WHAT CAUSED THE STEAM SYSTEM

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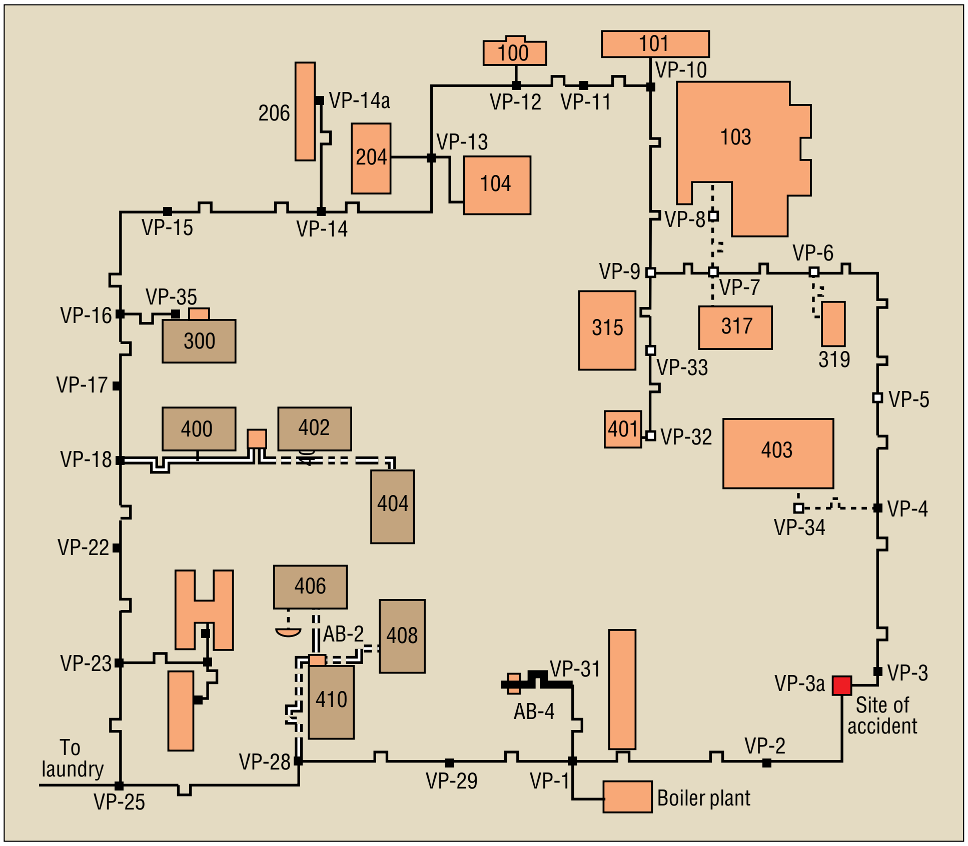
It was 12:35 PM on a sunny June day. Jack had just returned from lunch and was entering Steam Pit 1 to open the steam valve. He had finished repairing the blown valve gasket in Steam Pit 2 the day before. The steam isolation valves in Pits 1 and 3a had been closed two weeks earlier to facilitate the work at Pit 2. The steam system formed a loop around the campus so steam could reach almost every pit from two directions (Fig. 1). Jack felt it was time to put the cold 800-ft section of steam pipe between Pits 1 and 3a back into service.

Jack opened the gate valve at Pit 1, emitting 85 psig steam to the cold pipe section. He probably heard the hiss of steam as it rushed under the valve disk to fill the relative void in the 800-ft pipe section. Jack turned the handle of the gate valve until it was fully opened. It took less than a minute. He climbed out of Pit 1 and headed for Pit 3a to open that valve. He didn't want to spend any more time in the hot steam pits than necessary.

As Jack drove the short distance to Pit 3a and parked his truck, newly admitted steam was rapidly condensing in the cold pipe section faster than the steam plant could supply it. Condensate coated the inside pipe surfaces and rolled off the pipe walls, forming a small rivulet at the bottom of the pipe. About 600 lb of condensate would form in the first minutes after steam entered the 800-ft pipe section.

The steam pipe was pitched downward from Pit 1 to Pit 2 (Fig. 2). At Pit 2, the pipe jumped up about 8 in. and then continued its downward pitch to Pit 3. The rivulet of condensate forming at the bottom of the pipe flowed down toward the drip legs provided at the low points at Pits 2 and 3.

Under normal operation, steam traps located in the drip legs of Pits 2 and 3 were supposed to carry away condensate to keep the 8-in. diameter steam main dry and safe. Why safe? Steam mains are designed to carry steam at velocities upwards of 100 mph at full load. With a 100 mph hurricane of steam blowing down a pipe, you don't want a lake of condensate at the bottom of that pipe. Above 30 mph, a steam "wind" can pick up waves that, if there is enough condensate, can lap up and block the pipe.[1] Once the pipe is blocked, the steam is no longer blowing over the condensate; it is now pushing a lethal slug of water



1 Campus steam loop.

**Mr. Kirsner performed the initial investigation into the cause of the accident for the Georgia Dept. of Human Resources and was later retained as a consultant and expert witness to assist in the defense of the engineering firm and contractor who redesigned the steam pits to improve their safety.*

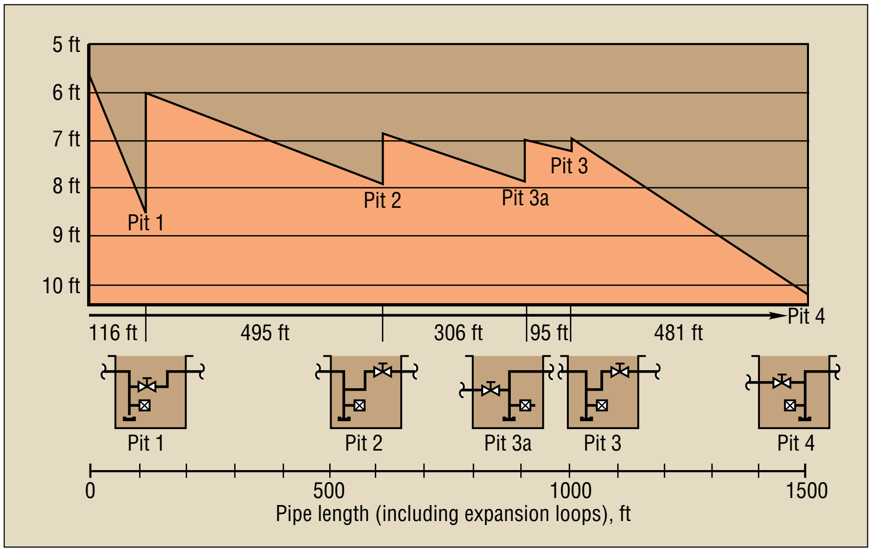
An investigation into the factors contributing to a rare and little understood class of steam system accident that likely will kill again

ACCIDENT THAT KILLED JACK SMITH?

