Chapter 10. **Water in Steam Lines**

(This is the BP title in existing Manual)

When saturated steam gives up heat, it turns to water, more commonly referred to in steam parlance as "condensate". Thus, as saturated steam is conveyed to processes and equipment in steam mains, heat lost through pipe and insulation creates condensate in the steam lines. Even if a steam system is distributing superheated steam[1], wherever or whenever the steam flow is dead-ended, steam will lose its superheat, become saturated, and with continued heat loss deposit condensate. All steam systems, therefore, generate water or have the potential to generate and accumulate it.

The primary concern of Engineers in designing a steam distribution system is to get the water out so as to not let it accumulate. Design layouts call for horizontal steam lines to be pitched toward trapped collection pots (sometimes called drip legs or mud legs) typically provided every 100 meters or so; collection pots are also provided at every rise in the line, and on the upslope side of isolation valves that, if closed, would permit condensate to accumulate against them. Why so much concern about preventing condensate from accumulating in steam pipes? The answer, of course, is Waterhammer.

The photo at right shows an 18" (450 mm) steel pipe blown open at a tee junction by waterhammer in a 225 psi (15.5 bar) steam system. The peeling open of the pipe demonstrates the power of the blast that can be unleashed by waterhammer. In this accident, no one was killed, but operators and maintenance mechanics have been killed by steam and scalding water jetting out of ruptures or even just gasket failures in high pressure steam systems caused by waterhammer.

To prevent waterhammer in steam systems, operators and maintenance workers have to understand what causes it. Yet, it is widely misunderstood by the vast majority of engineers, operators, and vendors working with commercial and industrial steam systems.

To understand waterhammer in steam systems, let's start with what it's not. Waterhammer in steam systems, the kind that can rupture pipes, blow out gaskets, and kill operators is not caused by fast moving steam picking up a slug of condensate and hurling it against a change in direction in the pipe, like an elbow. This phenomena, although understood to be waterhammer by most in the steam community, is not waterhammer in the technical sense and, more to the point, does not have the destructive potential of a true waterhammer event[2]. An event of this type can occur in steam systems, but it's overpressure—that is the momentary pressure over and above the system pressure-- is typically in the hundreds of psi (less than 20 bar), not the thousands of psi (> 70 bar) as is possible with waterhammer. This type of event can cause pipes to move and jolt pipe supports, but it is not powerful enough to rupture a

[1] Dry steam heated to above its saturation temperature

[2] I'm defining waterhammer as a water collision where the transient pressure is proportional to ρcv, e.g., the Joukowski equation.

standard weight steam pipe, shatter a cast iron valve, or spit out a properly torqued gasket. Waterhammer is a different physical phenomenon.

First of all, waterhammer--all waterhammer--is caused by moving water being abruptly decelerated-- as in a collision--so that water running into itself is forced to *compress* on itself. The water is not able to deflect around an elbow or slosh within a pipe, it collides and compresses on itself in a waterhammer. Water, being virtually incompressible, resists mightily when being forced to compress. (Any diver having experienced the *slap* of a belly flop can attest to that). A common example of waterhammer occurs when water flowing in a pipe is abruptly stopped by a fast acting valve which closes suddenly. The kinetic energy of the water in the full pipe is converted into a rise in pressure as the water compresses. The pressure rise expands the pipe that contains the water and exerts this additional pressure on every component connected to the water-filled pipe[3].

Experts classify waterhammer into 5 or 6 different types (depending on the expert) but all types are different only in the mechanisms they use to either get the water moving, or the particular way in which water is abruptly decelerated. While several types of waterhammer can occur in steam systems, there's only one that leads to the kind of serious damage shown in the photo above. It's "Condensation-Induced Waterhammer". This is the type of waterhammer that can kill steam workers when operating valves in high pressure steam systems.

"Condensation-induced" refers to how water in a steam system gets *induced* to move. Here is what can happen in a near horizontal pipe to enable a Condensation-Induced Waterhammer:

1st. Condensate accumulates at a low point in a steam system, due to, say, lack of an operable steam trap, until condensate fills the pipe. Isolation from the steam interface allows the condensate to cool below the saturated steam temperature. **(Figure 1a)** . Subcooling, i.e. cooling below the saturated steam temperature is a necessary condition to enabling a condensation-induced waterhammer therefore the condensate must become isolated from the steam by filling the pipe.

