FLOODED MANHOLES & Submerged Steam Lines

Understanding the danger of nucleate boiling

The flooding of a manhole or culvert containing a live steam line is more dangerous than most people imagine. In a nutshell, if a high-pressure steam main becomes submerged causing the insulation to slough off the line or otherwise become ineffective, the heat-transfer regime from the surface of the pipe to the flood water will likely transition to “nucleate boiling.” The rate of heat transfer due to nucleate boiling is on the order of 1,000 times greater than that normally expected from an insulated steam main (compare rows 6 and 7 in Table 1 with row 1).

Essentially, a steam main submerged in flood water becomes a condenser generating hundreds of pounds of condensate per linear foot of pipe. Steam traps, even though they typically have a safety factor on the order of 25 times that needed to drain a well-insulated system, cannot handle this condensate load. If as little as 4 to 6 ft of steam main becomes submerged in water, which then proceeds to vigorously boil, the condensate production within the pipe will likely overcome the ability of the local trap to drain it. The ensuing buildup of condensate in the steam main can set the stage for destructive waterhammer.

HOW DESTRUCTIVE CAN THIS FORCE BE?

The waterhammer may only cause banging, but in at least one case I know of, waterhammer due to flooding led to the death of two steamfitters when they neglected to drain the accumulated condensate

Understand that fast moving steam is not required to generate a waterhammer, only fast-moving condensate.

Wayne Kirsner, PE, performs forensic investigations of steam accidents and troubleshoots large chilled-water distribution problems. He has authored 10 feature articles including “What Caused the Steam Accident that Killed Jack Smith?” and “The demise of the Primary-Secondary Pumping Paradigm for Chilled Water Plant Design.” Kirsner is a 2002 ASHRAE Distinguished Lecturer. He can be reached at kirsner@kirsner.org.
sate before opening a valve. In other cases, cast-iron valves have “mysteriously” exploded after manholes have flooded—apparently for no reason, according to puzzled supervisors. Speculation sometimes blames thermal stress across the valve body for the rupture or inadequate provision for contraction of the steam line. I believe the real reason for these incidents is waterhammer due to the accumulation of condensate resulting from nucleate boiling on the outside of the pipe. An incident that illustrates this point occurred at a large refinery and chemical complex in 2000.

An electric power loss at a refinery caused sump pumps to shut down, allowing wastewater to flood two culverts carrying utilities beneath a public road. Two steam mains containing 200-psig steam through the culverts were submerged. Workers observed floodwater boiling in one of the culverts. Twelve hours later at 6 a.m., a pipe segment located downstream of the other culvert (as seen in Figure 1) startled the crew coming off the night shift when it began to violently and repeatedly hammer. Each time the pipe hammering, a 6-in. safety relief valve set at 226 psig lifted, releasing a blast of steam. The recurring waterhammer lasted for 20 minutes.

During an investigation, the utilities team leader described the scene: “There was a loud knock—thwack—and then the safety valve lifted again, releasing a blast of steam. We could see the 24-in. pipe line from Culvert 2 bucking off its supports. The 18-in. line between Valve 2 and the safety valve was jumping, too. The line gave a big kick, and we moved back. Hot condensate was pouring out of a break at Valve 3. The hammering continued for 20 minutes.”

**WHAT HAPPENED?**

Flooding in the culverts soaked the 2-in. mineral-wool insulation covering the steam pipe. This was not the first time the culvert had been flooded, so the original insulation was not in good condition in the first place. Saturated insulation sagging from the pipe presumably allowed floodwater to come into direct contact with the 388-F steam pipe. The difference in temperature between the surface of the pipe and the flood water—even after the water reached its boiling

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**TABLE 1. Steam main condensate generation.** Note: 10-in. (Schedule 40) pipe, 100 psi, 85 F ambient temperature.

<table>
<thead>
<tr>
<th>Fiberglass Insulation Thickness</th>
<th>Btu per ft</th>
<th>Ratio to Base</th>
<th>Btu per sq ft of pipe OD</th>
<th>Lb condensate per hr per 300 linear ft of pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-in. fiberglass with ASJ 100% efficiency</td>
<td>95</td>
<td>Base</td>
<td>0.13</td>
<td>32</td>
</tr>
<tr>
<td>Per trap manufacturer (Tamb = 70 F, 80 percent efficient insulation)</td>
<td>450</td>
<td>5</td>
<td>0.63</td>
<td>153</td>
</tr>
<tr>
<td>No insulation, still air</td>
<td>2,145</td>
<td>23</td>
<td>3.0</td>
<td>731</td>
</tr>
<tr>
<td>No insulation, 12 mph breeze</td>
<td>3,968</td>
<td>42</td>
<td>5.6</td>
<td>1,353</td>
</tr>
<tr>
<td>3-in. wet fiberglass, submerged</td>
<td>11,253</td>
<td>119</td>
<td>15.8</td>
<td>3,836</td>
</tr>
<tr>
<td>No insulation, submerged, no steam flow</td>
<td>86,820</td>
<td>918</td>
<td>122</td>
<td>29,598</td>
</tr>
<tr>
<td>No insulation, submerged, 180 fps steam flow</td>
<td>155,618</td>
<td>1,645</td>
<td>218.7</td>
<td>53,052</td>
</tr>
</tbody>
</table>
point of 212°F—almost assuredly exceeded the minimum 9°F temperature difference needed to sustain nucleate boiling.

