model, pipe temperatures are assumed to be constant due to the conduction heat transfer in the pipe occurring much faster than the convection and radiation heat transfer to the pipe. The physical parameters used in this model are presented in Table 1.

The appropriateness of a lumped capacitance approach was verified through calculations of the Biot number, which compares the pipe's internal resistance to heat transfer by conduction to the resistance to convection (or radiation) at the surface.[5] If the Biot number is sufficiently small (< 0.1), conduction within the pipe occurs quickly enough for the temperatures inside the pipe to be uniform and the lumped capacitance model may be considered valid.[6] For convection, the Biot number is defined as

$$Bi = h \cdot th/k_{pipe}$$

and was calculated to be $1\text{x}10^{-4}$, within the range where lumped capacitance is considered valid.

For radiation, the Biot number is calculated as[7]

$$Bi = \frac{h_{rad}th}{k_{pipe}} = \frac{\varepsilon\sigma(T_{fire} + T_{pipe})(T_{fire}^2 + T_{pipe}^2)th}{k_{pipe}}$$

The Biot number calculation for radiation depended on several assumptions. A value of 1,500°F was used for the fire temperature, which was based on Penny and Richardson (2019).[8] Since higher pipe temperatures raise the Biot number, the pipe temperature was conservatively assumed to be 600°F, which bounds the temperature discussed in the October 2019 report and presented in Figure 2. Calculated average pipe temperatures for surface, brush, and crown fires. For this calculation the lowest thermal conductivity value of carbon steels at ~600°F presented in Incropera et al (2019) of $k_{pipe} = 40$ (W/m-K) was used as the lowest thermal conductivity resulted in the highest, most conservative, Biot number. The emissivity value used was a conservative assumption of $\varepsilon = 1$. Even with these conservative assumptions, the resulting Biot number was 0.03, a condition for which the use of a lumped capacitance model is appropriate.

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5 Incropera et al. *Introduction to Heat Transfer,* 5th ed., John Wiley and Sons, 2007.

6 Ibid.

7 Ibid.

8 Penny, Greg and Richardson, Steven. "Modelling of the Radiant Heat Flux and Rate of Spread of Wildfire within the Urban Environment." *Fire,* 2019.

Table 1. Heat transfer parameters.

Variable	Parameter	Value
ρ_{pipe} (kg/m^3)	Pipe density	8050
$c_{p,pipe}$ (J/kg-K)	Pipe heat capacity	510
k_{pipe} (W/m-K)	Lowest pipe thermal conductivity at 600 K	40
ρ_{gas} (kg/m^3)	Gas density	Calculated from gas temperature and pressure of 268 psia
$c_{p,gas}$ (J/kg-K)	Gas capacity	
k_{gas} (W/m-K)	Gas thermal conductivity	
T_0 (K)	Initial temperature (pipe and gas)	293
th (in)	Pipe thickness	0.356
D_o (in)	Pipe outer diameter	10.75
D_i (in)	Pipe inner diameter	$D_o - 2\,th$
L (ft)	Length of span	47
Δx (ft)	Length of pipe segment	L/200
F (kW/m^2)	Heat Flux	0-300
ΔV_{pipe} (m^3)	Incremental pipe volume	$\pi\, th \frac{D_o + D_i}{2} \Delta x$
ΔV_{gas} (m^3)	Incremental gas volume	$\pi \frac{D_i^2}{4} \Delta x$
σ (W/m^{2}K^4)	Stefan-Boltzmann constant	5.67x10^{-8}
ε	Emissivity	1

This calculation of a relatively low Biot number, and the appropriateness of the lumped capacitance model, show that, although temperatures within the fire may be much higher locally for brief periods of time, these high peak temperatures will not affect the bulk pipe temperature.

Pipe temperature calculations and radiation measurements from Frankman et al. (2012) for all four locations identified in Figure 1 are shown in Figure 2. For crown and brush fires, average pipe temperatures reach $\sim 600°F$, whereas surface fires only reach $\sim 130°F$.

In the October 2019 Exponent report, temperatures required for material yield under different assumptions were calculated using a structural model. These results are summarized in

Table 1. Given that under both calculated crown fire conditions, as well as the calculated brush fires, peak temperatures approach $600^{\circ}F$, this table shows that, depending on the specific assumptions (yield or ASME 31.8), the Buckeye Ranch and Girl Scout Spans may be at risk of reaching the elastic limit under wildland fire conditions.

Table 2. Pipe structural calculations.

<table>
<tr><td colspan="4">Buckeye Ranch</td></tr>
<tr><td colspan="2">Cold Bend</td><td colspan="2">No Residual Stress</td></tr>
<tr><td>B31.8</td><td>Yield</td><td>B31.8</td><td>Actual Yield</td></tr>
<tr><td>$150°F$</td><td>$350°F$</td><td>$450°F$</td><td>$572°F$</td></tr>
<tr><td colspan="4">Girl Scout Camp</td></tr>
<tr><td colspan="2">Cold Bend</td><td colspan="2">No Residual Stress</td></tr>
<tr><td colspan="2" rowspan="2">No Bend or Residual Stress in Girl Scout Camp Span</td><td>B31.8</td><td>Actual Yield</td></tr>
<tr><td>$480°F$</td><td>$680°F$</td></tr>
</table>

Figure 1. Vegetation in Ichauway 4 (surface fire) top left, Rombo 2 (brush fire) top right, Rat Creek (crown fire) bottom left, and Mill Creek (crown fire) bottom right measurement sites from Frankman et al. 2012.[9]

[9] Ibid.

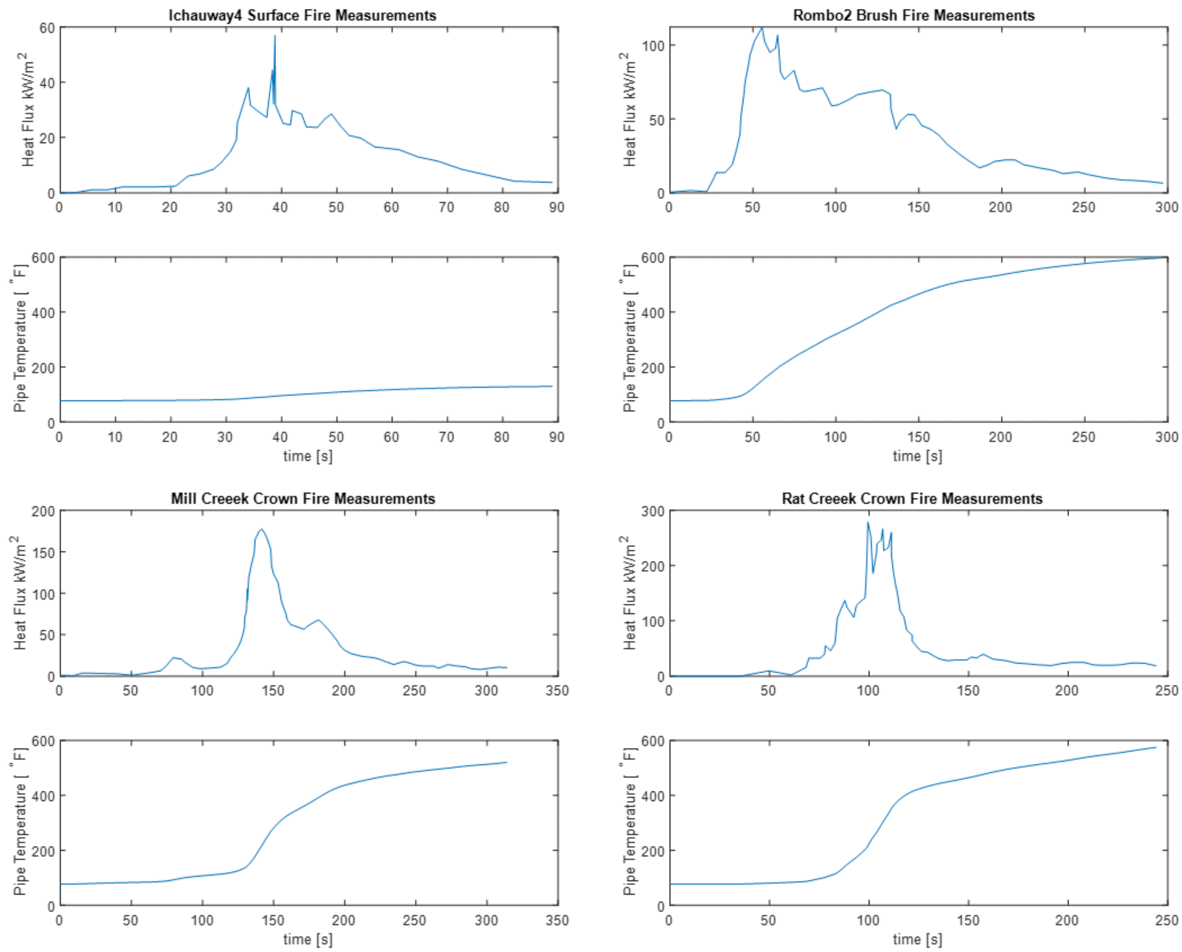

Figure 2. Calculated average pipe temperatures for surface, brush, and crown fires.

Vegetation Encroachment Specification

In the October 2019 Exponent report on this subject, a recommendation was provided to cut back all vegetation within 40 feet of the pipe span. The following discussion provides additional analysis and detail regarding recommended cut back distances. Following this additional analysis, the original 40-foot clearance recommendation has been refined, and recommendations are provided using language consistent with the current PG&E vegetation encroachment standard.

To reduce the expected pipe temperature under wildland fire conditions, the distance between the exposed spans and surrounding vegetation can be increased. For underground pipe, PG&E uses Utility Standard TD-4490S, an excerpt of which is shown in Figure 3. This excerpt defines the *Pipe Safety Zone*, *Border Zone* and *Outer Zone* that limit the types of vegetation within a certain radius of the pipe. This standard defines each zone as follows:

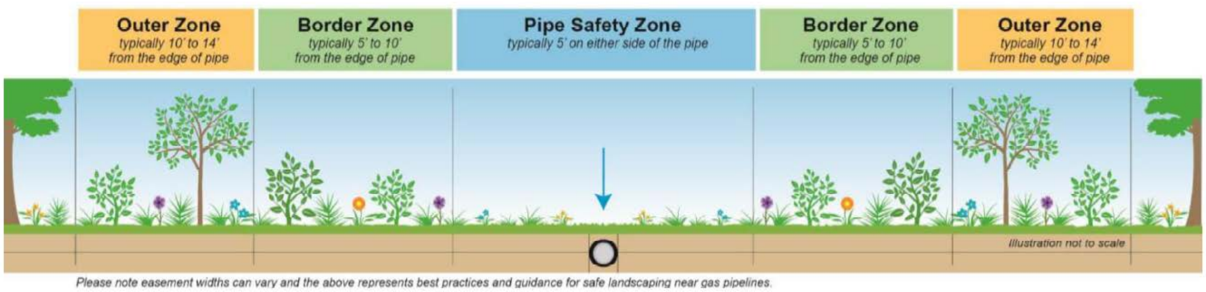

Figure 3. Underground gas pipe vegetation control zones. Reprinted from Utility Standard TD-4490S.