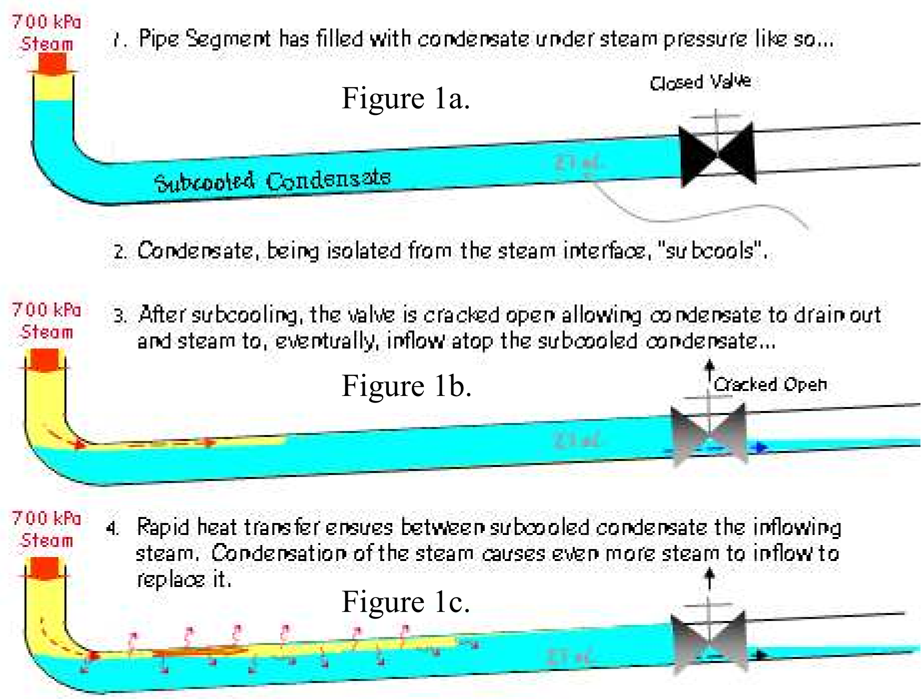

Figure 1a.
Figure 1b.
Figure 1c.

2nd. sufficient time elapses for the condensate to cool to a minimum of 30oC below the saturated steam temperature.

Now a triggering event is needed to mix the subcooled condensate with the high pressure steam so that a portion of the steam can be *entrapped* in the condensate.

3rd. Say, a steam valve is opened allowing condensate to drain from the line, but, more significantly, allowing steam to re-enter the portion of the steam line containing the subcooled condensate (**Figure 1b**).

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3 The pressure only lasts the time it takes to transmit it (at the speed of sound which is ~ 1300 m/s) to an expansion in the line where the pressure is relieved and then this unloading pressure is reflected back toward the closure point to cancel the original transient pressure. While this "unloading wave is reflected again, and can cause a "ringing" in the pipe, the initial transient pressure is the most forceful.

4th. Rapid heat transfer now takes place between the entering steam and the subcooled condensate and pipe which is uncovered. (**Figure 1c**) As steam gives up heat to the relatively cool condensate and pipe walls, it condenses drawing in more steam to replace the condensing steam. The induced steam flowing over the condensate, if rapid enough, results in waves being picked up on the surface of the condensate as shown in **Figure 1d** below.

5th. If a wave is high enough to momentarily "plug" the pipe, so that it cuts off steam inflow into the steam pocket, continued condensation inside the now isolated steam "bubble" will drop the pressure in the bubble as depicted in **Figure 1e**.). With extremely rapid heat transfer between the saturated steam and surrounding subcooled condensate and pipe walls, the pressure drop can be almost instantaneous—occurring on the order of milliseconds.