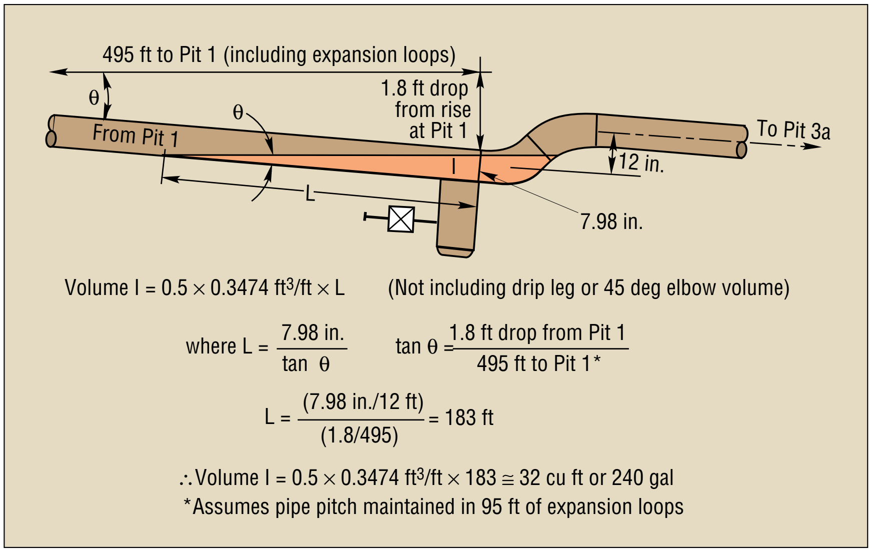
down the pipe with the same differential pressure that motivates the steam at high velocity. The pressure will attempt to accelerate the slug to approach the flow velocity of the steam—55 mph is achievable with 85 psid.

A slug of water just 8 in. long in an 8-in. diameter pipe weighs as much as a bowling ball. Steam piping systems and their supports are not designed to withstand the impact of 55-mph bowling balls striking their elbows, valves, and fittings. Removal of condensate in steam systems is paramount to their safe operation.

There were no operable steam traps, however, removing condensate from the 800-ft section of pipe between Pits 1 and 3a that day when Jack opened the steam valve at Pit 1. This was partly by accident and partly by design. The trap located in Pit 3a was on the downstream side of the closed gate valve in Pit 3a. Thus, the trap was isolated from the cold pipe section. The design engineers had anticipated the problem of condensate pooling against the isolation valve when it was closed, however, and provided a 1-in. diameter "blowoff" pipe with a ball valve shutoff immediately upstream of the valve. Its function was to purge condensate that puddled upstream of the valve at startup. Unfortunately, the 1-in. ball valve was closed.



2 Gradient profile of steam main between Pits 1 and 4.



Volume I = $0.5 \times 0.3474\ \text{ft}^3/\text{ft} \times L$ (Not including drip leg or 45 deg elbow volume)

$$\text{where } L = \frac{7.98\ \text{in.}}{\tan\ \theta} \qquad \tan\ \theta = \frac{1.8\ \text{ft drop from Pit 1}}{495\ \text{ft to Pit 1}^*}$$

$$L = \frac{(7.98\ \text{in.}/12\ \text{ft})}{(1.8/495)} = 183\ \text{ft}$$

$\therefore$ Volume I = $0.5 \times 0.3474\ \text{ft}^3/\text{ft} \times 183 \cong 32$ cu ft or 240 gal

*Assumes pipe pitch maintained in 95 ft of expansion loops

3 Volume of condensate puddle at Pit 2.

As for the steam trap in Pit 2, it was nonfunctional. Its discharge line had been disconnected years ago when the building containing the condensate receiver to which it had discharged had been torn down. The fact that the trap discharge had nowhere to go had apparently slipped through the crack at the time of the building demolition and had never been noticed in subsequent years.

The lack of an operable trap at Pit 2 allowed condensate to back up in the steam main and form a resident puddle starting at Pit 2 and extending upstream (Fig. 3). During periods of low steam flow, as in summer, we surmise that the puddle would build almost to block the 8-in. diameter pipe at the rise at Pit 2. Only enough space between the puddle's sur-

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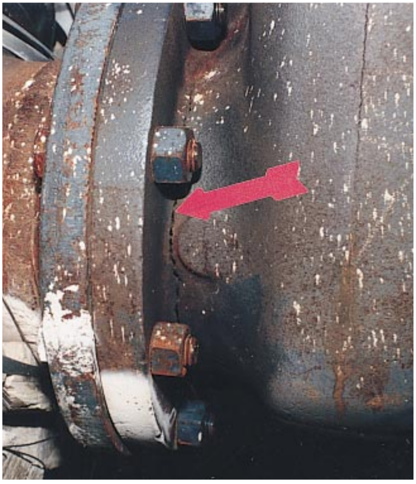
[1] *Wallace and Dobbson predict a gas velocity of less than 30 mph is sufficient to initiate slugging behavior in an 8-in. pipe ("Onset of Slugging in Horizontal Stratified Air-Water Flow,"* Int. J. Multiphase Flow, *Vol. 1, 1973, pp. 173-193).*

4 Pit 3a 8-in. cast-iron gate valve. Note the broken gusset.



5 Pit 3a 8-in. cast-iron gate valve. Note the crack extending around circumference of flange neck.

face and the top of the pipe would remain for what little steam was needed by downstream buildings to blow by. While this puddle posed a continual threat of water hammer, if steam flow was lazy enough (as it apparently had been in that section of pipe), the threat would never turn to action. The puddle would just sit there burping over condensate when too much accumulated. At its maximum capacity where it would just block the pipe, the puddle could hold 1900 lb of water stretching for 183 ft up the 8-in. pipe from Pit 2 toward Pit 1. (The prediction of the existence of the puddle was verified some months after the accident when, during the course of maintenance at Pit 2, a large quantity of water was drained from the drip leg.)

The puddle of condensate upstream of Pit 2 was probably sitting there when Jack opened the steam valve at Pit 1. Opening the valve permitted a rush of steam to blow down the pipe section from Pit 1 over the puddle at Pit 2 toward the closed valve at Pit 3a. The initial shock of 85 psig steam rushing into the pipe probably blew a substantial portion of the puddle over the hump at Pit 2 and down toward Pit 3a.

Did this create a water hammer at Pit 3a? I don't think so. If a slug formed that did fill the entire pipe and was moving down the pipe toward the closed isolation valve in Pit 3a, it would compress the air still residing in the pipe as it sped toward the dead end. This compressed air piling up in front of the slug would act as a shock absorber to cushion the blow of the slug as it approached the closed valve at Pit 3a. Thus, if there was an initial water hammer incident caused by retained condensate at Pit 2 being swept toward Pit 3a, I believe it was a mild one. Probably the primary result of the inrushing steam on the puddle posted at Pit 2 was to push a portion of it to Pit 3a where the cold residual condensate came to rest against the valve disk at Pit 3a.