a. *The **Pipe Safety Zone** area around the pipe extends from the edge of the pipe 5 feet (ft) to the border zone.*
    1) *Per the criteria in Section 3.2, any trees and vegetation (e.g. brush or shrubs) obstructing the line of sight and access to the pipeline must be removed AND are not permitted to be planted in the pipe zone.*
    2) *Lawns, flowers, low-profile grasses, and low-growing plants are permitted within the pipe zone.*

b. *The **Border Zone** extends from the edge of the pipe zone out an additional 5 ft on each side of the pipeline. Per the criteria in Section 3.2, incompatible vegetation found in the Border Zone include the following:*
    1) *Trees and vegetation exceeding 8 inches (in.) in diameter, OR of species likely to exceed 8 in. in diameter at breast height (DBH) at maturity at 4.5 ft above ground, AND the trunk or main branch is more than 5 ft to 10 ft from the outer edge of the pipeline, must be removed AND not permitted to be planted in the border zone.*

c. *The **Outer Zone** extends from the edge of the border zone out an additional 4 ft on each side of the pipeline.*

1) *Trees, exceeding 36 in. in DBH, OR of a species likely to grow to and exceed 36 in. in DBH at maturity, AND the trunk or main branch is 10 ft to 14 ft from the outer edge of the pipeline, must be removed AND are not permitted to be planted in the outer zone.*

Comparing this specification to the surface fuels, brush fuels, and crown fuels described in Frankman et al.,[10] the *Pipe Safety Zone* (within 5 feet of the pipe) permits only surface fuels, while the *Border Zone* (5 feet to 10 feet from the pipe) permits surface and brush fuels. Crown fuels are permitted only in and beyond the *Outer Zone*.

Cohen and Butler studied the effect of distance between radiant heat flux on structures and fires of varying types and sizes.[11] Figure 4, excerpted from their text, shows the decrease in radiant heat flux from 3 to 15 meters (10–49 feet) for shrub and tree flames. Based on PG&E and Exponent inspections and tree measurements (see Appendix A), trees in the region of both the Buckeye Ranch and Girl Scout camp spans range from 30 feet to 90 feet (9 meters–27 meters) and there is scattered brush ~ 4 feet (1.2 meters) tall. These measurements suggest that the brush fire in the *Border Zone* can be characterized by the 5-meter-wide x 2-meter-high (16 x 6 feet) flame curve in Figure 4, while the crown fire in the *Outer Zone* and beyond can be characterized by the largest flame curve in Figure 4[12] (30 meters wide x 20 meters high, 98 x 66 feet).

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[10] Frankman et al. “Measurements of Convective and Radiative Heating in Wildland Fires.” *International Journal of Wildland Fire*, 2012.

[11] Cohen, J.D. & Butler, B.W. (1996) “Modeling Potential Structure Ignitions from Flame Radiation Exposure with Implications for Wildland/Urban Interface Fire Management,” 13th Fire and Forest Meteorology Conf., Lorne, Australia.

[12] Ibid.

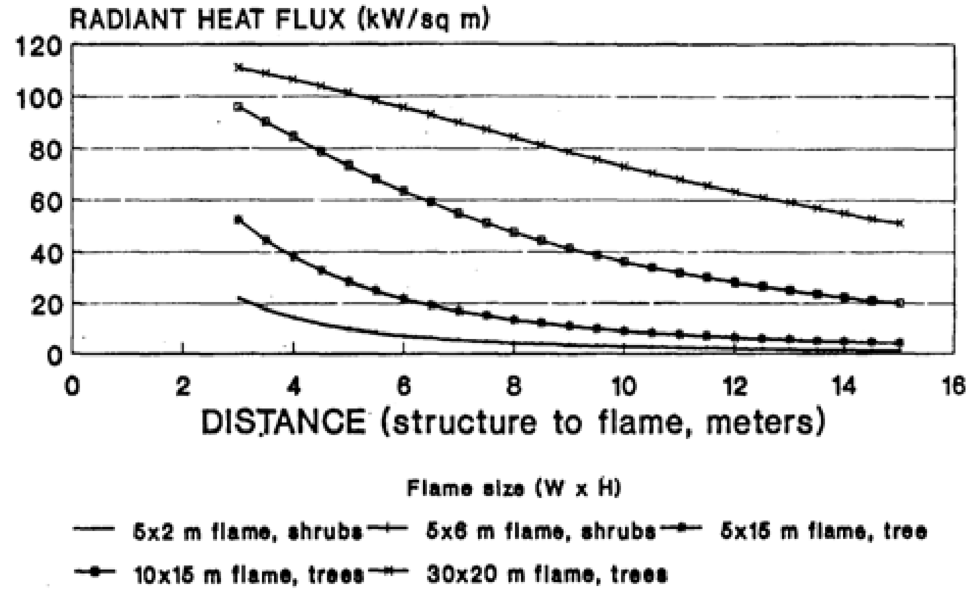

Figure 4. Radiant heat flux to distance reprinted from Cohen and Butler 1998.[13]

To estimate the heat flux for the composite environment created by the TD-4490S standard, the heat flux of each environment (surface, brush, crown) is considered, and the heat flux is scaled for distance based on Figure 4. As the brush fire measurements made in Frankman et al.[14] include the radiative component of surface fires, and crown fires include the radiative component of both surface and brush fires, the radiation flux from just the crown component is calculated as

$$Flux_{Crown} = Flux_{RatCreek} - Flux_{Rombo2} - Flux_{Ichauway4}$$

And the brush component as

$$Flux_{Brush} = Flux_{Rombo2} - Flux_{Ichauway4}$$

The Rat Creek test site was chosen for the crown fire measurements because it had the highest heat flux, and thus highest expected temperatures. Based on the TD-4490S vegetation encroachment standard, ground and surface fuels are permitted within 5–10 feet and, as such, their heat flux is not reduced based on Figure 4. Crown fuels are to be cut back 10 feet (~3 meters), which is the minimum distance measured by Cohen and Butler, and does not decrease the heat flux sufficiently to reduce the pipe temperature.

In the original report from October 2019, the removal of all vegetation up to 40 feet from the pipe was proposed to reduce the radiative heat flux by 40% and to reduce the peak heat flux to

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13 Ibid.

14 Frankman et al. "Measurements of Convective and Radiative Heating in Wildland Fires." *International Journal of Wildland Fire*, 2012.

approximately $150kW/m^2$ such that the estimated pipe temperature would drop to $T_{Pipe}{\sim}376°F$. Under this condition, the pipe safety factor was increased above 1.0 for both the Girl Scout Camp and the Buckeye Ranch span for all but the most extreme cold bend stress calculations of the Buckeye Ranch span. The heat flux and temperature estimates are shown in Figure 5.

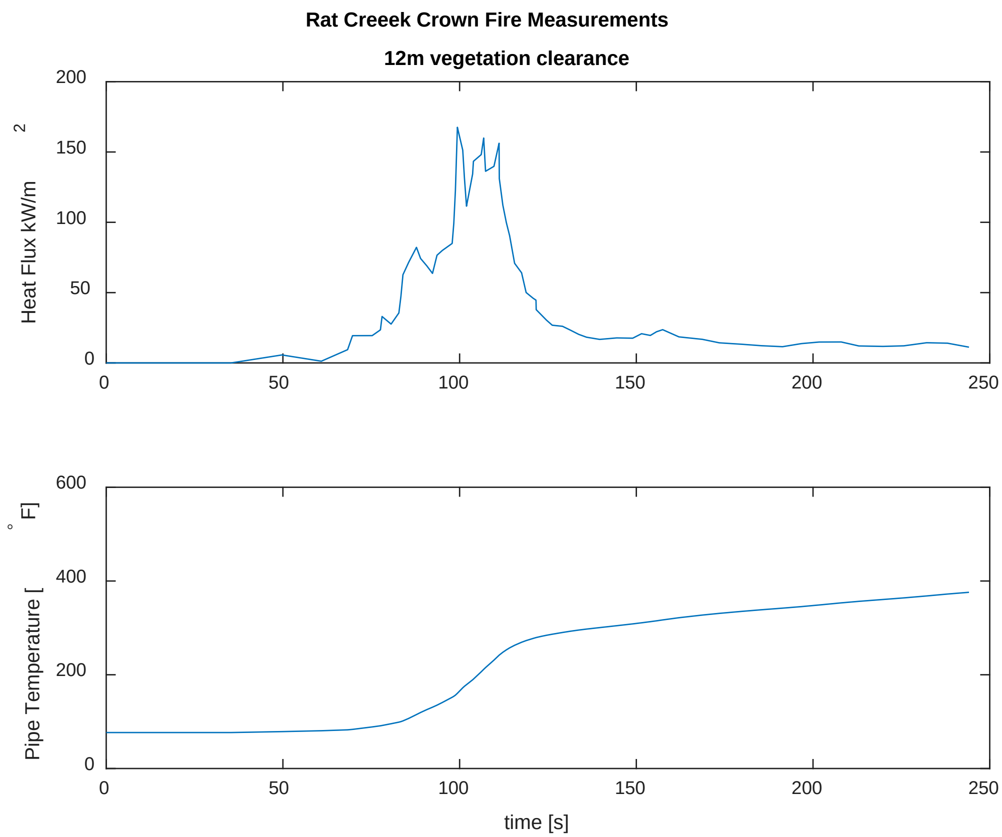

Figure 5. Rat Creek crown fire heat flux and estimated pipe temperature with vegetation cut back 12 meters.

The TD-4490S encroachment standard attempts to limit the visual impact of the pipeline clearance by feathering small vegetation into larger along the pipeline clearance.[15] As written, the standard does not provide sufficient clearance to reduce the pipe temperature in these two instances within a safety factor of 1.0. However, the standard can be modified (extended) such that the calculated safety factor remains above 1.0. The components of the heat flux, as well as the composite heat flux, used to calculate pipe temperature for one such proposed strategy is shown in Figure 6. In this strategy, the *Pipe Safety Zone* where only ground fuel such as grasses are permitted, is extended to 20 feet and the *Border Zone* is extended to 40 feet. Within this extended *Border Zone*, vegetation only up to 6.5 feet is permitted (modifying the 8-inch trunk diameter of the TD-4490S standard) to prevent crown fire. Outside the *Border Zone* limit of 40 feet, crown fuels are permitted as defined in the TD-4490S standard.

[15] PG&E Utility Standard TD-4490S Gas Pipeline Encroachment Management 07/05/2017.