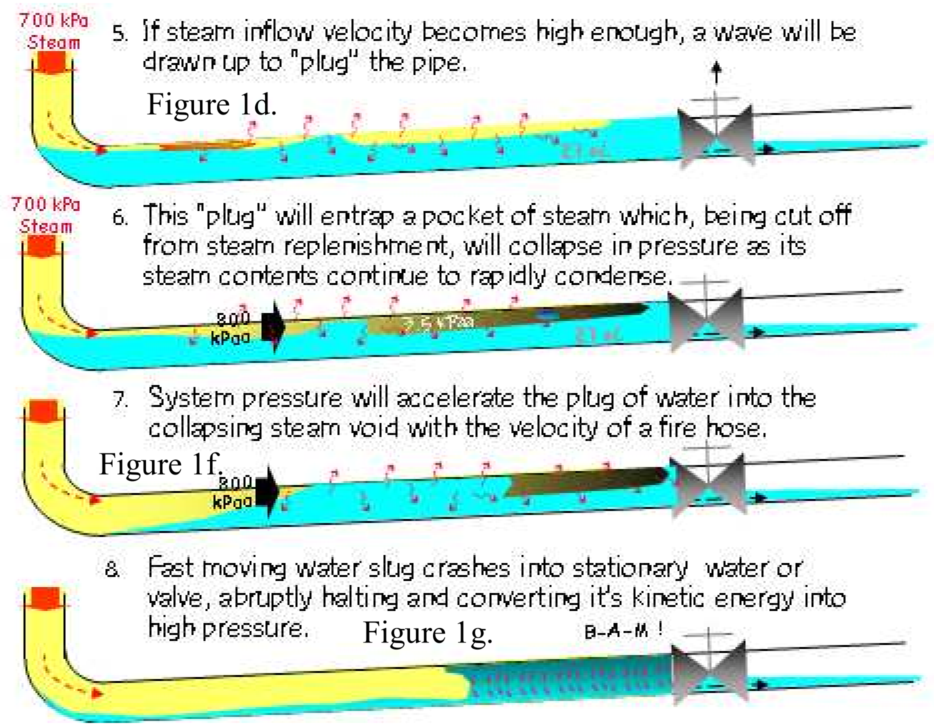


Figure 1d.
Figure 1f.
Figure 1g.

The pressure drop is understandable because the condensate formed from the steam occupies on the order of less than one-hundredth to one-thousand the volume of the steam it replaces. In fact, if the surrounding subcooled condensate is below 100oC, the pressure in the entrapped steam bubble will drop into a sub-atmospheric vacuum.

6th. With the pressure differential between the disappearing steam bubble and full system steam pressure on the surrounding condensate outside the bubble, the condensate is accelerated into the void to smack into itself. **Figure 1g**.

7th. The overpressure due to the waterhammer will be transmitted to all water-filled portions of the pipe. If the pressure is great enough, it will break the element most susceptible to shock. This could be a cast iron valve, a gasket in a bolted joint, or even a steel pipe if it's over 18" in diameter.

What makes this type of waterhammer so destructive is the high velocity to which the condensate can be accelerated when being pushed by high pressure steam into the collapsing steam bubble, and the fact that the water slaps to an abrupt halt as it fills the void. For example, a 100 psig (7 bar) steam pressure can easily accelerates water to 40 fps if given a large enough steam void, causing a transient waterhammer pressure of around 2000 psi (140 bar).. For comparison, the pressure needed to break an 18" (450 mm) standard weight pipe with a continuously welded seam in hoop stress can be as low as 1100 psi (76 Bar)[4].

Now, what does understanding the mechanism of Condensation-Induced Waterhammer tell you about what to watch out for when opening a steam valve in a pressurized high pressure steam system?

#1. **There must not be subcooled condensate resting against either side of the valve you are about to open.**
Your first safety check should be to make sure there's an operable steam trap draining the pressurized

[4] Assuming Std Wt pipe with 12.5% mill tolerance, .065" corrosion allowance per ASHRAE 2004 Systems 7 Equipment, p. 41.7, and .60 weld joint efficiency

steam pipe on each side of the valve where condensate could accumulate. That's easy to test by checking the temperature of the inflowing side of the trap—it should not be significantly below steam saturation temperature[5]. Then check the pipe surface temperature on either side of the valve too to insure it's not below saturated steam temperature too. . Because a minimum of 30oC subcooling is necessary for condensate to be subcooled enough to enable condensation-induced waterhammer, subcooled condensate is detectable by measuring the pipe surface temperature. The outside pipe surface temperature will be within 1/2oC of the interior temperature if you make an accurate measurement.

#2. If you find subcooled condensate, don't open the valve or try to drain the condensate. Any action which drains condensate will enable steam to enter the region formerly occupied by the subcooled condensate. If the pipe configuration is such that the steam can be entrapped, you're in danger of triggering a destructive waterhammer. The one surefire means of draining the condensate is to isolate steam pressure by closing an upstream valve and bleeding the pressure, then draining the line.

#3. If, however, you are operating a looped steam system, i.e. a system where steam pressure is present on both sides of the condensate you're trying to drain, you can't isolate steam pressure on one side of the condensate plug without steam pressure on the opposite side accelerating the plug toward the valve being isolated. In this case, the safest procedure is to find a single valve which cuts off steam pressure to both sides of the condensate simultaneously. Trying to isolate two valves on either side of the condensate *simultaneously* to cut off steam pressure is not feasible.

[5] Unless the trap is a thermostatic traps, in which case the temperature should be within the range of subcooling required to open the trap.