It took Jack about a minute to reach Pit 3a; he drove the 800 ft. Jack climbed down the ladder at Pit 3a. We surmise that he did not notice condensate or steam shooting out of the downturned 1-in. blowoff pipe that emptied into the grass above Pit 3a because the 1-in. ball valve in the line was not open. Had he opened it, the cold residual condensate from the puddle at Pit 2, which was now residing upstream of the 8-in. gate valve in Pit 3a, would have been shooting out of the 1-in. line with great force. After the water was emptied, hot flashing condensate and steam would have blown out the pipe. Jack and other passersby could hardly have failed to notice the steam plume and hear the discharge of water, steam, and air rushing out of the pipe.[2] Interviews revealed that no one noticed a steam plume.

Once in the pit, Jack positioned himself behind the 8-in. gate valve so he could turn the handle to open it. The valve was a 125 lb Class, cast-iron, outside screw and yoke valve requiring 14 turns to open it fully. It had been about 3 min since Jack had opened the valve at Pit 1.

It was probably hard to turn the valve handle. The pressures on the two sides of the valve had not equalized yet, and the differential pressure would be pressing the valve disk hard against its seat. Jack must have tugged hard. It took a half turn for the disk to begin to lift off the valve seat. Jack turned the handle two more revolutions. He probably realized as soon as the disk cleared the seat that there was trouble. He probably heard the metallic "clang" and then a roar as steam on one side of the valve met cold condensate on the other side and violently collapsed, shaking the pipe and valve with up to 1000 psi of "implosive" pressure. He may have even hurriedly tried to open the 1-in. diameter blowoff valve at this

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[2] *If there was no water upstream of the Pit 3a valve and only air was rushing out, I calculate the air volume of the 800-ft 8-in. diameter pipe section could exit the system in about 40 sec. After air, steam and condensate would be discharged.*

point, realizing that there was still condensate in the 8-in. diameter line.[3] But it was too late.

The valve pit exploded as if struck by thunder. The valve Jack was opening ruptured, spewing steam and hot condensate in all directions. Jack could not escape the 300+ F steam and flashing condensate spewing out into the pit through large fissures opened up in the body of the valve. Jack died in the pit. His body was found wedged under the broken gate valve beneath 2$^1/_2$ ft of hot condensate that eventually emptied into the pit.

The initial theory

It was not immediately clear what caused the accident. The first theory espoused by the consulting engineers hired to analyze the cause of the accident was that a slug of condensate crashed into the Pit 3a valve from the direction of Pit 2 and the steam plant. The motive force for the slug was the differential between the pressure at the plant and the reduced steam pressure on the other side of the gate valve at Pit 3a after it was opened. Recall from Fig. 1 that the steam system is a loop. The steam on the other side of Pit 3a had to travel approximately 6300 ft around the entire loop to reach the back side of Pit 3a. It was postulated that the flowing friction would have reduced the steam pressure sufficiently by the time the steam got to the back side of Pit 3a to create the pressure differential. The slug of condensate that hit the valve was presumed to have come from the rapidly forming condensate in the 800-ft section of cold pipe that was being returned to service.

The physical evidence

The engineers felt that the physical evidence supported their theory. Fig. 4 shows the valve and pit after the accident. The gusset connecting the outlet flange of the valve to the steam pipe heading toward Pits 3 and 4 (downstream of Pit 3a from the steam plant) is broken, and a crack extends around the front of the valve up through the valve body bonnet flange. Fig. 5 shows that the crack adjacent to the downstream outlet flange extends around the entire neck of the valve body connected to the flange. In fact, when the valve was removed from its connecting piping, the entire flange fell off, carrying with it a large chunk of the upper valve body at the gusset. The upstream side of the valve (toward Pit 2 and the steam plant) sustained a crack on the back side of the valve body (Fig. 6), but in general, the upstream side of the valve was not as severely damaged as the downstream side.

What does the physical evidence tell you? Does it support the theory that a slug of condensate struck the valve disk from the upstream side—*i.e.*, from the direction of Pit 2 and the steam plant—as the consulting engineers postulated? If so, the slug would have struck the disk inside the valve head-on, which would have transferred the impact to the internal valve guides inside the valve body (Fig. 7). This would have put the downstream half of the valve body in compression and the upstream half in tension, tending to split the valve in half down the middle.

6 Back side of valve at Pit 3a.

Cast iron is roughly three times as strong in compression as it is in tension. If the impact had come from the upstream side, we would expect most of the damage to be on this side of the valve since it would have been placed in tension. Instead, the damage is concentrated on the downstream side of the valve, where the gusset was broken and the flange neck completely separated from the valve body.

7 Pit 3a after the accident. To the right are Pit 2 and the steam plant; toward the top are Pits 3 and 4.

It is evident then, from the orientation of the damage, that the slug that struck the valve did not come from the upstream side of the valve but from the "back side" of the steam system loop.

Take a look at how the drip leg in Pit 3a is supported in Fig. 7. The drip leg actually is the termination of a downturned elbow in the pipe coming from Pit 3. Of course, the original design engineers planned on steam and condensate "going to" Pit 3 from Pit 3a. This is the normal direction of steam flow from the steam plant out into the system. Steam or condensate was not supposed to flow from Pit 3 back to 3a. The elbow and drip leg are supported "officially" from an anchor in the pit wall at the top of Fig. 7, a few feet from the drip leg. "Unofficially," however, the drip leg and elbow

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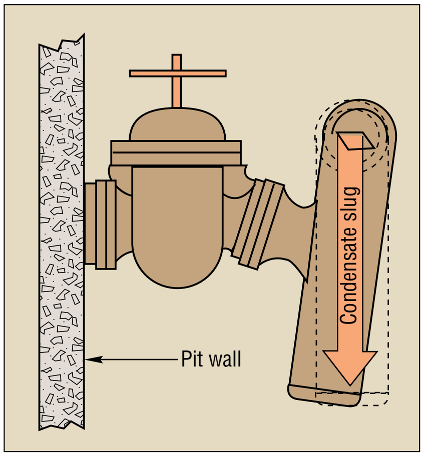
[3] *The 1-in. quarter-turn blowoff valve was found half open.*

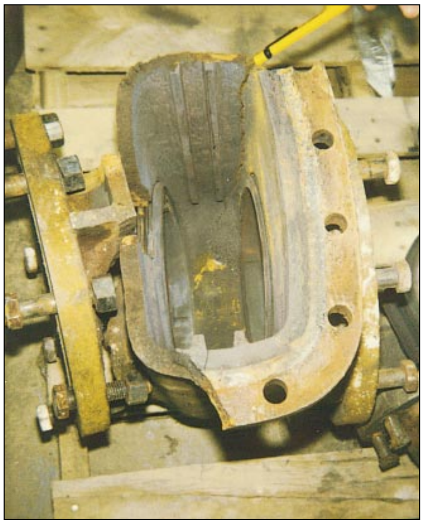
are also supported by the cast-iron gate valve via its connection to the drip leg elbow. The unofficial valve support cantilevers out from the kitty-corner pit wall. There is no support under the drip leg termination to transfer its load to the concrete floor of the pit.

The stiffest connection closest to the load will carry the load imposed on the drip leg. The support containing the cast-iron valve has the shortest cantilevered distance and is very stiff. It is this "unofficial" support that carries most of the drip leg's load.