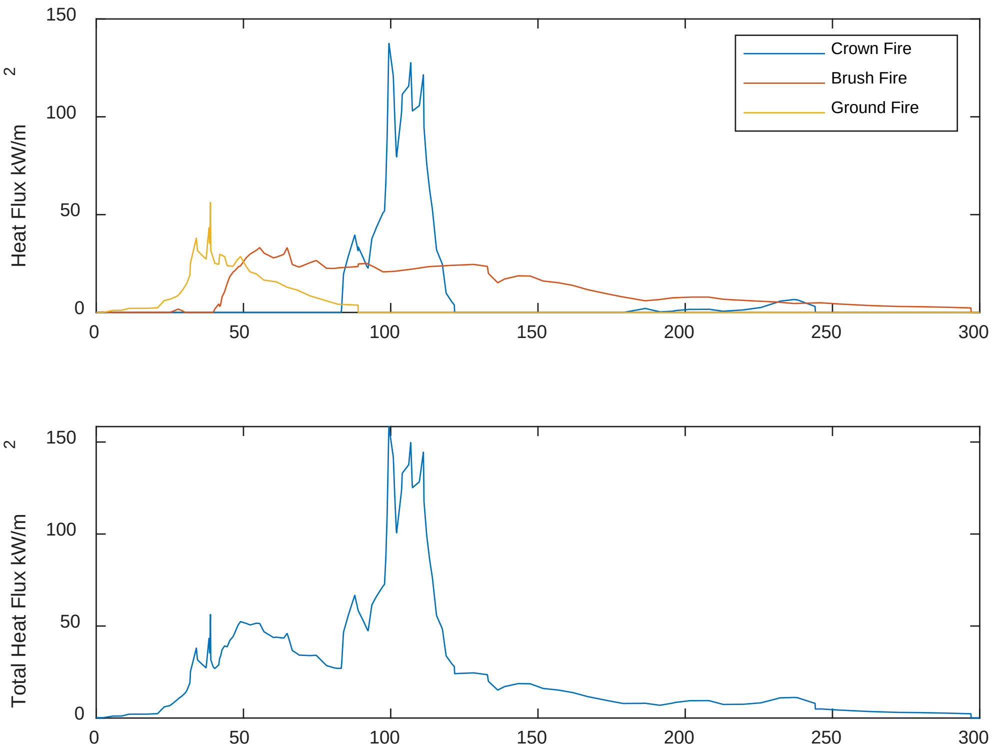

Figure 6. Forty-foot crown fuel and 20-foot brush fuel clearance. Heat flux from each fuel type (top) and the composite heat flux of all components (bottom).

The estimated pipe temperature based on this vegetation encroachment strategy is shown in Figure 7. Using this strategy, the peak pipe temperature is reduced to a predicted value of $T_{Pipe} = 415^{\circ}F$. At this pipe temperature, calculated safety factors are above 1.0 for the no-residual-stress condition for both the Buckeye Ranch Trail span and the Girl Scout Camp span. Increasing the pipe safety zone, and removing all but surface fuels up to 26 feet decreases the estimated pipe temperature to $T_{Pipe} = 345^{\circ}F$, which is below $350^{\circ}F$, the maximum temperature that still maintains a safety factor of 1.0 for the cold bend case relative to yield.

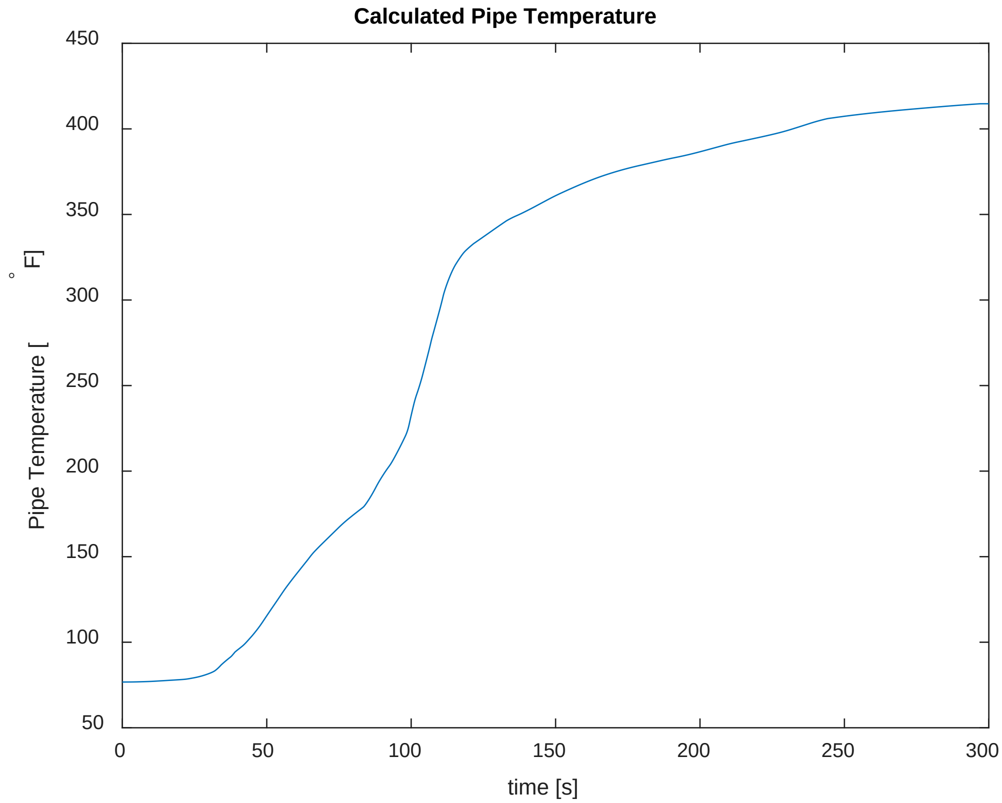

Figure 7. Calculated pipe temperature with crown fuel clearance to 40 feet and brush fuel clearance to 20 feet.

Effects of Gas Flow

In the previous Exponent report, potential cooling effects of the gas flow within the pipeline was not included in the analysis, which resulted in a conservative calculation of the maximum estimated temperature of the pipe. In this section, the effects of the expected gas flow on the pipe temperature is calculated.

To perform these calculations, the lumped capacitance heat transfer model was extended to include the heat transfer from the pipe to the moving gas. The model divided the pipe into 200 segments along the length of the span, with length, Δx, and corresponding pipe and gas volumes ΔV_{pipe} and ΔV_{gas}. For each span segment, the radiative heat flux into the pipe and convective cooling were used to determine the change in the pipe and gas temperatures over a time Δt. The calculations were iterated by advancing by Δt for the duration of the fire being modeled.

The pipe temperatures were calculated according to:

$$\frac{\Delta T_{pipe}}{\Delta t} = \frac{\dot{q}_{rad} - \dot{q}_{conv}}{\rho_{pipe}\Delta V_{pipe} c_{p,pipe}},$$

where the radiant heat flux, $\dot{q}_{rad}$, was taken from the Rat Creek case. Pipe parameters are provided in Table 1.

The gas temperature within each segment was determined using the convective heat transfer, the gas flow rate through the pipe, and gas parameters in Table 1 according to:

$$\frac{\Delta T_{gas}}{\Delta t} = \frac{\dot{q}_{conv} + \dot{m} c_{p,gas}(T_{in} - T_{out})}{\rho_{gas}\Delta V_{gas} c_{p,gas}}$$

Both the pipe and gas temperatures are affected by the convective heat transfer, which was calculated in each segment as:

$$\dot{q}_{conv} = h(\pi D_i \Delta x)\left(T_{pipe} - \frac{T_{in} + T_{out}}{2}\right)$$

The heat transfer coefficient h was determined using correlations from Incropera et al. 2007.[16] The flow in the pipe was sufficiently low to yield laminar conditions, where the heat transfer coefficient is calculated from:

$$Nu = \frac{hD_i}{k_{gas}} = 3.66$$

[16] Incropera et al. *Introduction to Heat Transfer,* 5th ed., John Wiley and Sons, 2007.

Gas flow rates were based on data for summer and winter conditions provided by PG&E from a hydraulic analysis of the spans.[17] The flow rate in the span approached zero in the summer when there is limited gas demand, to 724 standard cubic feet per hour (scfh) in the winter. Under the zero flow condition, lower convective cooling from the gas is expected.

To determine the potential cooling of the gas flow, the maximum flow rate, 724 scfh, was used for the heat transfer calculations. Gas pressures from the hydraulic analysis stayed within a narrow range. A pressure of 268 pounds per square inch absolute (psia) was used for the calculation of the gas properties, which were based on data for methane from the National Institute of Standards and Technology (NIST) at varying temperatures.[18]

Temperatures of the pipe and gas at the span entrance and exit under the maximum winter gas flow rate are shown in Figure 8. Due to the low gas flow rate, there is little convective heat transfer and the pipe temperature still approaches 600° F, as was the case when the gas flow was neglected. The total convection at the end of the applied radiation flux is 0.2 megajoule (MJ) compared to over 120 MJ of radiative heat transfer from the fire. The low amount of convective heat transfer also limits the temperature rise of the gas to less than 20° F.

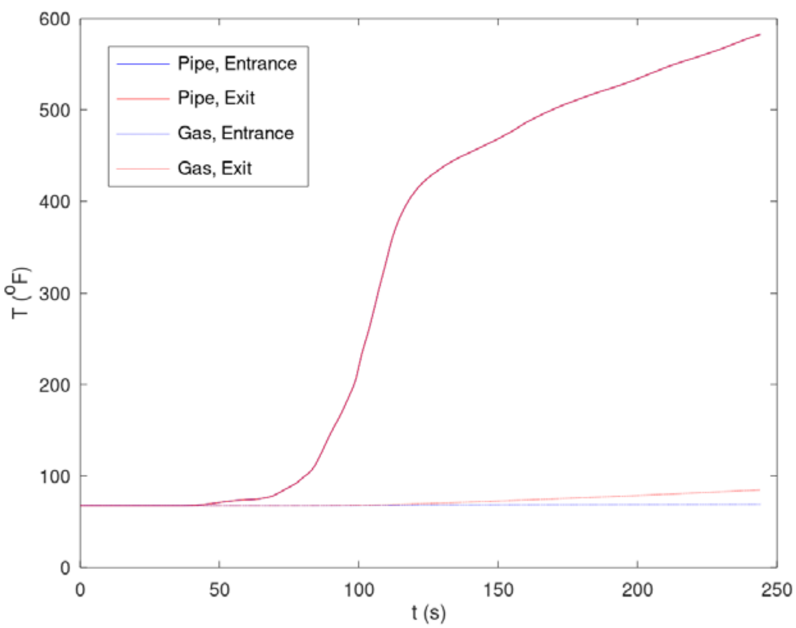

Figure 8. Calculated pipe and gas temperatures at the entrance and exit of the span. Note the pipe exit and entrance temperatures are nearly the same and indistinguishable in this figure.

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17 L191-1 Briones Span Hydraulic Analysis 0204020.xlsx.

18 NIST Chemistry WebBook, Thermophysical Properties of Fluid Systems https://webbook.nist.gov/cgi/fluid.cgi?Action=Load&ID=C74828&Type=IsoBar&Digits=5&P=268&THigh=600&TLow=280&TInc=1&RefState=DEF&TUnit=K&PUnit=psia&DUnit=kg%2Fm3&HUnit=kJ%2Fkg&WUnit=m%2Fs&VisUnit=Pa*s&STUnit=N%2Fm.

Pipe Pressure Calculations

The addition of heat to the gas due to a wildland fire has the potential to increase the internal pressures within the pipe. Under high flow velocities, gas pressure and flow in the pipe may be affected by the compressibility of the gas. If the valves upstream and downstream of the spans are closed, and the flow is shut-in, the gas pressure will increase with increasing temperature. In this section both flowing and shut in conditions are addressed.