Chapter 11. **Example of a Waterhammer in a Steam System**

On June 7, 2000 at the BP Plant in Grangemouth, Scotland, the 18" steam pipe pictured on the first page of the previous section fractured opening a gaping hole which spewed a steam jet 100 foot across a public "A" road and created a blast so loud it knocked a pedestrian off his feet. A schematic piping layout of the relevant portion of the BP Grangemouth steam system is shown on the next page. The 18"(450 mm) steam main from the Steam Plant at top left delivers 200 psig (13.8 barg) steam through a culvert beneath a public road than bisects the north and south sides of the Plant. Here's what happened during this Accident.

A. Isolation Valves 2 and 3 (shown in the piping layout on the next page) were closed due to a previous mishap while the steam line upstream from the Steam Plant remained pressurized. Five days before the accident, to facilitate a safety inspection of the pipe and insulation in the culvert, the steam trap at the south end of the culvert was temporarily valved-off by closing a ¾" isolation valve in the trap piping. This prevented the trap from discharging hot condensate and flash steam on the ground while inspectors were in the vicinity. Inadvertently, the ¾"valve was not reopened after the inspection. This left the trap disabled during the days leading up to the Accident. Photo 1 shows the valve and trap draining condensate after the Accident.

B. The trap's function was to drain condensate from 470 feet of up and downstream steam pipe. With the trap disabled, condensate forming in the pipe due to heat loss through the pipe insulation could not be discharged. 83 liters/hr of condensate was generated as 200 psig (13.8 barg) steam at 388oF (198oC) condensed to water. The condensate flowed downhill to the culvert and trap where it accumulated. In 66.25 hours-- from the time the trap was disabled to the time the pipe exploded— a conservative heat transfer calculation shows that enough condensate would have formed to fill the 101 feet of pipe running through the culvert plus at least 25 ft more.

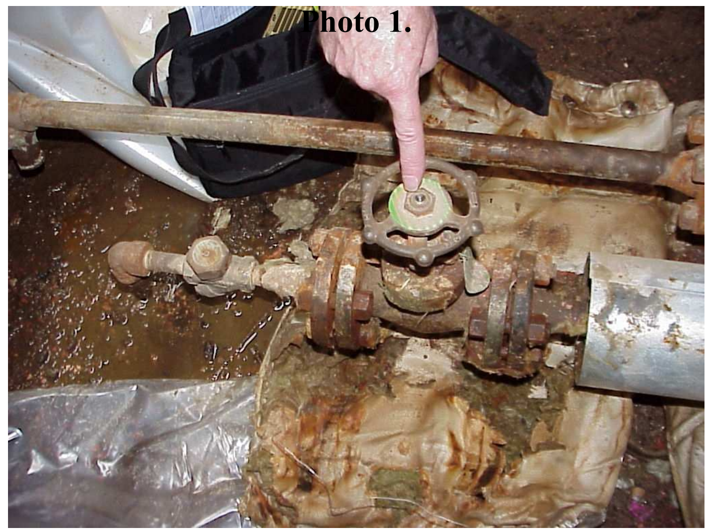


Photo 1.

C. Figure 11-2 below, representing a simplified schematic of the steam pipe running through the culvert to Valve 2, shows how, at first thought, one might think a depression in a steam-filed pipe would fill with condensate—that is, from the bottom up.. The drawing, however, is not correct. To understand how a steam pipe depression actually fills is trickier than you might imagine.

Schematic View of the 18" Steam Main in Culvert
(with the upper horizontal pipe shown in the same plane for simplicity)

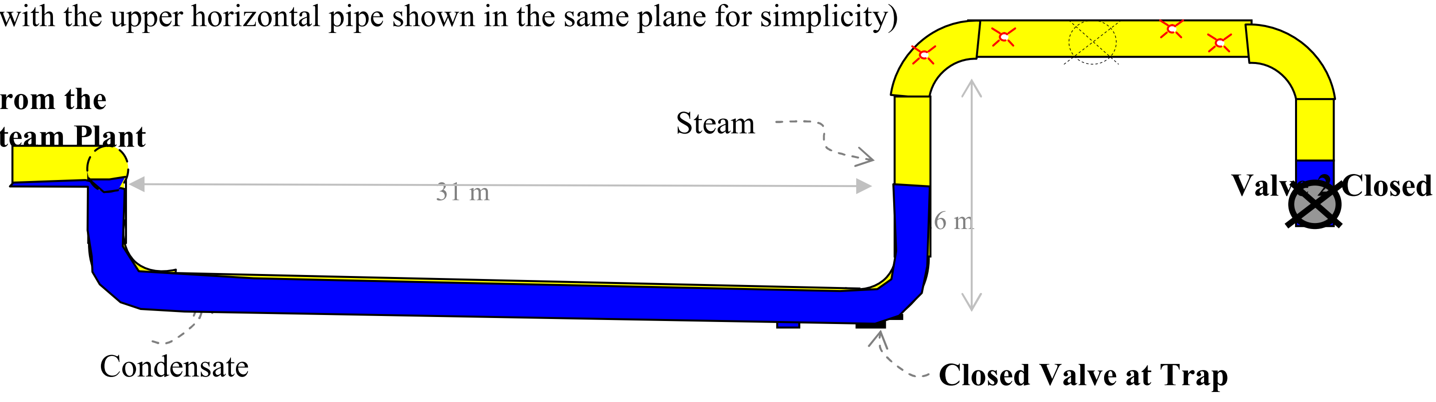


Figure 11-2.