With the onset of nucleate boiling, I calculate that the rate of condensate generation in the 110 ft of culvert pipe jumped by a factor of up to 777 times.

That is from approximately 35 lb per hour (for 2-in. mineral wool insulation on 18-in. pipe at 388°F, 70°F ambient temperature) to as high as 27,184 lb per hour if the wet mineral wool insulation sloughed off the pipe or was so loose that it had no insulating effect whatsoever (see the sidebar “Insulating Value of Wet Insulation”). There was a ⅛-in. thermodynamic trap located at the south end of the culvert that drained the culvert steam line, as well as 400 ft of pipe upstream of the culvert. The capacity of the trap was 1,100 lb per hour at 200 psig—plenty of capacity under ordinary circumstances, but only a small fraction of that needed to handle condensate produced under a nucleate boiling heat-transfer regime (see rows 6 and 7 of Table 1). Thus, with the onset of nucleate boiling, condensate began to buildup at a rapid rate in the culvert steam pipe.

As condensate filled the bottom of the 101-ft steam pipe, heat transfer and the rate of condensate formation slowed due to the insulating effect of the condensate accumulating on the bottom of the pipe due to the thermal resistance of condensate. At 0.26 (Btu/h sq ft/F degree) per inch of depth, its R-value is on the order of 100 to 500 times the film resistance for steam on the inside of the pipe (depending on whether steam is flowing or not).

In addition, trap-drainage capacity would have increased. Condensate below the condensate-steam interface subcools below the steam saturation temperature. With condensate subcooling (cooling below the saturated steam temperature), trap capacity increases as (1.01)^n, where “n” represents the degree of subcooling. At 70°F subcooling, for example, trap capacity doubles.

The net result of these two influences—the increasing capacity of the traps coupled with the decrease in heat-transfer surface—slowed, but was insufficient to stem, the condensate accumulation.

As the pipe filled, steam flowing through the annular space above the condensate would begin to pick up waves on the surface of the condensate as shown in Figure 2. Why was there steam flow—the isolation valve at the end of the line was closed? It was induced by normal condensation through the 608 ft of insulated and uninsulated portions of the steam pipe downstream of the culvert. As the annular space grew smaller, steam velocity increased. Eventually, as the accumulation of condensate almost filled the pipe, the velocity of the steam would be sufficient to pick up a wave of condensate to “plug” the pipe, as shown in Figure 2.

When the pipe “plugged,” the differ-
ential pressure between 200-psig steam upstream of the plug and the condensing steam downstream of the plug would start "the plug" moving downstream, and carry it up the 18.4-ft rise, as shown in Figure 3. Once started, this process would carry on continuously, essentially "pumping" condensate formed in the submerged steam pipe into the rest of the system. The video frames in the photo below demonstrate this process in a model constructed for this incident. I calculated that the culvert and 600 ft of pipe downstream could have filled in 10.5 hours.

When condensate had filled the stream main all the way back to the culvert, nucleate heat transfer would have been "switched off" by the displacement of entering steam with condensate. With the exception of a small amount of condensate formed in the several hundred feet of insulated pipe upstream of the culvert, condensate production would cease and the condensate would subcool.

With the cessation of most condensate
Insulating Value of Wet Insulation

Wet insulation may actually provide some retarding affect on heat transfer where the insulation continued to hug the pipe. After the flood, insulation was loose, but hadn’t come completely off the pipe, as is so often the case with flooded manholes. Nucleate boiling depends on free convection of steam away from the pipe surface and unimpeded replacement of the space vacated by the vapor by cool fluid at the bulk temperature. This is what makes nucleate boiling heat transfer so vigorous—rapid convection promoted by the buoyant and expansive nature of the steam, launching from nucleation sites on the surface of the pipe. Where the insulation clings to the pipe so as to impede steam escape or induction of bulk fluid to the surface of the pipe, it will reduce nucleate boiling heat loss. Professor Ming-C Chyu, PhD, of the Department of Mechanical Engineering at Texas Tech University, in essence, measured this effect in his paper “Effect of Underground Water Attack on the Performance of Mineral Wool Pipe Insulation” (ASHRAE Transactions, 1998). He found that the conductance of water-saturated mineral-wool insulation increased by a factor of 59 (to 1.1 Btu-H-ft) at a mean temperature of 150°F. This work was based on mineral wool insulation specially formulated with a water-resistant binder so that the insulation, even though unjacketed, suffered no physical damage when submerged in accordance with the Navy’s 24-Hour Boiling Water Test for insulation. The wet mineral wool provided enough resistance to stifle nucleate boiling, although not all boiling altogether. In his tests, with bulk water temperature maintained at 100°F, three-quarters of the circumference of the steam pipe surface beneath the saturated mineral-wool insulation reached the boiling point of water, but did not exceed it. Thus, nucleate boiling was suppressed.