In the case of flowing gas, the effect of this compressibility can be measured by the Mach number, where a Mach number of one indicates sonic flow. Under sonic flow conditions the internal pressure could increase substantially. A Mach number of above 0.3 indicates significant compressibility effects. At the extremely low flow velocities in the pipeline, the flow is expected to behave near incompressibly.

This simplification can be justified by treating the flow in the pipe as Rayleigh flow with heat addition. The heat addition causes a change in the Mach number and static pressure in the pipeline as follows:

$$\frac{T_2}{T_1} = \left(\frac{1+\gamma M_1^2}{1+\gamma M_2^2}\right)^2 \left(\frac{M_2}{M_1}\right)^2$$

$$\frac{p_2}{p_1} = \frac{1+\gamma M_1^2}{1+\gamma M_2^2}$$

The initial gas temperature is 293 Kelvin (K), and the speed of sound at this condition is approximately 450 meters per second (m/s). The incoming Mach number then is approximately $1.37 \cdot 10^{-5}$. From the heat transfer analysis, the gas temperature is expected to increase from 293 K to approximately 302.6 K across the entire span. The outgoing Mach number at this condition is approximately $1.39 \cdot 10^{-5}$. This acceleration produces a negligible compressible correction in the static pressure, meaning that no appreciable pressure change occurs.[19]

To evaluate the pressure increase if the pipe was shut in at the nearest valves the total volume of gas in the shut in section must be considered. The Buckeye Ranch and Girl Scout Camp spans are located near Mile Points 28.21 and 28.05 of Line 191-1 and are between valves at Mile Points 29.18 and 26.53; the measured distance between these two pipes is 13,285 feet.[20] Under the condition of the pipe section including the exposed span being completely shut in (nearest valves closed) the pressure will increase due to the heating of the contained gas. Under the extreme condition in which the temperature of the entire volume of contained gas is increased from $68°F$ to the wall temperature of $600°F$, the pressure of the gas, treated as an ideal gas, would rise from 268 psia to 537 psia. In this extreme scenario, the rates of temperature and pressure change in the pipe are approximately $0.048°F/s$ and 0.023 psi/s, respectively. Thus, in

[19] Kuethe and Schetzer. *Foundations of Aerodynamics*. John Wiley and Sons. 1959.

[20] Email from Kelly Leonard, Kelly.Leonard@pge.com, 2/12/2020.

the ~ 300 seconds that the span is exposed to significant heat flux from a wildfire, the average temperature of the gas would only increase $14.4°F$ and the pressure would only increase 7 psi.

Furthermore, the extreme condition of the entire volume gas increasing temperature to $600°F$ is unrealistic considering that the area of the pipe exposed to the heat flux is ~0.3% of the entire pipe length (47 feet or 40 feet is exposed respectively for the Buckeye Ranch and Girl Scout Camp spans in the 13,285 foot-long mainline). The remaining 99.7% of the pipe is buried underground and is surrounded by the soil at much lower temperature than the surface. Thus, the length of the pipe that is in contact with the soil would act as a heat sink preventing the temperature increase.

Coal Tar Coating Effects

The subject pipe is encased in an approximately ¼-inch-thick coating of coal tar enamel. This coating has the potential to affect the heat flux to the pipe in two different ways. First, the coating provides some insulative properties, thermally shielding the pipe from external heat flux from a wildland fire. Second, the coal tar enamel could potentially ignite, and the resulting flames could provide additional heat load to the pipe. To evaluate these two effects, a literature review and preliminary flammability tests were conducted.

The insulative properties of solid materials are quantified by a parameter called thermal conductivity. The lower the value of thermal conductivity, the higher insulative effect. The literature specifies the thermal conductivity of coal tar enamel as 0.16 watts per meter-Kelvin, or W/(m-K).[21] For reference, the thermal conductivities of coal tar and other materials are listed in Table 3.

Table 3. Thermal conductivity of select solid materials.

Material	Thermal Conductivity, W/(m-K)
Coal Tar	0.16
Steel (plain carbon)	60.5
Polystyrene (extruded)	0.027

Although the thermal conductivity of coal tar is relatively low, the small thickness applied to the pipe limits its insulative effects.

Small (~ one inch long by ¼-inch thick) samples of the coal tar coating material that had fallen from the pipe were collected during the site inspection of the Buckeye Ranch Trail span. Preliminary flammability testing of the coal tar coating was performed by exposing a sample of the coating to direct flame impingement from a BBQ lighter. The sample ignited within the first five seconds of flame exposure, maintained a flame, and produced flaming drips, as shown in Figure 9 and Figure 10. This test suggests that the coal tar coating can act as a fuel source and expose the pipe to direct flame if it is ignited.

[21] NIST Special Publication 1044, "Advanced Coatings R&D for Pipelines and Related Facilities," September 7, 2005.

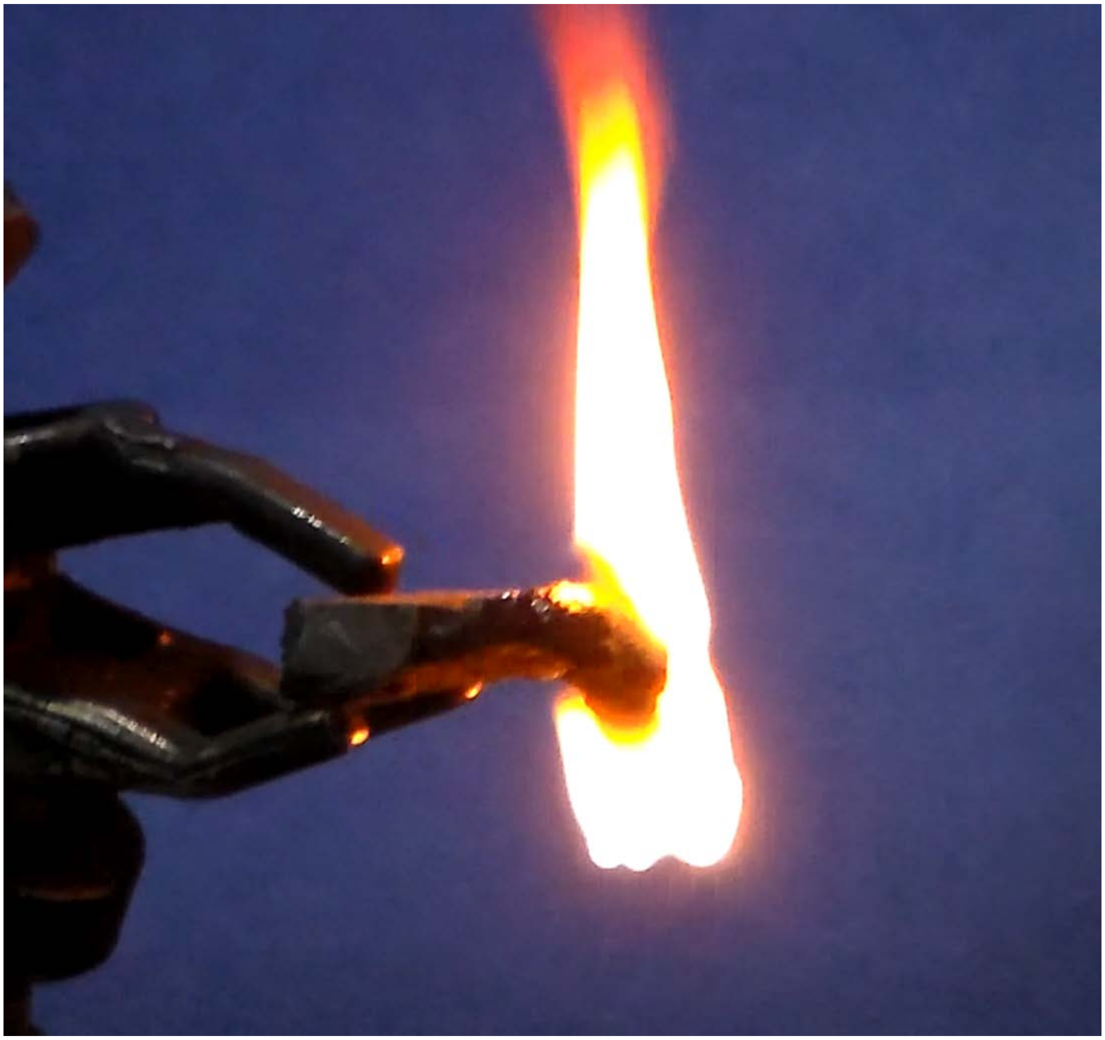

Figure 9. Coal tar enamel continuing to burn after ignition by a small flame.

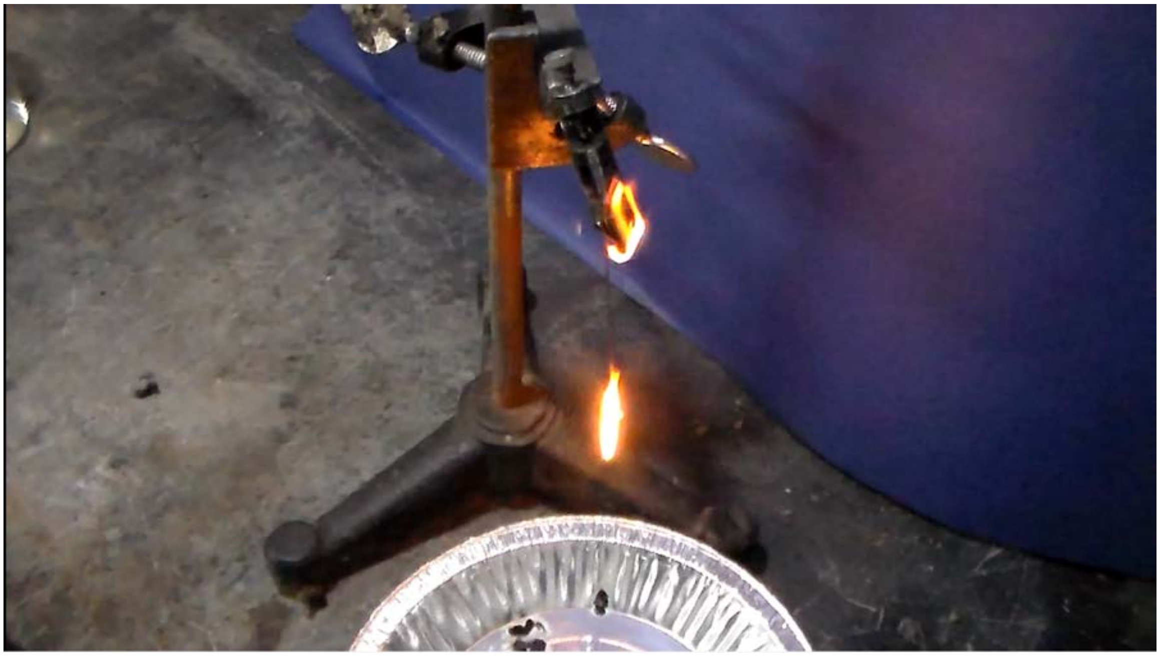

Figure 10. Coal tar enamel continuing to burn after ignition by a small flame and producing flaming drips that form a pool fire.