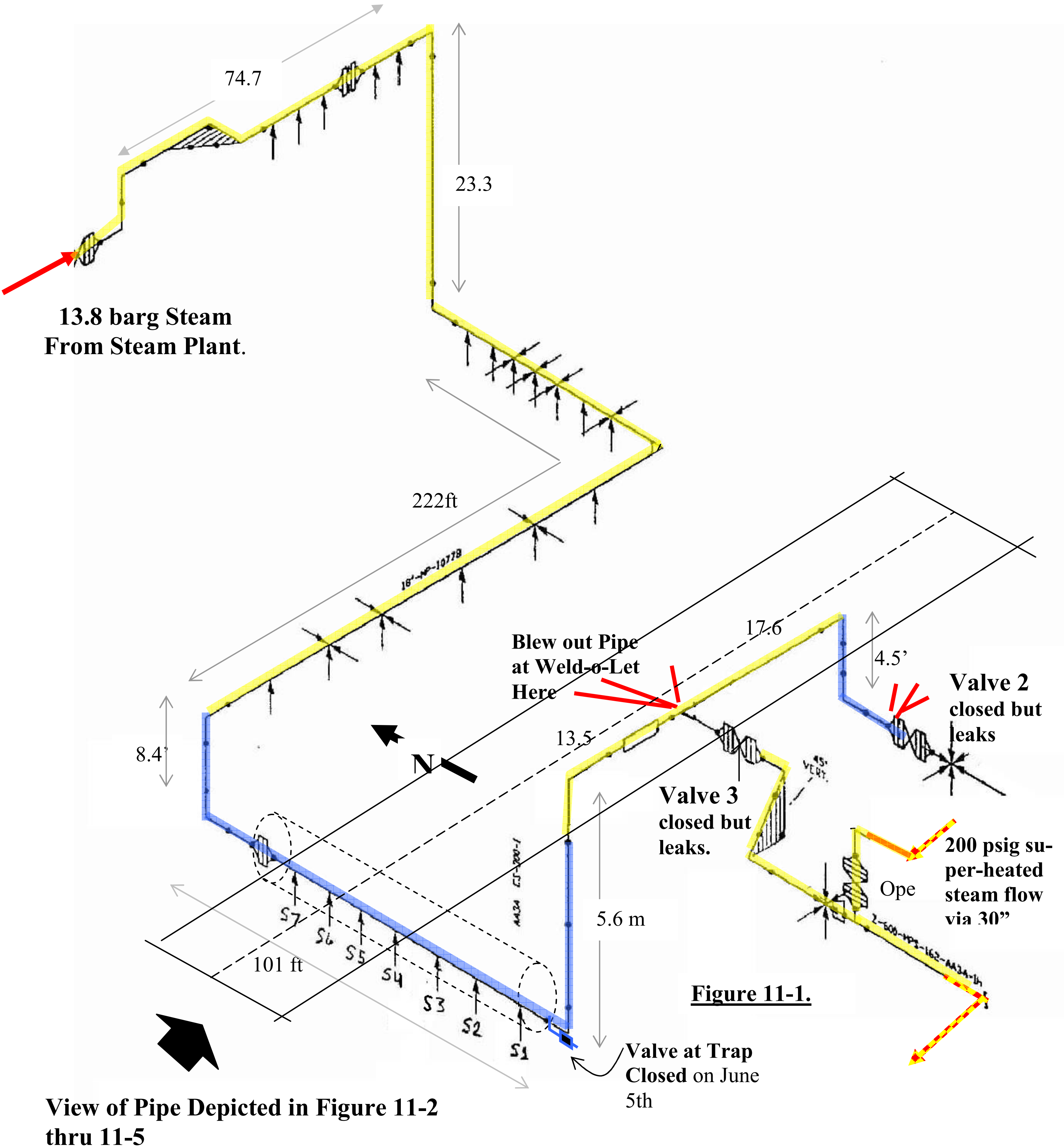


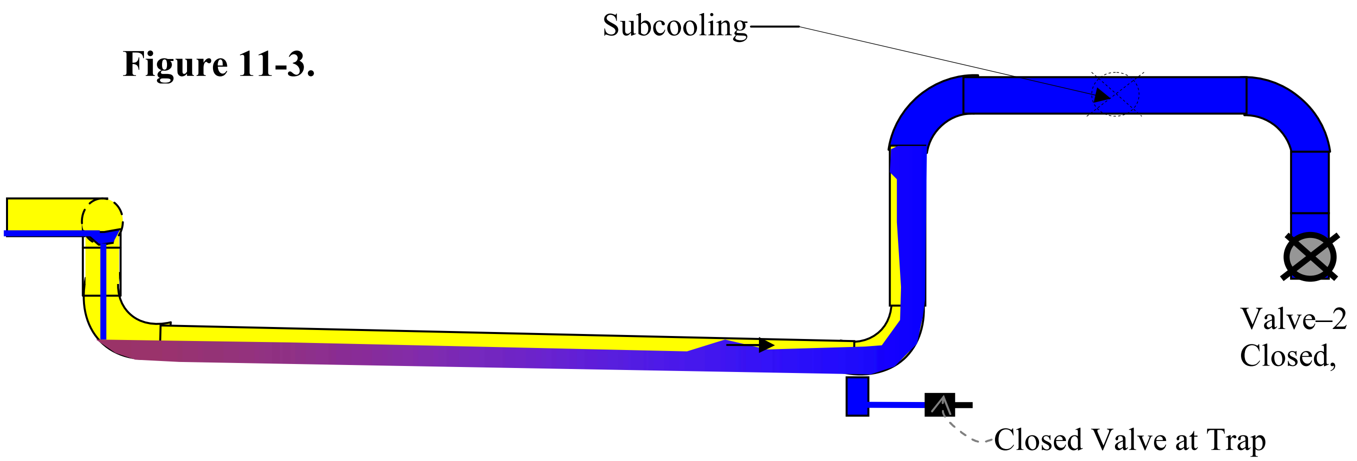
Figure 11-1. Steam Pipe Layout from Steam Plant Thru Valves 2 and 3 Showing where

The figure above shows steam trapped downstream of the condensate-filled lower segment of the pipe. A little thought reveals that this is not a stable situation: entrapped steam on the right side of the condensate plug would continue condensing due to heat loss through its insulation, and with no way for upstream steam on the left of the plug to make-up the condensing steam lost on the right. Thus, pressure would drop in the entrapped steam volume. The condensate filling the culvert depression would then act like a manometer; higher pressure from the Plant side on the left would lift water on the right side due to the differential steam pressure. Consider that just a 1/10th bar pressure drop on the entrapped steam side relative to full steam pressure on the upstream side of the culvert would lift water over a meter. Continued steam condensation in the entrapped steam