8 Inside of Pit 3a valve. Pencil points to valve disk guides.



9 Imaginary performance of Pit 3a "ductile" valve as slug struck (view from the direction of Pit 3).



10 Disassembled Pit 3a valve.

Now imagine if the slug of condensate that broke the valve came from the direction of Pit 3—*i.e.*, from the backside of the steam loop. It would have entered Pit 3a from the top, as shown in Fig. 8, rounded the full radius elbow, and then crashed into the dead end at the bottom of the drip leg, wrenching the drip leg and its elbow violently down.

Fig. 9 shows the torque the slug would have applied to the valve and how I imagine the valve would have deformed if the valve body were made of some imaginary ductile material. Cast iron, of course, is not ductile. It will not accept any appreciable strain. Deformation as shown in Fig. 9 would severely strain the gusset, tend to rip the flange out of the valve body, and if the gusset fractured, probably break off the entire flange. (It does not take much energy to propagate a crack in cast iron once it is started.) The right side of the valve body might sustain a crack as well, widening toward the top of the valve body (which was in tension) as the root of the cantilever (*i.e.*, the valve) tried to resist bending.

Judging by the damage to the valve, shown again in Fig. 10, this appears to be what happened. But if the slug came through the "back door," where did the motive force to accelerate it come from, and where did the slug of condensate come from?

Initial theory's motive force

The initial theory presumed that the steam pressure was higher on the steam plant side of the Pit 3a valve than on the back side of the valve toward Pits 3 and 4. Let's examine this assertion.

For there to have been a significant pressure drop in the steam pipe as steam circumnavigated the campus to the back side of the Pit 3a valve, there would have had to have been significant steam flow in the pipe. But steam flow in the system was low. It was a warm day, the campus laundry had shut down for the day, and only one boiler was providing steam. Operators had placed the boiler controls on manual operation. Gas consumption charts indicate that the steam plant was only putting out about 5200 lb per hr or about 87 lb per min.

An 8-in. diameter steam line is routinely sized to carry 30,000 lb of steam per hr, so 5200 lb per hr would not create much pressure drop in the 8-in. main. Around the back side of the loop, however, the 8-in. main reduces to 6 in. and then 4 in. I estimate (roughly) that the pressure drop of steam flowing in 7000 equivalent ft of pipe around the back side of the loop to Pit 3a, before the valve in Pit 3a was opened, could have been in the neighborhood of 7 psi.

Is a 7 psi pressure differential enough to motivate a sufficient velocity of steam flow to pick up a slug of water, say from the puddle lying at Pit 2, and send it cannonballing toward the barely opened valve at Pit 3a? I don't think so.

To get moving, the steam had to flow under the partially opened gate valve in Pit 3a once it was opened. At $2\frac{1}{2}$ turns (of the 14 to open the valve fully), I estimate the valve disk would have raised about 1 in., exposing a crescent moon opening under the valve disk equal in area to about 10 sq in.

The steam flowing under this opening would have consumed *at least* one "velocity head"—

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$V^2/2g_c$—in pressure potential energy, which would have been converted to kinetic energy and not regained. If the entire 7 psi pressure differential was consumed in only overcoming one velocity head of static pressure drop, then steam velocity through the 10 sq in. valve opening would have been:

$$V = \sqrt{2g_c \times 7 \text{ psi} \times 2.31 \text{ ft/psi}}$$
$$= 32.3 \text{ ft/sec}$$

Volumetric flow through the opening, then, would have been no more than:

$$Q = 32.3 \text{ ft/sec} \times 10 \text{ sq in./144}$$
$$= 2.3 \text{ cu ft/sec}$$

A volumetric flow rate of 2.3 cu ft per sec through the full cross-sectional area of an 8-in. pipe equates to a velocity in the pipe of:

$$V_{pipe} = \frac{2.3 \text{ cu ft/sec}}{0.3474 \text{ sq ft}} = 6.6 \text{ ft/sec}$$

6.6 fps is about 5 mph. The velocity would be greater while passing over the puddle at Pit 2 but would subside again downstream of the puddle. I do not believe that a 5 mph steam velocity caused this accident.

But if not, where did the motive force for this accident come from? Let's look closely at what was going on inside the 800-ft section of cold pipe in the 3 to 4 min before the valve at Pit 3a was opened.

Revised accident theory

I mentioned earlier that as steam entered the 800-ft section of cold pipe, it began to condense rapidly. This was a fast-moving transient heat transfer process.

Steam rushed into the 800-ft pipe section, compressing, mixing with, and warming the 247 cu ft of air that would have occupied the cold pipe section. The sudden expansion of the steam system caused steam pressure to drop in the entire system and steam to flash off from the surface of the active boiler. I estimate that steam pressure at the boiler plant dropped from around 85 psig to about 79 psig (94 psia) immediately. Because the operator had apparently not opened the 1-in. vent valve at Pit 3a to vent air and condensate, the air in the 800-ft pipe section could not escape. The resulting steam-air mixture consisted of approximately 79 percent steam and 21 percent air by mole content. This further dropped the steam pressure in the "mix" to its partial pressure—*i.e.*, 79 percent of the total pressure. Thus, steam partial pressure = 0.79 × 94 psia = 74.2 psia or 60 psig.

The drop in steam pressure from 85 to 60 psig caused the steam in the steam-air mixture to be slightly superheated. The superheat would tend to slow heat transfer until the superheat was given up and condensing heat transfer was initiated. Since the air in the pipe section had no means of escape, each new charge of steam that replaced that being condensed would initially be superheated.

Nevertheless, steam began rapidly condensing on the inside of the 8-in. steel pipe. The rate at which the condensing heat transfer proceeded was controlled by the connective heat transfer coefficient, h, for the steam-air mixture.

With no air in the system, I compute the initial value of h to have been about 500 Btuh per sq ft per deg F. At this rate, heat transfer would have proceeded at a lightning-quick pace, going to 99 percent completion within 1 min and thereby quickly stabilizing the system. Air in a steam system, however, drastically impedes heat transfer. As steam condenses out of the steam-air mixture at a heat exchange surface, the air is left behind. Very quickly, a layer of insulating air will blanket the heat exchange surface, slowing the rate of condensation to a fraction of its pure saturated steam value. For a mole fraction of air equal to 21 percent of the steam-air mixture, h is reduced to one-twelfth of its pure steam value.[4]

Fig. 11 shows the progression of heat transfer between the steam-air mixture and the 800-ft pipe section in terms of the number of pounds of steam condensed to warm the pipe section. It shows that it took over 6 min for the heat transfer to go to completion—*i.e.*, for the pipe to reach steam temperature.

The timing here is important. Let's focus on what was happening in the first 3 min after Jack opened the 8-in. valve at Pit 1, admitting steam to the 800-ft pipe section.

In the first minute, 230 lb of steam would have been consumed in heating the pipe, according to the table in Fig. 11. That is more than the one on-line boiler could produce. Remember, its controls were set in "manual fire" position, and it was only outputting about 5200 lb per hr or 87 lb per min of steam. In fact, Column 3 in the table shows that *during each of the first 3 min*, the rate of steam consumption due to heat transfer in the pipe *exceeded* the rate at which steam was produced in the boiler. Thus, instead of pressure being higher in the 800-ft pipe section compared to the rest of the system, as was postulated in the initial theory, *it was lower*!