The literature confirms these general flammability properties of coal tar enamel. For example, Mirza et al. gives the following comment about "disadvantages" of coal tar enamel: "Gives minimal protection and is highly toxic and flammable."[22] A U.S. Department of Interior document describes a fire incident involving coal tar.

> *A fire occurred on April 19, 1966, in the manifold section of the outlet works of the pumping-generating plant. The fire resulted from an unknown source of ignition and spread rapidly when the coal-tar enamel coating on the outside of branch line No. 3 ignited. Cutting operations on reinforcement bars, surrounding the main penstock in the immediate area, had ceased approximately 3 hours before the fire was discovered. This precluded a definite conclusion that ignition came from this source. No injuries resulted from the fire or firefighting operations.*[23]

To test the effect of the coal tar coating under controlled laboratory conditions, the 4-inch-by-4-inch samples of an 8-inch pipe coated with coal tar enamel were placed under a cone calorimeter with an incident heat flux of ~80 kW/m^2. Samples were tested in both the vertical and horizontal orientation, with the coal tar facing the incident radiation, as shown in Figure 11.

[22] Mirza, et al. "Surface Coatings on Steel Pipes Used in Oil and Gas Industries—A Review," *American Chemical Science Journal*, 13(1): 1-23, 2016, Article no.ACSJ.22790.

[23] United States Department of the Interior Bureau of Reclamation, "Technical Record of Design and Construction Senator Wash Dam, Dikes, and Pumping-Generated Plant," March 1970.

Samples in both orientations ignited within a few seconds after the radiation was applied and continued to burn under the incident radiation.

Figure 11. Cone calorimeter testing. Vertical orientation (left) and horizontal orientation (right).

Pipe temperature was measured on the back of the sample, and a comparison of the coated and noncoated tests is shown in Figure 12 and Figure 13. The temperature of the coated samples is lower than the uncoated samples for all tests in both the horizontal and vertical orientations, suggesting that the insulative effects of the coal tar coating dominate, and the pipe temperature is not increased by the combustion of the coal tar enamel coating when compared to the bare pipe.

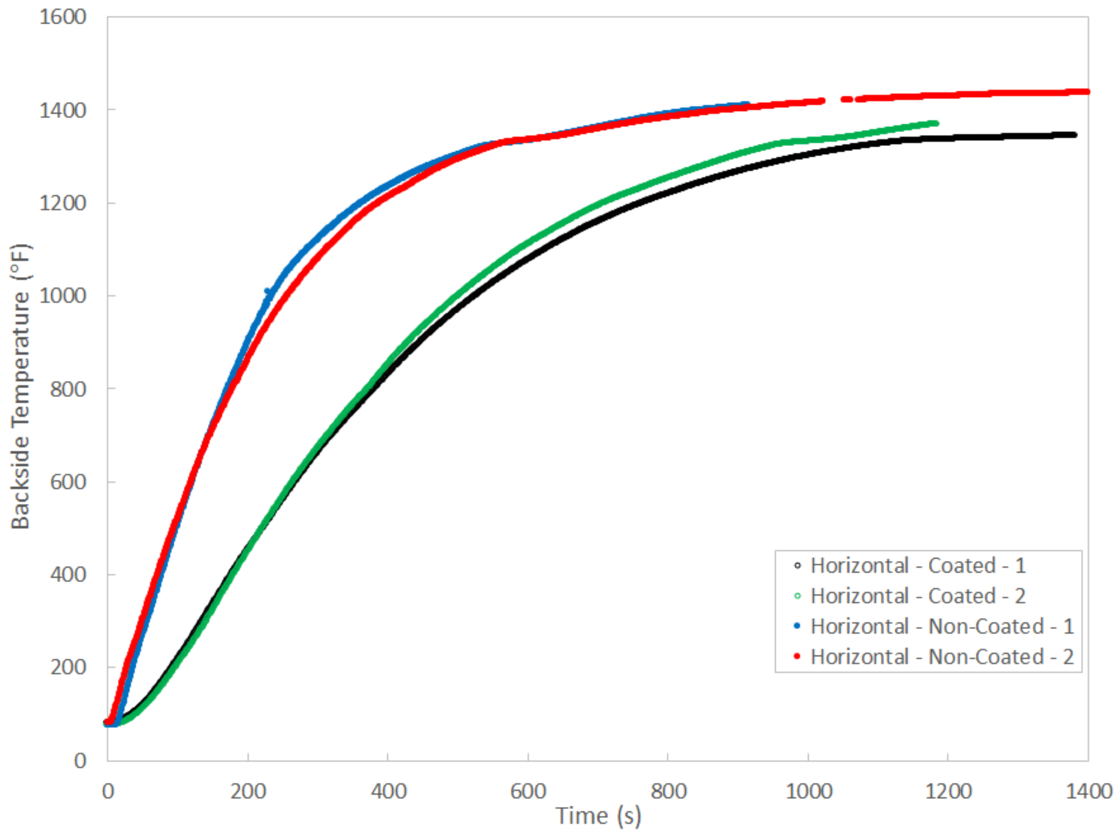

Figure 12. Pipe sample backside temperature in the cone calorimeter (horizontal orientation).

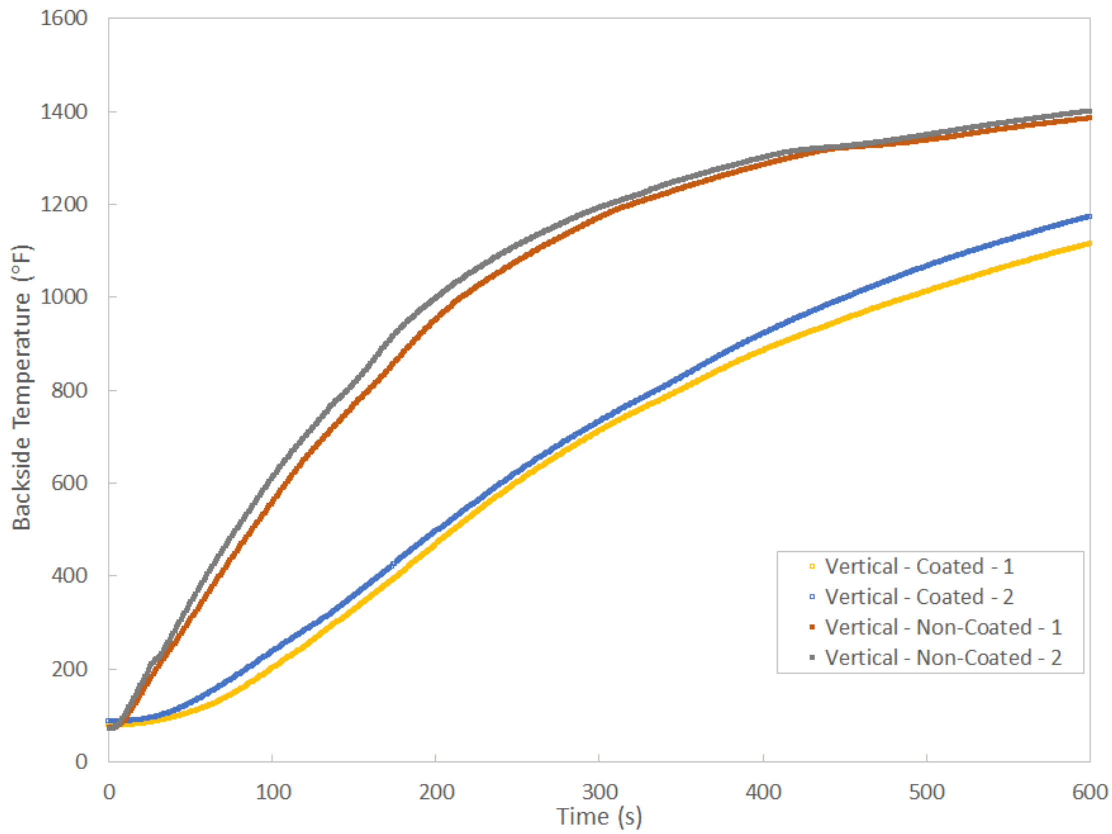

Figure 13. Pipe sample backside temperature in the cone calorimeter (vertical orientation).

The measured peak heat release rate for the horizontal samples reached up to ~460kW/m^2 and vertical samples reached over 600kW/m^2.

A recreation test was also performed by suspending an approximately 5-foot-long coal tar enamel coated 8-inch-diameter pipe over a wood fire, and allowing the wood fire to burn to completion. A photo of this test setup is shown in Figure 14, and photos during and after the test are shown in Figure 15 and Figure 16. During the testing, the coal tar enamel ignited, produced flaming drips, and maintained a burning surface on the outer diameter of the pipe. After the fire exposure, the coal tar continued to burn for a short period of time and then self-extinguished. The coal tar coating was not completely consumed by the fire, and a layer of material was left on the pipe after testing. Furthermore, not all of the coal tar was damaged during the test, indicating that a fire will not propagate along the pipeline after the coal tar enamel ignited.

Figure 14. Recreation test setup before pipe was fully engulfed in flame.

Based on the cone calorimeter and recreation testing, the coal tar enamel will serve as a fuel under a wildland fire condition, and may increase the intensity of a wildland fire near the exposed span. However, the effects of the coal tar on the temperature, and thus on the structural integrity of the pipe, are expected to be minimal.

Figure 15. Recreation testing.

Figure 16. Pipe section after recreation test.

Structural Behavior in Wildland Fire Conditions Beyond the Elastic Limit

While the prior Exponent report calculated safety factors relative to the elastic limit (ASME B31.8) and under the assumption of a straight pipe geometry, this did not afford an understanding of behavior in the plastic deformation regime and how that compares relative to the ultimate structural capacity of the pipe. The Buckeye Ranch Span was selected for detailed analysis in this study based on the higher calculated stresses in the prior Exponent report. In this section, an analysis using the actual, in-situ pipe geometry is presented which investigates the accumulation of plastic strain and structural deformation in a wildland fire condition.

Analysis Approach

A three-dimensional, finite element model was developed to simulate the structural response of the Buckeye Ranch Trail pipe span in a wildland fire condition. The model geometry was developed based on pipe specifications and laser scan data taken from field measurements. Figure 17 shows the idealized in-situ pipe span trajectory from the laser scan data. The model incorporated residual stresses related to an assumed cold bend process that consisted of a cross-section rotational bend and subsequent relaxation. The simulated cold bend process was iterated until a reasonable match to the in-situ pipe configuration was achieved under operational conditions. Figure 18 shows the initial model configuration as an idealized straight pipe; the boundary condition locations and cold bend rotation locations are identified.

Figure 17. Idealized in-situ pipe span trajectory from the laser scan data.

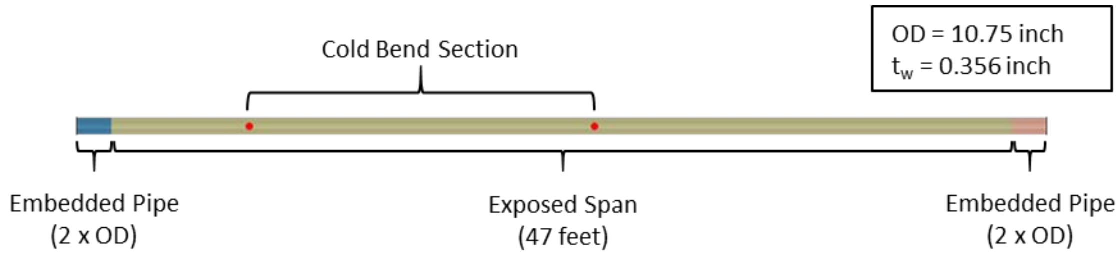

Figure 18. Initial model configuration as an idealized straight pipe. Constrained embedded pipe regions are shown at the ends, and the cold bend section is annotated.