volume on the right would allow water to be pushed up the 5.6 meter rise to fill the developing vacuum, if it didn't break the water seal in the depression first.

The water lifted would not result in a waterhammer--there wouldn't be enough subcooling for a rapid condensation event to get the water moving fast enough to cause a waterhammer. Condensate would simply be sucked up into the entrapped steam void forming on the right side of the system and eventually fill this void all the way to Valve 2.

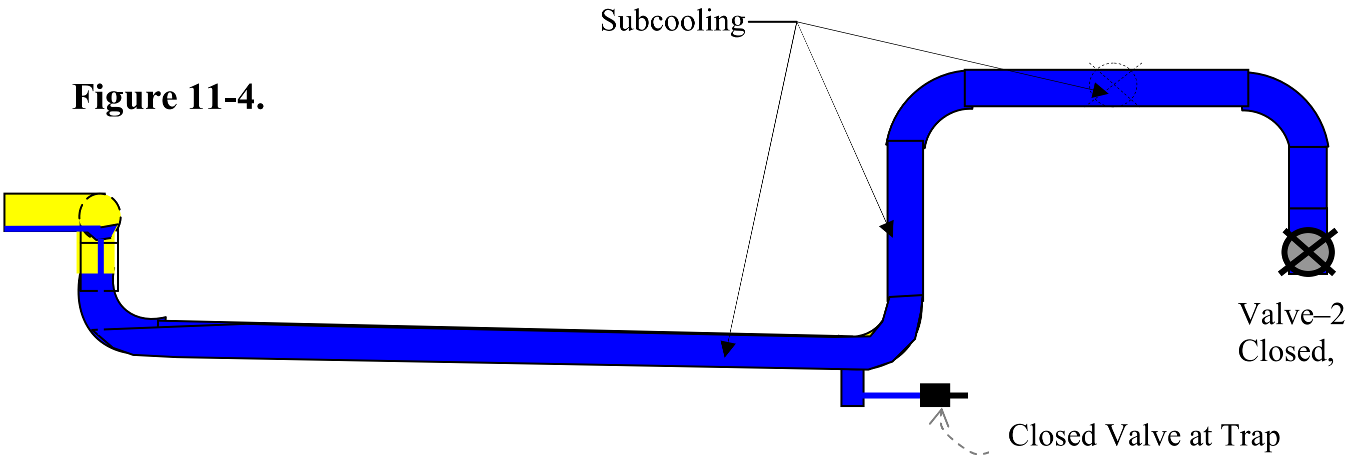
Figure 11-3 shows how the pipe section would actually fill. When the water level in the lower horizontal section of pipe grew high enough for waves to *momentarily plug* the pipe, the water plug along with continued condensation of steam remaining on the right side of the plug would cause the pressure drop to suck condensate up the pipe to fill the downstream steam void. In this way, the upper reaches of the pipe segment on the right would fill *before* the lower horizontal pipe fully filled.