Did the lack of steam generation from the steam plant starve the heat transfer process in the 800-ft pipe section? No, although it might have slowed it down slightly in the first few minutes. Steam would have been supplied by other sources. First, the on-line boiler would have contributed roughly 48 lb of steam due to internal flashing of boiler water to steam as steam pressure fell (from 79 to about 52 psig). The remaining shortfall of steam would have backflowed into the 800-ft

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[4] *Henderson,* Heat Transfer During Vapor Condensation in the Presence of Noncondensible Gas*, 1967, doctoral dissertation, University of Maryland.*

pipe section from the rest of the 7300 ft of steam-filled pipe. The steam accounting ledger during the first 3 min sums like this: The cumulative pounds of steam consumed was 482 lb, per the table in Fig. 11. The boiler generated 261 lb of steam in 3 min plus another 41 lb due to flashing in the boiler. This left a shortfall of: 482 – 261 – 48 = 172 lb of steam to be made by the rest of the system. Removing 172 lb of steam from the entire steam system would have dropped its pressure to 54 psig.

The situation, then, at Pit 3a when Jack climbed down to open the 8-in. valve was most likely this: Relatively cold water was resting against the valve disk on the upstream side of the valve toward Pit 2, and steam was pushing to enter the low-pressure 800-ft pipe section from the downstream side of the disk. The water mostly consisted of the residual condensate that had been swept over from Pit 2 with the initial violent inrush of steam. Its bulk temperature would still be cool since its relatively small exposed surface near the top of the pipe would have allowed little steam to contact the bulk of the water, especially that water resting against the valve disk where the water almost filled the pipe.

As the valve was opened, steam would have flowed underneath the valve disk into the cold condensate, forming an expanding steam bubble surrounded by cold water. Heat transfer between the 300+ F steam and the subcooled water would have been extremely high.

The bubble of steam would have almost instantaneously imploded as the steam transferred its heat to the cold water and collapsed to condensate occupying 1/350 of its former volume. Had the steam flow been restricted, the surrounding water would have slapped into the void, creating a loud and potentially destructive pressure pulse on the order of magnitude of 1000 psi. But with a ready steam supply from the 7200 ft “reservoir” of steam pipe in the looped system, the collapsing void would instead have drawn in more steam underneath the valve disk to refill the bubble and repeat the collapse. (In a race to fill the void, steam will beat water because of its lower inertia.) The frequency of bubble collapse and steam replenishment would have

Minutes	Temperature difference, F	Steam consumed during minute, lb	Cumulative steam consumed, lb	Heat transfer, percent
0	229	0	0	0
1	139	230	230	39
2	79	154	384	65
3	41	98	482	82
4	18	57	539	92
5	7	29	568	97
6	2	13	581	99
7	0	4	585	99
8	0	1	586	100

Solve for $\Theta(t)$:

1. Heat given up equals heat absorbed $$\dot{q}_{heat\ transfer} = \dot{q}_{heat\ absorbed}$$
2. Newtonion cooling $$hA(T_{sat} - T_{steel}) = mc\frac{dT_{steel}}{dt}$$
3. Let Θ be $(T_{sat} - T_{steel})$ $$h(\Theta)A\Theta = -mc\frac{d\Theta}{dt}$$
4. Note h is a function of Θ $$\frac{1}{h(\Theta)}\left(\frac{d\Theta}{\Theta}\right) = \frac{Adt}{mc}$$
5. From Rohsenow, $h(\Theta) = H/\Theta^{0.25}$ where $$\frac{\Theta^{0.25}}{H}\left(\frac{d\Theta}{\Theta}\right) = \frac{Adt}{mc}$$

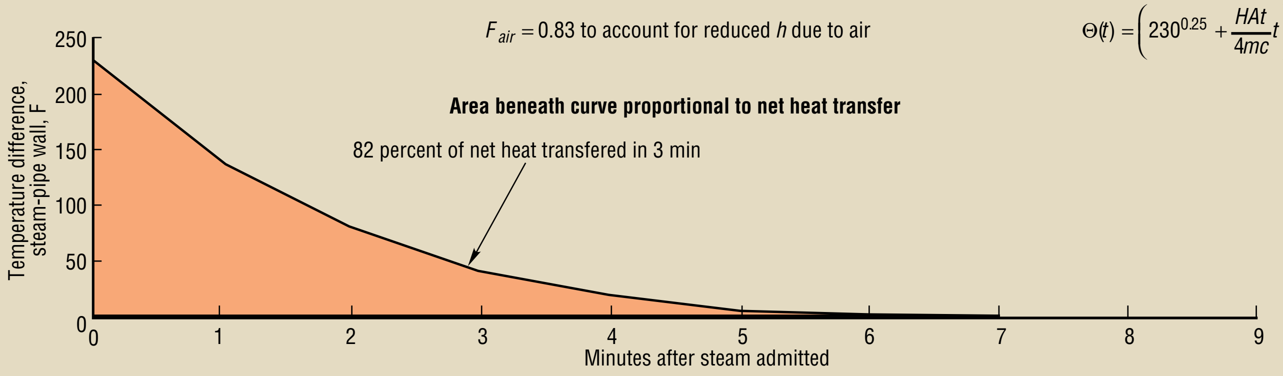
$$h = 0.555\left[\frac{r_1 g(r_1 - r_v)h_{fg}^{*}k_1^3}{m_1 g_c D(T_{sat} - T_{steel})}\right]^{0.25} \times F_{air} \qquad \frac{d\Theta}{\Theta^{0.75}} = \frac{HAdt}{mc}$$

where

$$h_{fg}^{*} = h_{fg} + \tfrac{3}{8}c_{p1}(T_{sat} - T_{steel}) \qquad \int_{230}^{\Theta(t)}\frac{d\Theta}{\Theta^{0.75}} = \int_{0}^{t}\frac{HAdt}{mc}$$

to account for heat transfer from condensate $$4\Theta(t)^{0.25} - 230^{0.25} = \frac{HAt}{mc}t$$

$F_{air} = 0.83$ to account for reduced h due to air $$\Theta(t) = \left(230^{0.25} + \frac{HAt}{4mc}t\right)^4$$



11 Progression of heat transfer to exposed 8-in. pipe.

been so rapid as to appear as a "condensate flame" blowing into the pool of water from underneath the valve disk. (This phenomenon is described in a number of experiments on rapid condensation carried out at Creare, Inc.[5])

The rate of steam consumption would have been very high in the first few seconds after the valve at Pit 3a was opened. The condensation rate would have only been limited by the rate at which steam would flow underneath the valve disk. This limit was the sonic mass flow rate—*i.e.*, the rate at which steam flow underneath the valve disk became "choked."