A nonlinear elastic-plastic material model with temperature dependency was assigned to the pipe model. The temperature-dependent material properties were based on data from ASME B31.1 and B31.8. The elastic modulus, yield strength, and coefficient of thermal expansion were defined as a function of temperature (ranging to 700° F). The ultimate tensile strength—60 kilopounds per square inch (ksi)—was not input as a function of temperature, as specified for the given range in the documentation. The hardening curve of the temperature-dependent nonlinear material was characterized by an idealized hardening curve using the initial yield and ultimate strength. Figure 19 through Figure 21 show the temperature-dependent material properties used in the FEA.

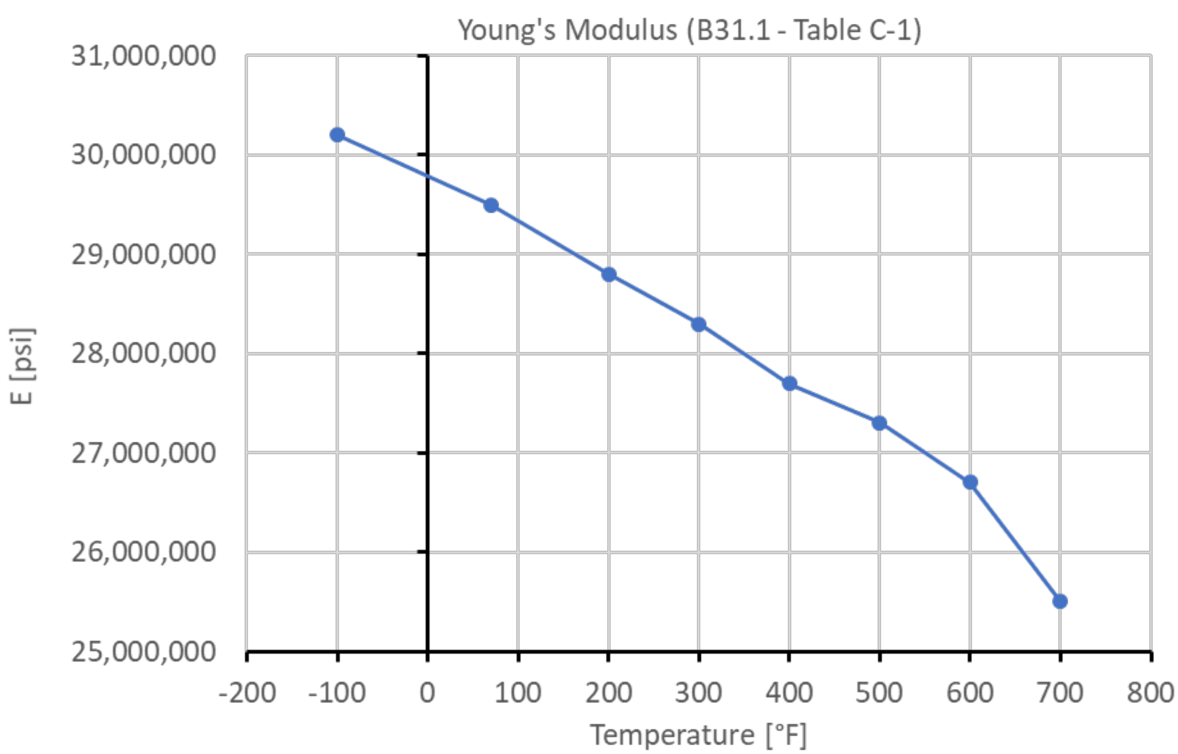

Figure 19. Temperature-dependent Young's Modulus (B31.1—Table C-1).

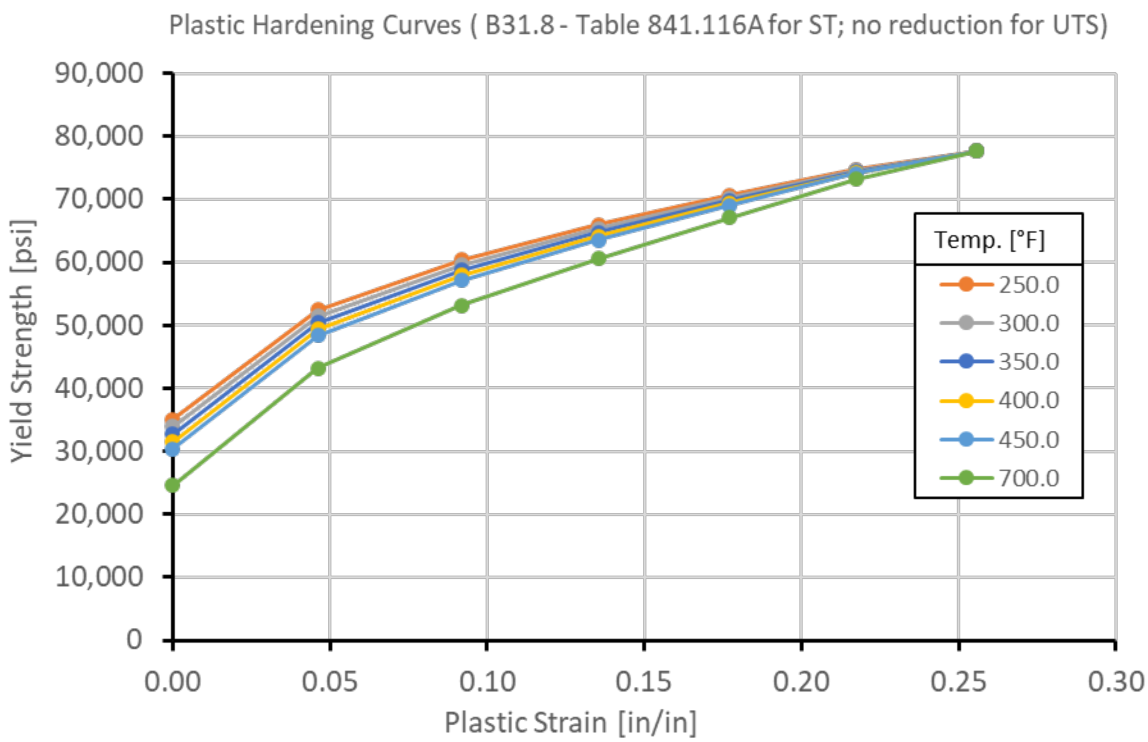

Figure 20. Temperature-dependent yield and idealized hardening curve. Yield strength properties were taken from B31.8—Table 841.116A.

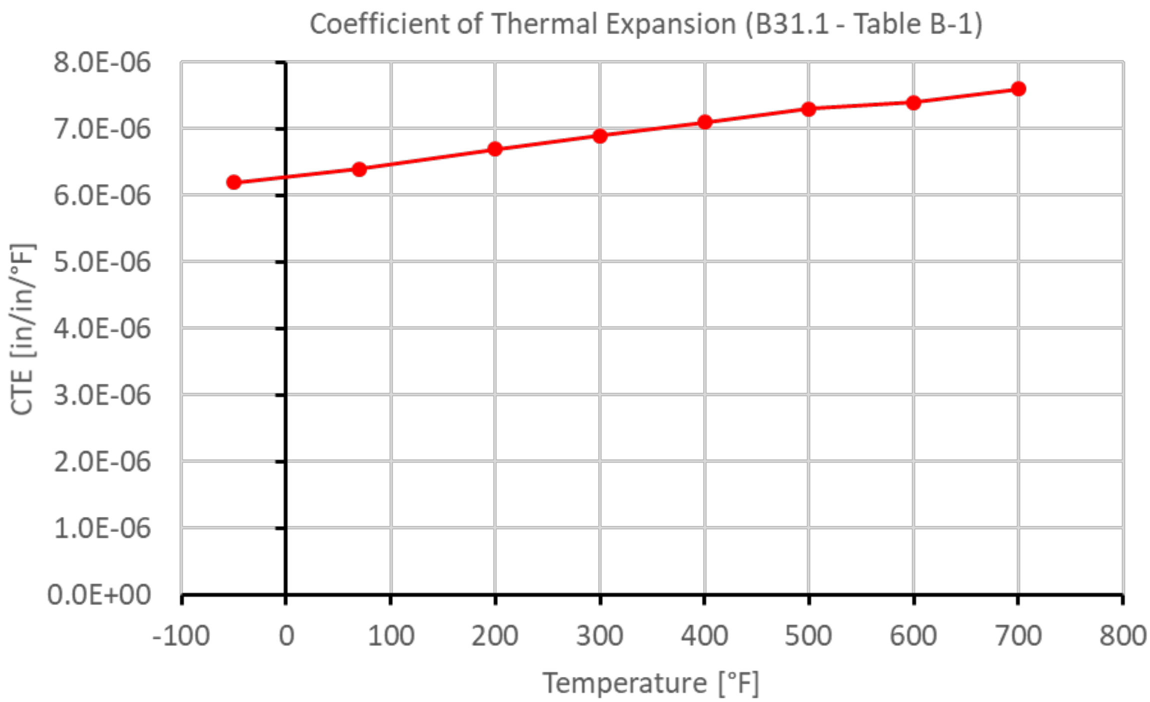

Figure 21. Temperature-dependent coefficient of thermal expansion (B31.1—Table B-1).

The model was discretized using continuum shell elements (Abaqus element type SC8R). Five integration points were defined through the pipe wall thickness. The total number of elements in the model was approximately 5,000, with 10,000 nodes, and overall degrees of freedom totaling 30,000. The characteristic element length was 1.89 inches.

As referenced, the pipe model was constrained at either end at an effective length of two times the outer diameter, serving as a conservative boundary condition for thermal expansion, and simulating the embedded pipe in the earth. Both gravity and an operational pressure of 283 psi were applied. Subsequently, a thermal gradient to simulate a wildland fire condition was applied, resulting in a pipe temperature of 572° F.

Results

Figure 22 shows the resulting effective stress (von Mises) and deformed geometry after the simulated cold bend process and under operational conditions (i.e., gravity and pressure). A peak residual stress of 19.5 ksi was predicted, which is similar to what was determined in the previously referenced ATS report. The subsequent peak operational stress under gravity and pressure is approximately 20.3 ksi. The deformed geometry was qualitatively compared to the laser scan results (Figure 23) and deemed an acceptable representation of the current configuration of the pipe span. Note that the residual stress from the simulated cold bend is an estimate informed by the current pipe span configuration; the actual forming process is unknown and is a source of uncertainty in the modeling approach. Figure 24 shows the true strain contour plot under operational conditions. The peak true strain is approximately 0.5%. Figure 25 shows the equivalent plastic strain, also at a peak of approximately 0.5%.