Figure 11-3.



When the pipe depression finally did fill to overflowing, it would look like Figure 11-4.

Figure 11-4.



D. The condensate that filled the pipe, and was completely cut off from contact with steam, would begin to subcool. To generate a water hammer, experiments suggest condensate subcooling must exceed 30oC. It's calculated that, even with new mineral wool insulation, condensate in the condensate-filled culvert steam pipe would cool 22oC in 17 hours. In fact, the insulation covering the pipe in the culvert was deteriorated due to several incidents of flooding in the culvert so that the condensate that filled the pipe--especially on the right side of the pipe segment which filled first-- would have had plenty of time to subcool to the level necessary to enable a condensation-induced waterhammer.

Thus, with the steam pipe in the culvert and beyond full of subcooled condensate, the system was primed for a condensation-induced waterhammer. All that was needed was a "triggering event" that allowed steam to enter and become entrapped in the condensate as described in the previous Section.

E. There were several ways for a "triggering event" to occur. *They all involve draining condensate to admit steam into the lower horizontal line.*

For example, suppose a worker, maybe even the same worker who inadvertently left the trap isolation valve closed, recognized that the trap shouldn't be valved off, and took the initiative to reactivate the trap. Perhaps he even opened a drain to purge the condensate that he realized would have built up in the pipe. This seemingly responsible and proactive response—the kind of action a responsible person might *think* he should take-- *would actually trigger the Accident.*

The sequence of descriptions and figures on the following pages depicts the sequence of events culminating in the waterhammer.

1. As condensate was drained, *either* through the reactivated trap or a drain, the level of condensate on the left side of the pipe segment would drop until steam was able to re-enter the nearly-horizontal section of pipe in the culvert. This would permit 200 psig (13.8 barg) saturated steam at 198oC to contact the sub-cooled condensate and pipe.

   Waterhammer might have occurred as soon as the steam tongue licked into the horizontal pipe if there was sufficient subcooling. But subcooling at this end of the pipe, which was the last to be completely filled with condensate, may not have been great enough to cause severe waterhammer.
2. As more condensate drained out of the line, the steam tongue would reach further into cooler condensate as shown in the second figure in the sequence. . As explained in the previous section, the condensing steam from the surface of the steam tongue would induce more steam flow until the flow velocity was sufficient to raise up a wave plugging the top of the pipe thereby entrapping steam to the right of the plug,
3. The entrapped steam, surrounded by subcooled condensate and steel pipe, would rapidly condense causing its volume and pressure to plunge thereby motivating the high pressure steam on the left side of the condensate slug to accelerate a slug of condensate into the collapsing steam void.
4. The rapidly moving condensate slug would crash into the stationary condensate on the other side of the void creating an overpressurization pulse on the order of 1000 psi. The overpressure would be transmitted through-out the water-filled portion of the pipe—both forward and backward from the point of impact.
5. The pressure needed to break an 18" (450 mm) pipe of 10mm thickness with a continuously welded seam in hoop stress can be as low as 1435 psi (99 Bar)[6]. Thus, with a steam pressure of 200 psig (13.8 barg), the overpressure created by the waterhammer needed only be 1435 – 200 = 1235 psi (85 barg) to burst the pipe. The pipe running through the culvert did not burst, but the strength of the tee joint adjacent Valve 3 was considerably weaker . The waterhammer overpressure was apparently great enough to burst the tee section but not the pipe upstream or it.

The same sequence of events could have been triggered by cracking open either Valve 2 or Valve 3 to re-establish steam flow to the processes downstream, or any action that let condensate flow out of the pipe so steam could flow in. In fact, once the condensate had subcooled sufficiently to support condensation-induced waterhammer, there was no simple way steam flow could have been restored, or the water drained from the depression to avoid waterhammer as long as the system was under steam pressure.