An approximate formula for the choked mass flow of steam through the area, A, beneath the valve disk is:

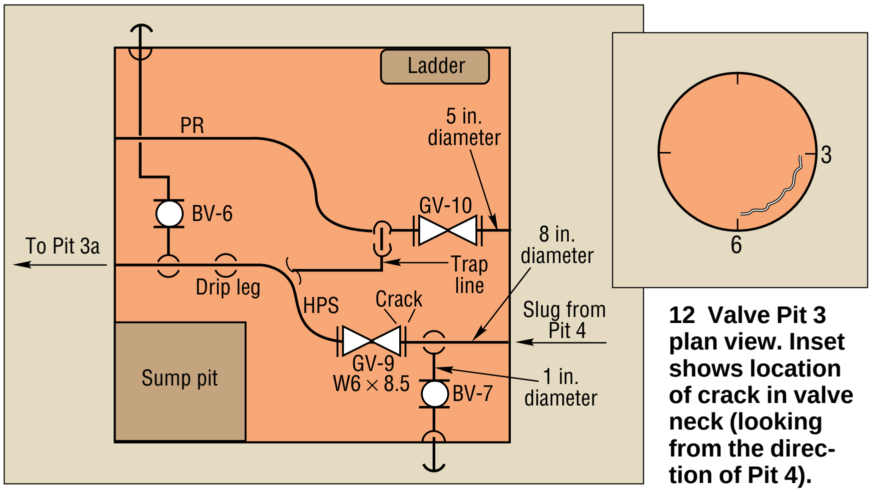
$$m^* = 35\rho\sqrt{T}A$$

where ρ and T are the inlet conditions.[6] Thus, at inlet steam conditions of 54 psig (ρ = 1/6.38 lb per cu ft, T = 327 F with 24 F superheat):

$$\begin{aligned} m^* &= 35 \times 1/6.38 \text{ lbm/cu ft} \times \\ &\quad \sqrt{327+460\text{F}} \times \frac{10 \text{ in.}^2}{144 \text{ in.}^2/\text{ft}^2} \\ &= 10.7 \text{ lbm/sec} \\ &= 641 \text{ lb/min} \\ &= 38{,}475 \text{ lb/hr} \end{aligned}$$

This is a large steam flow. In the full cross-section of an 8-in. pipe, this steam flow would move through the pipe with a velocity of 134 mph.

If we imagine steam was being emptied from the 8-in. steam main extending back toward Pits 3 and 4, roughly 200 ft of steam pipe would have been evacuated per second due to the steam consumption of 10.7 lbm per sec in the condensate flame at Pit 3a. I believe this rapid steam movement was the motive force that picked up a slug of condensate that struck the drip leg at Valve Pit 3a.



12 Valve Pit 3 plan view. Inset shows location of crack in valve neck (looking from the direction of Pit 4).

But where did the slug of condensate come from? We don't know for sure, but I suspect that the slug of condensate was sitting in the system between Pits 3 and 4. 125 cu ft of water filled Pit 3a to a depth of 2½ ft after the valve ruptured. Only 50 cu ft of this amount can be accounted for as coming from the residual condensate that had been resident upstream of Pit 3a prior to the accident plus condensing steam that flowed into the cold pipe section before Pit 3a was isolated. Therefore, the other 75 cu ft of water that filled the pit plus 10 percent to account for flash steam lost to the atmosphere must have come from the pipe section downstream of Pit 3a toward Pits 3 and 4. 150 cu ft of condensate could have accumulated there if the trap failed closed (the F&T trap at Pit 4 was replaced and discarded after the accident; hence, we were never able to examine it).

Additional damage found at Pit 3 after the initial accident supports the theory that the slug came from this direction. At Pit 3, a crack was found in the flange neck of the cast-iron gate valve, and the valve's connecting gasket was blown out. But if the slug that slammed into Pit 3a traversed Pit 3, why didn't it fracture the cast-iron valve at Pit 3 as well, instead of just cracking it? This would have saved Jack's life.

Examine the schematic diagram of the Pit 3 layout in Fig. 12, taken from the design engineer's drawings. The layout is very different from that of Pit 3a. There is no dead-ended drip leg, as is the case at Pit 3a. The most abrupt change of direction in the high-pressure steam (HPS) main is two long radius 45-deg elbows. The inertial force imposed on the valve when the condensate slug hit this change in direction would be much less than that exerted at Pit 3a. Nonetheless, the reaction force was apparently enough to crack the valve but not rupture it. The location of the crack, as shown in the figure, is consistent with the location of maximum tensile bending stress placed on the valve body by a slug traveling from the direction of Pit 4 through Pit 3 and heading to Pit 3a.

Shock to valve at Pit 3a

The question remaining is: Could the force of the shock caused by the slug of condensate described above have fractured the valve at Pit 3a? Water hammer theory predicts the overpressure due to the collision of a fluid to be ρ times c times V. In this case:

- ρ is the density of the conden-

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[5] *Block, James A., "Condensation Driven Fluid Motions,"* Int. J. Multiphase Flow*, Vol. 6, 1980, pp. 113-129.*

[6] *Lindeburg,* Mechanical Engineering Review Manual*, 6th edition, Equation 26.69.*

Steam system accident

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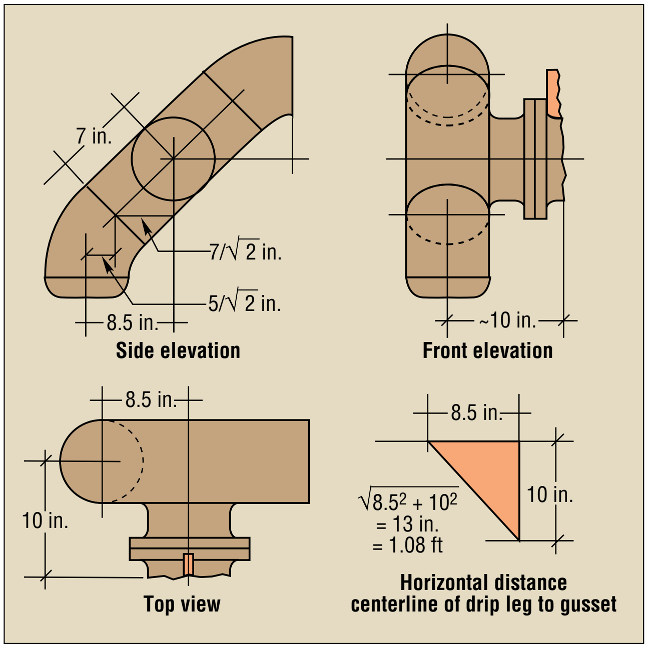
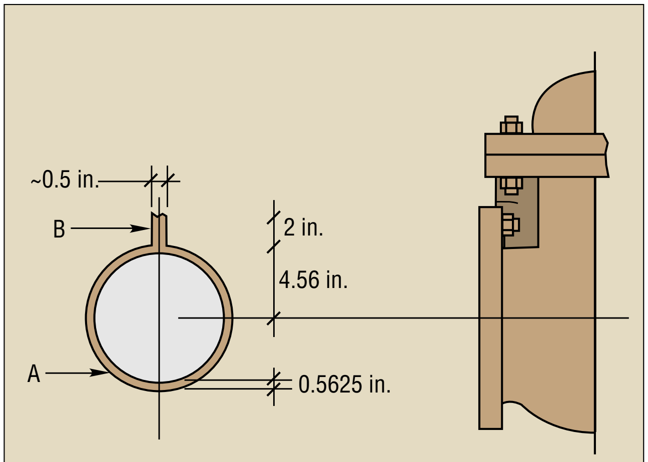


13 Pit 3a drip leg.



$$I = I_A + I_B + A_B d^2$$
$$I_A = pr^3 t = p(4.28\ \text{in.})^3 \times 0.5625 = 138.5\ \text{in.}^4$$
$$I_B = \tfrac{1}{12}(0.5\ \text{in.})(2\ \text{in.})^3 = 0.33\ \text{in.}^4$$
$$A_B d^2 = (0.5\ \text{in.} \times 2\ \text{in.}) \times (5.56\ \text{in.})^2 = 30.9\ \text{in.}^4$$
$$\therefore \quad I = 170\ \text{in.}^4$$

14 Moment of inertia at flange neck.

sate in the slug.