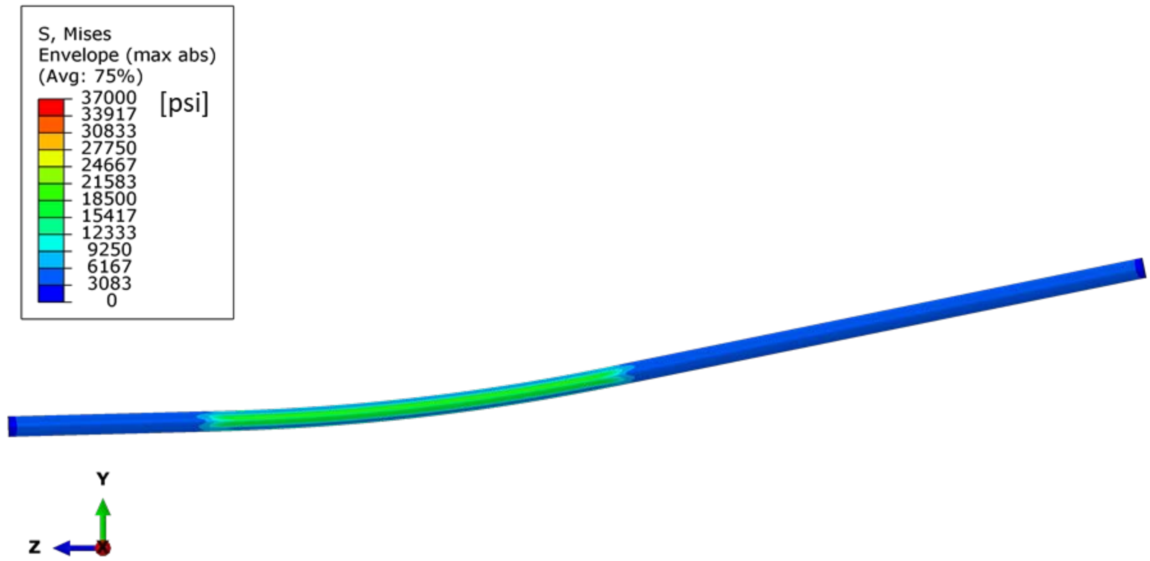

Figure 22. Effective stress contour plot of the pipe span after the simulated cold bend process and under operational gravity and pressure conditions.

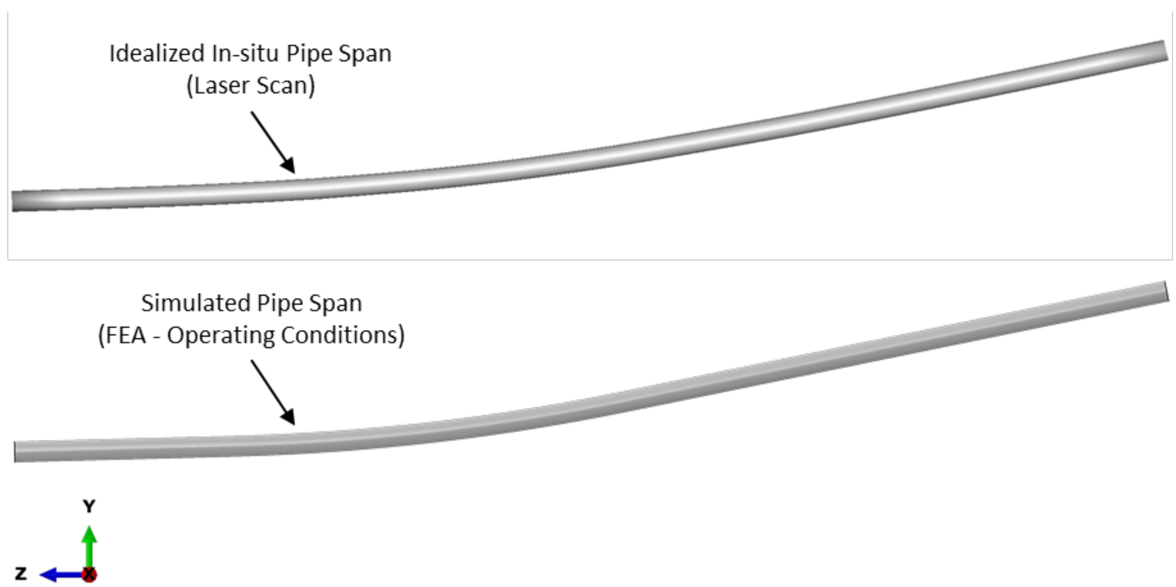

Figure 23. Comparison of the in-situ pipe span geometry as measured from the laser scan data and the simulated pipe span geometry using finite element analysis (FEA).

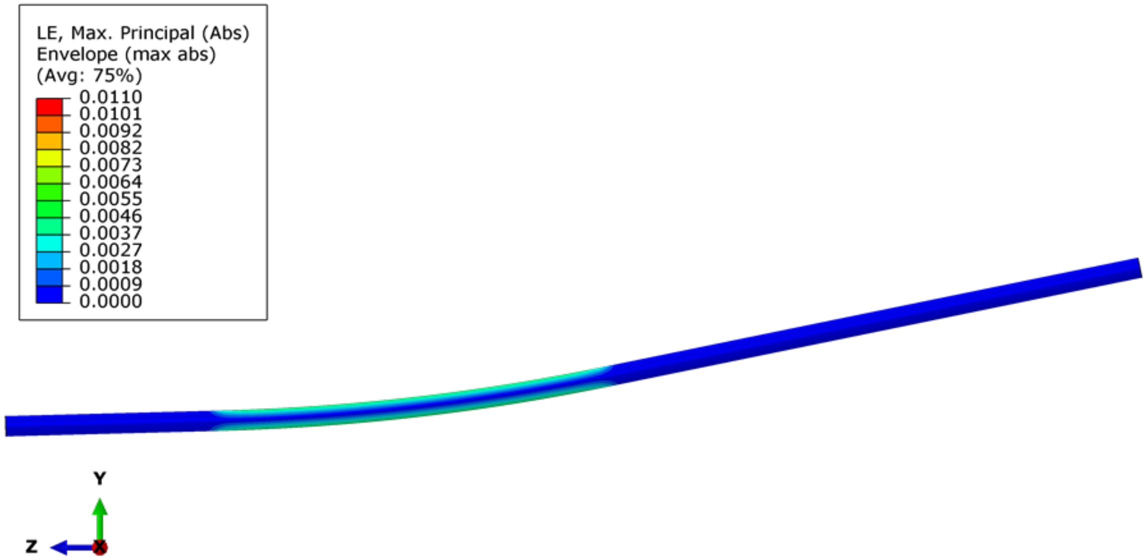

Figure 24. True strain contour plot of the pipe span after the simulated cold bend process and under operational gravity and pressure conditions. Units [in/in].

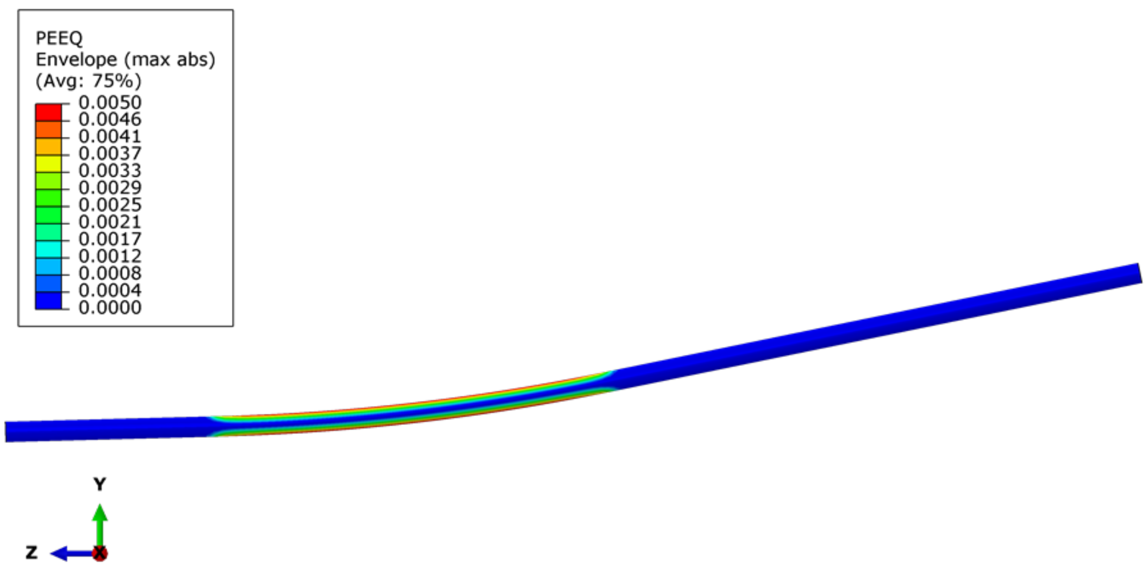

Figure 25. Equivalent plastic strain contour plot of the pipe span after the simulated cold bend process and under operational gravity and pressure conditions. Units [in/in].

The effective stress, total true strain, and equivalent plastic strain as a result of a thermal gradient simulating wildland fire conditions (572° F) are shown in Figure 26, Figure 27, and Figure 28, respectively. The effective stress in the region of interest (removed from the embedded boundary conditions) increased to a peak of approximately 31.4 ksi. The peak true strain increased to 1.1%, with the equivalent plastic strain rising to 0.98%. The expected range of percent elongation for typical steels of similar vintage is 12% to 22% (History of Line Pipe

Manufacturing in North America CRTD-Vol.43, 1996), corresponding to 11.3% and 19.9% total true strain. The true strain predicted by the FEA is low, 1.1%, when compared to the converted elongation true strain metric, indicating sufficient margin remaining prior to expected failure.

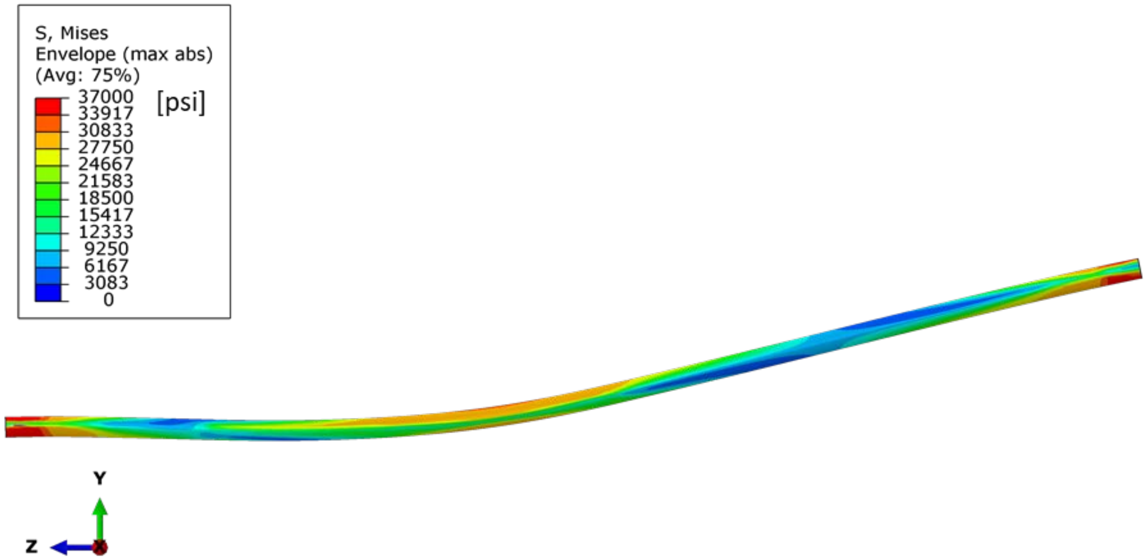

Figure 26. Effective stress contour plot of the pipe span after the simulated wildland fire conditions.