To avoid this accident, the steam pressure upstream of the culvert would have had to been cut off, bled, and only then could the condensate be drained to defuse the potential accident.

Of course the root cause of the accident was the failure (by inadvertent disabling) of the steam trap.

[6] Assuming Std Wt pipe with 12.5% mill tolerance, .065" corrosion allowance per ASHRAE 2004 Systems 7 Equipment, p. 41.7, and .60 weld joint efficiency

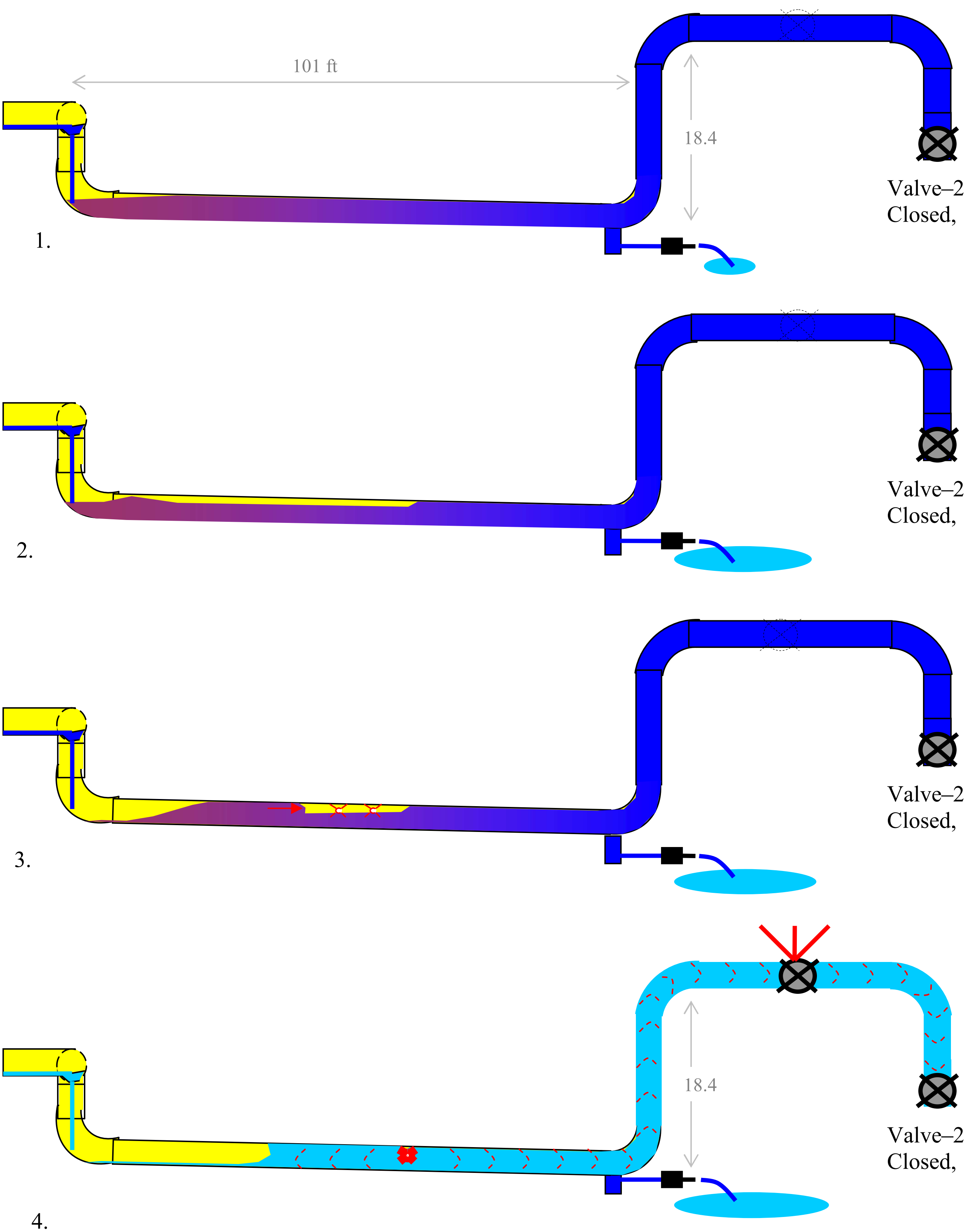

101 ft
18.4
Valve–2
Closed,
1.
Valve–2
Closed,
2.
Valve–2
Closed,
3.
18.4
Valve–2
Closed,
4.

Figure 11-5.