- *c* is the speed of sound in 300 F water—3825 ft/sec.
- *V* is the velocity at which the slug was traveling when it struck the end of the drip leg. The maximum theoretical velocity the slug *could* attain is:

$$V = \sqrt{\Delta P / \rho}$$

ΔP is the pressure differential accelerating the slug of condensate.

If we assume that the steam pressure on the back side of the valve had a value intermediate between the pressure when the valve opened and the eventual reduced pressure and also assume that the steam downstream of the slug had essentially been evacuated by the rapid condensation flame taking place beneath the valve, the ΔP across the slug conceivably approached 71 psia.

Thus, the theoretical velocity of the condensate slug from the formula and assumptions above could have been as high as 52 mph. This is a rough "higher bound" on the velocity of the slug since it assumes the pressure differential across the valve equaled the full steam pressure, and it does not account for any resistance to flow.

Another way to estimate the velocity of the slug is to assume that it attained a velocity at which the flowing friction along its path equaled the pressure differential pushing it. If the slug was picked up near Pit 4, the average flowing distance is about 375 ft to Pit 3a. There are 12 elbows between Pits 4 and 3a where flow energy would be given up. If the velocity of the slug increased until the flowing pressure resistance, including the dynamic losses at elbow and fittings, equaled the ΔP motivating the slug, the velocity of the slug would have been 30.3 ft per sec or 20.7 mph.[7] We consider this figure to be a "lower bound" on the slug's velocity. The overpressurization that would result from the slug of condensate traveling at the lower bound velocity and slamming into the dead end at Pit 3a would be:

$$\frac{(57.2\ \text{lb/ft}^3)(3825\ \text{fps})(30.3\ \text{fps})}{(144\ \text{in.}^2/\text{ft}^2)g_c}$$
$$= 1430\ \text{psi}$$

At 52 mph (the higher bound on slug velocity), the overpressure would be 2½ times as much. How much damage could 1430 psi, the *lower bound* of overpressurization, do?

Stress on the valve

The valve in Pit 3a was a Class 150 cast-iron valve built to ASTM A 126 Class B specifications. This means that the ultimate tensile strength (UTS) of the cast iron from which the valve body was poured was tested to a strength of at least 31,000 psi (since strength tests are conducted on separately poured test bars in accordance with ASTM A 126, actual valve body strength can, and is expected to, vary from 31,000 psi).

Sample coupons cut from the valve body after the accident were tested in a materials lab for UTS. The coupons pulled apart at UTSs from 16,000 to 22,000 psi.

Fig. 8 showed that the cast-iron valve was the closest and most rigid support for the drip leg that absorbed the force of the water hammer. The water hammer force hitting the bottom of the drip leg would have created a moment at the valve to resist the

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[7] Psi loss = 65 psi = $\rho/f(L/D + \text{fittings})$ = 375 ft/0.66 ft + 1.975. Solve for *V* where *f* is a function of *V*.

movement of the drip leg in response to the shock. The moment would equal the moment arm, r, times the impact force. From Fig. 13, $r = 13$ in. or 1.08 ft. F equals the overpressurization calculated above times the cross-sectional area of the drip leg. Thus, for the lower bound estimate of overpressurization, $F = 1430$ psi $\times$ 50.03 sq in. = 71,543 lb. The moment, M, equals 1.08 ft $\times$ 71,543 lb, or 77,000 ft-lb (lower bound estimate).

The valve acted as a cantilevered beam in supporting the drip leg. Bending stress, s, for a cantilevered beam is: $s = My/I$, where M is the moment just calculated, y is the distance from the neutral axis, and I is the moment of inertia of the beam.

If, as a first cut estimate, we model the valve at the flange neck where it fractured as an annular section of 8-in. pipe with a 2-in. gusset on top,[8] as shown in Fig. 14, the moment of inertia is 170 in.^{4}, y is 6.5 in. from the neutral axis to the point where the gusset broke, and thus, bending stress is:

$$s = \frac{(77{,}000 \text{ ft - lb})(12 \text{ in./lb})(6.5 \text{ in.})}{170 \text{ in.}^4}$$
$$\cong 35{,}000 \text{ psi}$$

The valve was also placed in torsion by the impact of the slug of water, as shown in Fig. 13. The torsional stress tending to twist the neck of the valve flange off combined with the bending stress increased the overall stress felt by the gusset and valve neck at the point of fracture.

In an analogous calculation to that of the bending stress, I estimate the torsional stress on the valve at the point of fracture to equal roughly 10,000 psi. Thus, the maximum stress due to combined effects of bending and torsion at the point where the gusset fractured, combined by means of Mohr's circle equations, would be over 37,000 psi.

The combined stress of 37,000 psi is greater than the UTS of the material from which the valve was cast and much higher than the tensile strengths exhibited by the samples cut from the valve body. While the computation of this number is only a first cut based on some rough assumptions, it does demonstrate that the torque exerted by the lower bound estimate of overpressurization generated by a slug of water hitting the drip leg could have, and likely would have, broken the valve at its gusset and flange neck.

Summarizing . . .

By opening the gate valve at Pit 1 wide open, the operator allowed steam to rush into the 800-ft cold piping section and begin condensing at a rate greater than steam could be supplied by the steam plant's single operating boiler, which was set to manual low fire. This put the cold piping section between Pits 1 and 3a at a negative pressure with respect to the rest of the system. Because the system was a loop, steam wanted to flow into the cold piping section from the direction of both the steam plant and the back side of the steam system loop.

A more-or-less permanent puddle of 1900 lb of cold residual condensate resided upstream of Pit 2 due to an unintentionally disconnected trap. Much of this water was swept down to Pit 3a by the initial inrush of 85 psig steam when the valve at Pit 1 was opened. This water, as well as that being formed by condensation, was not purged from the system by the operator using the 1-in. blowoff line provided for that purpose directly upstream of the gate valve at Pit 3a, nor did the operator allow the cold piping to warm to equilibrium temperature with the rest of the system and thereby stabilize. Instead, he immediately traveled to Pit 3a, climbed down the pit, and attempted to open the 8-in. gate valve.