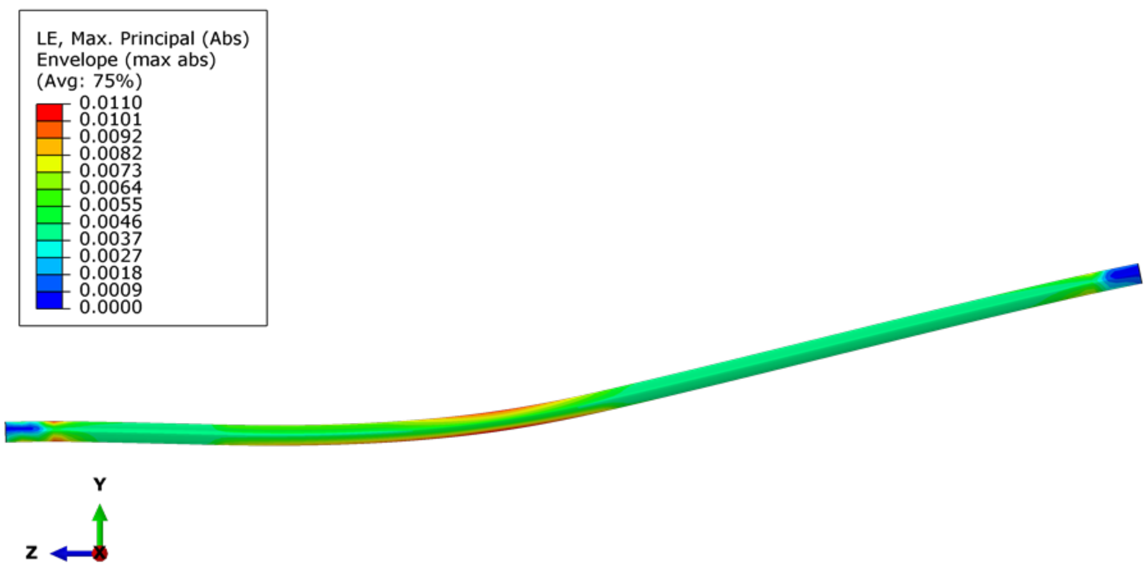

Figure 27. True strain contour plot of the pipe span after the simulated wildland fire conditions. Units [in/in].

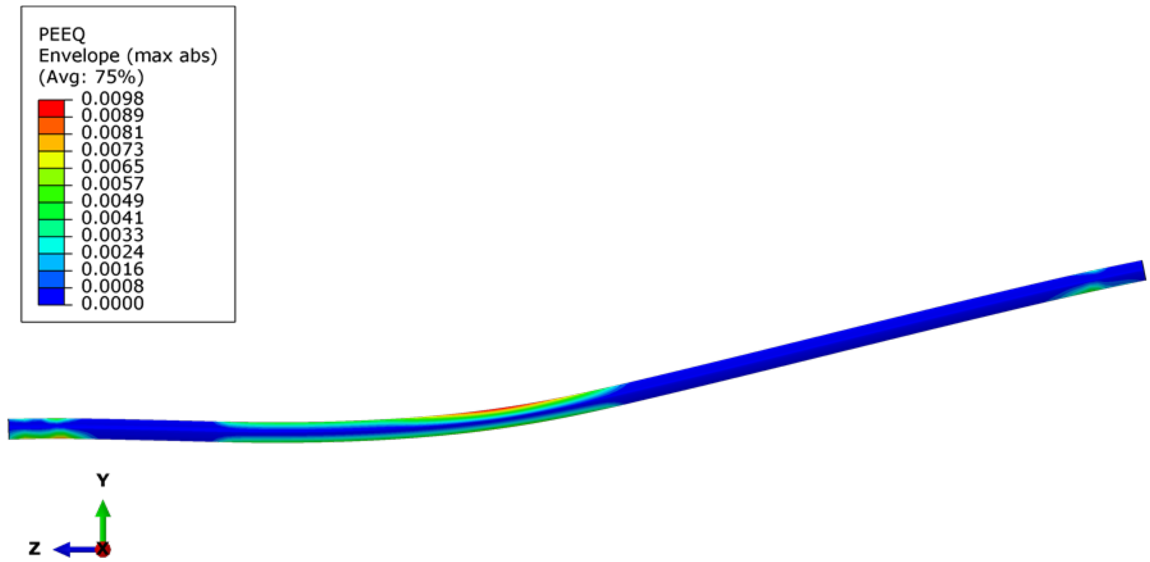

Figure 28. Equivalent plastic strain contour plot of the pipe span after the simulated wildland fire conditions. Units [in/in].

Conclusions

Based on our investigation, we have come to the following conclusions:

1. Under wildland fire conditions,[24] average pipe temperatures may reach $600°F$, resulting in a decrease in the material strength, and a yield safety factor per ASME B31.8 of less than 1.0. However, a safety factor of less than 1.0 does not indicate catastrophic failure, only that the elastic limit has been reached and plastic deformation may occur in the form of pipe bending.

2. A three-dimensional finite element analysis (FEA) computer simulation has shown that the Buckeye Ranch Trail span will retain sufficient structural capacity in wildland fire conditions (i.e., will not be at risk of collapse under their own weight), as shown by a comparison of the maximum predicted plastic deformation (1.1% true strain) relative to the expected ductility of the Grade B vintage steel (11.3 to 19.9% true strain). Unlike the previous work (Exponent report dated October 16, 2019), which calculated safety factors relative to the maximum allowable stress according to ASME B31.8, the current FEA incorporates a simulated geometric configuration and allows for an understanding of the structural behavior beyond the elastic limit and the actual geometry of the span.

3. Under wildland fire conditions, conduction within the pipe walls will dissipate the heat quickly and will maintain the pipe temperature near the $600°F$ value despite peak wildland fire temperatures potentially exceeding $1500°F$.[25] [26]

4. Removal of large trees within 40 feet, and brush (under six feet high) within 20 feet are likely to maintain calculated safety factors relative to ASME B31.8 above 1.0 for both spans under the no-residual-stress case.

5. Gas flow within Line 191-1 at the span locations will not result in substantial cooling under wildland fire conditions. Flow rates from both typical summer and winter days were analyzed, and neither was found to result in substantial cooling of the pipe.

6. The internal gas pressure will not increase substantially as a result of heating of the pipe under wildland fire conditions, even if the nearest mainline valves are closed, due to the large volume of contained gas as compared to the relatively short length of the exposed sections.

[24] Frankman et al. "Measurements of Convective and Radiative Heating in Wildland Fires." *International Journal of Wildland Fire*, 2012.

[25] Penny, Greg and Richardson, Steven. "Modelling of the Radiant Heat Flux and Rate of Spread of Wildfire within the Urban Environment." *Fire*, 2019.

[26] Dennison et al. Wildfire Temperature and Land Cover Modelling using Hyperspectral Data. Remote Sensing of Environment. 2006

7. Based on precise lab experiments and recreation testing, the coal tar enamel coating is expected to ignite under wildland fire conditions; however, it is not expected to increase the temperature of the pipe. Furthermore, testing showed that fire did not propagate along the length of the pipe, away from the heat source.

Recommendations

Based on the results of our analysis:

1. Exponent recommends that PG&E consider adopting a modified vegetation encroachment management practice for these exposed spans at Buckeye Ranch Trail and Girl Scout Camp on Line 191-1, in which:
    a. Within a 20-foot radius from the pipe, only surface fuels such as grasses are permitted.
    b. Within a 40-foot radius from the pipe, only brush that is less than 6 feet 6 inches high is permitted.
    c. Outside a 40-foot radius, vegetation is permitted.

Limitations

At PG&E's request, Exponent has conducted an investigation of two exposed pipe spans from Line 191-1 near Mile Point 28.21. Exponent investigated specific issues relevant to these pipe sections, as requested by PG&E. The scope of services performed during this investigation may not adequately address the needs of other users of this report, and any reuse of this report or its findings, conclusions, or recommendations presented herein is at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

The findings presented herein are made to a reasonable degree of engineering certainty. We have made every effort to accurately and completely investigate all areas of concern identified during our investigation. If new data become available or there are perceived omissions or misstatements in this report regarding any aspect of those conditions, we ask that they be brought to our attention as soon as possible so we have the opportunity to fully address them.

Appendix A

Tree Data from PG&E and Exponent Inspections

Table A1. Buckeye span tree data provided by PG&E.

Tree	Dist. to Span (ft)	Diameter (in.)	Height (ft)	Tree Species
1	15	18	80	Live Oak
2	30	22	40	California Bay
3	30	12	40	California Bay
4	15	25	75	California Bay
5	15	24	75	Live Oak
6	15	24	30	Live Oak
7	20	16	55	California Bay
8	80	42	80	Live Oak
9	30	11	75	California Bay
10	15	36	85	Live Oak
11	50	15	50	Live Oak
12	75	14	90	California Bay
13	15	8	40	California Bay
14	75	52	95	Live Oak
15	75	52	90	Live Oak
16	5	16	75	Live Oak
17	45	6	70	California Bay
18	35	6	70	California Bay
19	30	6	70	California Bay
20	15	36	75	Live Oak
21	45	30	75	Live Oak
22	35	18	35	Live Oak
23	35	18	55	Live Oak
24	30	14	50	Live Oak
25	30	26	55	California Bay
26	25	10	25	California Bay
27	75	24	75	Live Oak
28	80	72	80	Live Oak
29	75	18	75	Live Oak
30	95	30	95	Live Oak
31	60	30	60	Live Oak
32	30	14	60	Live Oak
33	25	20	55	California Bay
34	40	16	70	California Bay

Tree	Dist. to Span (ft)	Diameter (in.)	Height (ft)	Tree Species
35	30	18	80	Live Oak
36	15	20	70	California Bay
37	25	20	85	Live Oak
38	45	24	75	Live Oak
39	75	30	75	Live Oak
40	20	12	70	California Bay
41	0	0	4	Brush (misc.)

Table A2. Buckeye span tree data gathered by Exponent.

Tree	Dist. to Span (ft)	Diameter (in.)	Height (ft)
1	29	23	59
2	68	25	29
3	5	19	48
4	50	19	35
5	14	8	30
6	38	15	35
7	22	21	39
8	23	21	40
9	29	13	47
10	30	13	30
11	53	15	71
12	26	6	32

Table A3. Girl Scout Camp tree data gathered by Exponent.

Tree	Dist. to Pipe (ft)	Diameter (in.)	Height (ft)
1	29	15	55
2	30	19	71
3	51	15	38
4	52	15	50
5	19	10	46
6	31	15	46
7	37	10	49
8	35	17	45