That said, the mean temperature of the mineral-wool insulation for the case discussed in this article would be much higher at (308 + 212)/2 = 300°F than the maximum allowed in Chyu’s tests. The “k” of insulation increases with mean temperature and ΔT. This was in fact the trend for the “wet k” data reported by Chyu, but data was not taken above T_mean = 150°F. The trend suggests that the “wet k” of mineral wool at a higher T_mean is likely to have been significantly greater than 50 times the dry value of mineral wool.

**FIGURE 2.** When the condensate level is high enough, steam flow passing through diminished free area will draw up a wave to “plug” the pipe. Pressure downstream of the plug will drop as steam continues to condensate.

**FIGURE 3.** Pressure differential pushes most of the 101 ft/157 cu ft condensate accumulation downstream until steam rounds the corner at rise.

production, traps would begin draining condensate from the system faster than it was being generated. Besides the thermodynamic trap in the culvert, there were three thermostatic traps downstream of the culvert. With subcooling—the degree of cooling below the saturated steam temperature—the discharge capacity of these steam traps increased dramatically. As condensate downstream of the culvert drained, condensate in the culvert steam pipe would be siphoned up the riser so that the condensate level in the culvert steam pipe would drop first. This permitted steam to re-enter the system, as shown in Figure 4.

Steam entering a horizontal line filled with subcooled condensate will generate waterhammer, especially if there’s an upturn in the line downstream of the steam entry point, as there is in this case. It is important to understand that fast-moving steam is not necessary to generate a waterhammer, only fast-moving condensate. The condensate can be accelerated by the differential pressure created when steam, which becomes entrapped in subcooled condensate (Figure 5), rapidly condenses, leaving a low-pressure void. Surrounding condensate is accelerated into the low-pressure void by the steam pressure behind it.

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If condensate is sufficiently subcooled so that the steam void collapse is rapid, and the void left by the vanishing steam is large enough for the condensate to appreciably accelerate, the momentum picked up by the condensate will cause a powerful waterhammer when the water slams to a stop in what was formerly the void. Figure 5 depicts the impending collision. The overpressure due to a collision can easily exceed 1,000 psi, which is sufficient to fracture a cast-iron valve, rupture an accordion-type expansion joint, or blow out gaskets.

As condensate sloshes back and forth, repeatedly entrapping steam voids, waterhammer will continue until enough condensate drains from the system to empty the steam pipe to below 20 percent of its full cross-sectional area. That is what happened in this incident.

At the refinery, as a result of the repeated hammering, 18-in. valves 2 and 3 were both damaged enough that they would no longer seat properly, and gaskets were blown out at the valves. Fortunately, no one was hurt.

What is interesting about this incident is that it was seemingly spontaneous. Unlike most waterhammer incidents, which need some type of triggering event, such as a valve being opened or startup of the system, this incident was self-initiating. It was caused by a two order-of-magnitude increase in heat transfer due to nuclear boiling. This exceeded the capacity of steam traps to drain the system. Next, as Murphy’s Law would have it, whatever could go wrong, did. The filling of the system turned the condensate-generating process off, allowed condensate time to subcool, and then permitted steam to re-enter the system at a piping configuration ideal for generating waterhammer.

CONCLUSION

If a high-pressure steam line becomes submerged in flood water that then proceeds to boil, the increased rate of heat transfer will likely overcome the ability of traps to drain the condensate generated. Beware: The piping segment where the condensate will pool will become hazardous. If the steam cannot be isolated to this segment, or the water pumped out of the flooded area, brace for waterhammer.

If you have steam manholes or culverts you know are susceptible to flooding, consider the following prophylactic measures:
- Insulate steam lines with insulation that has passed the U.S. Navy 96-Hour Boiling Water Test.
- Install a backup large-capacity trap at low points in the steam system where condensate would accumulate. This trap should be a non-cycling high-capacity trap (such as a thermostatic trap) that is piped off the condensate line to the existing trap, but above it, so that it only operates if the primary trap begins to backup condensate. This will give an added measure of safety to a critical location while not wasting energy.
- Maintain operable sump pumps in manholes known to be susceptible to flooding.

FOOTNOTES

1) Calculation assumes no fouling resistance on the outside of pipe and no steam flow in pipe, conditions to which the calculation is quite sensitive.