Cold water sat on one side of the valve disk, steam on the other side. When the valve's disk was raised off its seat, 300+ F steam was sucked underneath the valve disk into the cold piping section and was enveloped by cold water. Extremely rapid heat transfer between the steam and cold water instantaneously collapsed the steam, creating a void that voraciously demanded more steam to fill it. The rapid condensation took the form of a "condensate flame." The only factor limiting the rate of condensation and steam consumption was the flow rate at which steam could feed the flame. The flow rate was limited by the sonic choked flow of the steam beneath the valve disk. The magnitude of the choked flow was sufficient to evacuate 200 ft of the steam main per second and generate a steam flow velocity in the 8-in. main of 134 mph.

About 400 ft downstream of Pit 3a, between Pits 3 and 4, a 75 cu ft slug of condensate was drawn to Pit 3a by the sudden evacuation of steam. The slug crashed through Pit 3, where it cracked the pit's cast-iron gate valve and blew out its gasket. The slug continued on to Pit 3a, where it slammed into the pit's dead-ended drip leg with a force of over 70,000 lb. The drip leg's closest and stiffest support was the 8-in. cast-iron valve that was cantilevered off the pit wall. The bending moment and torsion caused by the impact force combined to stress the valve at its flange neck and gusset beyond the ultimate tensile strength of the material from which the

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[8] *This is the point at which the gusset fractured. Since bending tension is maximum farthest from the neutral axis, our first cut assumption is that only the neck of the valve and 2 in. of the gusset participated in resisting bending at the cross-section of the valve that first gave way.*

valve was cast. The valve fractured, spewing hot condensate, flashing steam, and live steam into the pit.

Was accident preventable?

This accident would not have happened if:

- The operator had allowed the 800-ft pipe section to warm to steam temperature before attempting to open the gate valve at Pit 3a.
- The operator had blown off the residual condensate resting upstream of the valve at Pit 3a before attempting to open the valve.
- The trap at Pit 2 had been operational, thereby preventing formation of the large puddle of cold condensate that resided upstream of Pit 2.
- The drip leg at Pit 3a had not been inadvertently cantilevered off the cast-iron gate valve (all this required was a 3-in. pipe support beneath the drip leg to the floor of the pit).
- The gate valve had been steel rather than cast iron.
- The steam system had not been a loop.
- The boiler at the steam plant had not been on manual low fire.
- The valve at Pit 3 had broken, relieving the pressure before the slug reached Pit 3a.

Could it happen again?

Yes. A very similar accident with almost identical causes occurred two years earlier in the Con Edison system that serves New York City. Below the street in a manhole in the Gramercy Park region of the city, two Con Ed employees were killed when they opened a 24-in. gate valve, allowing 150 psig steam on one side of the valve to backflow into cold condensate resting on the other side of the valve. Just as in our accident, the workers were reactivating a cold portion of a looped steam network and did not drain the cold condensate directly upstream of the gate valve before attempting to open it. The resulting explosion severely cracked the cast-iron disk of the gate valve and blew out an expansion joint, killing the workers in the pit as well as a resident of a nearby apartment building and injuring 24 others. An *implosive* collapse due to extremely rapid condensation of the inflowing steam was blamed for the overpressurization that blew out the expansion joint and cracked the valve.[9]

So what was learned as a result of the 1989 Gramercy Park accident, and what was learned about this accident, which occurred in 1991? Not much, I'm afraid, by those who are in the line of fire.

Steam system operators, in general, are not aware of this type of water hammer event or the magnitude of destructive power that can be released by it. Neither are engineers. Most of the scientific and engineering references I found were directed at the nuclear power industry. The operator of our story was almost certainly unaware of the previous accident at Gramercy Park, as were most people outside the Con Ed system.[10] There was no "Notice to Steam System Operators" as there would be to airmen after a serious aircraft accident. The operator of our story was probably lulled into complacency on that summer day after lunch by the laziness of the steam flow in the mains, the knowledge that the boiler was fixed at low fire, and the absence of any eventful episode in the three years he had worked there. Only a few academicians and some very gun-shy Con Ed employees could have predicted what might have happened when he opened the valve at Pit 3a.

So can't training get the word out on accidents of this nature? As of this writing, there is no certification or continuing education required of steam system operators in Georgia, where this accident occurred. That is the case in all but eight states, according to the National Institute for the Uniform Licensing of Power Engineers. The State of Georgia, which owns the hospital where this accident took place, did administer a nine-question test on steam plant operation to the operator subsequent to his employment, and there were records of training. But the test, while perhaps adequate to determine employability, was not sufficient to indicate that the operator was fully trained, and the ongoing training was in-house and sometimes conducted by the operator himself. Still, I imagine this is a better program than most institutions can probably demonstrate.

More ominous is the fact that this accident was never thoroughly investigated by the State. Once excused from the lawsuit that was brought by the widow of the operator, the State's interest in finding out what caused the accident noticeably waned. (The excusal was not based on a lack of culpability but on worker compensation laws that shield the State from liability.) Effectively, the State left it up to the lawyers and courts to sort out what happened.

The lawyers' objective, of course, was not to get at the ultimate cause of the accident—especially if aspects of the cause were unflattering to their clients' interests. They wanted to win an attractive settlement for their clients. Their focus was on simple arguments that would appeal to the emotions of the jury rather than on the salient facts of what caused the acci-

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[9] *Con Edison, Report of Gramercy Park Steam Explosion: August 19, 1989, December 1989.*

[10] *Training in rapid condensation type water hammer was recommended for Con Ed personnel as a result of the accident.*

dent. To them, the pictures of the scalded body of the deceased operator were of much greater significance than the photos of the broken valve.

The engineers who came forward as expert witnesses should have helped keep the focus on what really happened and what caused it. They did not. The opinions of the consulting engineers, in too many cases, seemed to conform plastically to the interests of the side by which they were being paid. In the plaintiff's case, I believe this extended effectively to egging on the attorney with exaggerated stories of malfeasance by the engineer and contractor who were the defendants—*e.g.*, "No competent engineer would specify cast-iron valves in a high pressure steam system"; "Steam pits are totally unsafe, and no operator in his right mind would go into one of those steam pits"; "The operator did nothing wrong—he just happened to be in the wrong place at the wrong time"; and "The contractor who retrofitted the pits did not provide proper training for the steam plant operators." The lawyers, of course, rewarded those who told them what they wanted to hear with handsome hourly fees to give depositions and such. Unfavorable information or doubt as to the origin of the accident was not well received.

As might be expected, this turned out to be a lousy way to get at the truth. Three years after the accident, the case settled. No statement was ever released as to who or what was to blame. The State has never undertaken to get the word out on what caused the accident or to train its steam system workers at other institutions on precautions to take to avoid a similar accident. In light of the fact that several of the State's other large institutions were designed by the same engineering firm that designed this steam system (and that has long been out of business), I believe the State has been less than vigilant in fulfilling its responsibility to protect the safety of its workers.

This accident was a tragedy for the operator who died in the pit and the wife and four children he left behind. More tragic will be the next steam system operator who dies a horrible death in a steam pit because of a failure to learn from this accident and disseminate what was learned. Ω