INTEGRATING RESEARCH AND DESIGN: A STEAM LEAK ACOUSTIC DETECTION FACILITY

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Abstract

A Senior Capstone Project is being undertaken by three senior undergraduate students whereby a facility to establish acoustic profiles for low pressure steam leaks is being designed and constructed. This facility will then be used in research efforts to develop more effective leak monitoring systems in Kraft recovery boilers, used in pulp and paper mills to burn the organic wastes from the pulp-making process and produce electricity. A smelt-water explosion is a hazard to their operation when water from a steam leak reacts with the sodium-rich waste compounds. There has been concern that the leak monitoring systems presently used are ineffective because of uncertainty over the acoustic signatures of the leaks.

The facility to be constructed involves a small electric boiler, a leak containment vessel, a holding tank, and associated valves and piping. Leaking pipes of various materials and geometries are attached to a flange in the leak containment vessel, and as steam generated by the boiler leaks out of these pipes, acoustic detectors in the vessel measure the associated leak acoustic profiles. Sound propagation will be measured through air, water, and mud, and other materials similar to those present in a Kraft boiler. The results of such investigations can be used to design monitoring systems that effectively differentiate between steam leak noise and background noise.

From an educational standpoint, the authors will gain valuable experience in engineering design, in addition to working with a faculty member in participating in a worldwide research effort to solve a practical engineering problem.

Introduction

The purpose of this Senior Capstone Project is to design and construct a facility whereby experiments may be conducted to determine the acoustic profiles of a variety of different types of steam leaks. The results of these experiments may perhaps be used to design more effective acoustic steam leak detectors in Kraft recovery boilers, and may have other applications as well.

The basic design calls for a small boiler to produce low-pressure steam which will travel through copper piping to a separate and sealed steam containment vessel. The top of the containment vessel can be opened to allow experimenters access to the inside of the vessel to set up experiments. Experiments are set up by attaching capped pipes with pre-existing flaws to the incoming steam line, and it is expected that steam will leak out at various flow rates into the vessel through these holes or cracks in the pipes. Acoustic sensors are placed at points along the bottom of the vessel to measure acoustic power at variable frequencies, and these measurements will be sent to a data acquisition system. The final output is expected to be a plot of acoustic intensity as a function of frequency, and it is hoped that this information can be used to design steam leak detection devices, particularly in Kraft recovery boilers, that will more quickly and accurately distinguish the acoustic profile of a steam leak from background radiation.

Background

Vakkilainen in provides an extensive description of the Kraft recovery process, which is the primary focus of the investigations conducted in this Senior Capstone Project [1]. Basically, spent cooking chemicals and dissolved organic compounds are separated from pulp during the washing stage of the pulp making process. The resulting weak, black, alkaline liquor contains about 12 – 20% organic and inorganic solids. The black liquor is then concentrated by an evaporation process involving the direct or indirect heating and flashing of the liquor. Multiple effect, steam heated evaporators are commonly used. The resulting concentrated black liquor can then be burned in a Kraft recovery boiler to produce energy for the generation of steam and electricity. In many cases sufficient energy is produced to provide for the steam and electricity needs of the entire pulp mill.

Black liquor combustion in a Kraft recovery boiler has been studied in detail and described by Hupa and Solin [2]. The process involves several stages. In the first, or drying, stage water is evaporated from the droplet. In the second, or devolatilization stage, gases such as methane, carbon dioxide, hydrogen, and hydrogen sulfide are released. The black liquor droplets swell considerably, and a visible flame appears. Both of these stages occur primarily in the upper cavity of the boiler, but in the later stages a "char" bed, which continues to burn, forms over the water tubes at the bottom of the boiler. This black liquor char primarily contains carbon, sodium carbonate, sodium sulfate, and sodium sulfide, and a primary combustion reaction involves the formation of sodium sulfate from sodium sulfide:

$$Na_2S + 2O_2 \rightarrow Na_2SO_4 \qquad (1)$$

The predominance of sodium, and sodium compounds, in the char bed composition, is a major concern. Heinävaara has made measurements of char bed composition and determined that the char bed is slightly over 40% sodium by weight, and that over 90% by weight consists of the sodium compounds described above [3]. Since the sodium-rich smelt layer covers water tubes, even a small water leak into the furnace can cause a smelt-water explosion. Vakkilainen [1] sums up the attendant explosion and safety hazard as follows:

> "The force is usually sufficient to cause all furnace walls to bend out of shape. Safety of equipment and personnel requires an immediate shutdown of the recovery boiler if there is a possibility that water has entered the furnace. All recovery boilers have to be equipped with a special automatic shutdown sequence."

Jarvinen, Hildebrand, Carroll, and Miettinen have analyzed the current practice of monitoring for water leaks in the bottom wall with the use of acoustic emission sensors, which are most sensitive at very high frequencies (100 kHz or more) [4]. Once a leak is detected, the automatic shutdown sequence described above can be performed, but one of the major results of this study was that it may not be possible to detect this leak in time due to sound attenuation in the char bed. These same four researchers have also developed and will be presenting a low-frequency attenuation model which investigates the possibility of detecting the leak through vibrations in the bottom wall itself, but major uncertainty is associated with the actual frequencies of the sound generated by the various possible steam leaks [5]. Is the leak a high frequency hissing sound? A low frequency rumble? As of this time, the "source term" which forms the basis for the design of these detectors has not yet been determined, and it is this process that the present Senior Capstone Project addresses.

Steam Leak Acoustic Detection System Description

Figure 1 depicts the basic layout of the Steam Leak Acoustic Detection Facility. A portable low-pressure electric steam boiler readily available in the Thermal/Fluids Laboratory is used as the steam source. The steam pressure can be set to between 10 and 15 psig and the relief valve can also be set accordingly. Presently the boiler generates 10 psig steam and the relief valve is set to lift at 11 psig, an arrangement adequate for the detection facility. The boiler is portable in that it is mounted on a cart which can be transported around the lab, and the remaining components will be mounted on a similar cart which can be placed in proximity to the boiler when it is being used to supply steam to the detection facility (obviously, the boiler has other uses as well).

Steam is transported via piping to a flange connection high on the front wall of the containment vessel, which is approximately two feet long, a foot wide, and a foot high. As a result of a thermal analysis of the system which will be explained later, it was determined that the containment vessel needed to have the same design pressure as the boiler, and a relief valve also set at 11 psig is included. Both relief valves empty to a 55-gallon drum half-filled with cold water.

The facility will operate as follows: capped pipes of various materials marked with pre-existing flaws of various geometries will be prepared and these specimens screwed onto a flange/union connection. The boiler will be brought up to pressure, at which time steam pressure will cause flaw propagation until the pipe containment is breached and a steam leak occurs. Detectors measure the acoustic profiles of the leak, both before and after steam is emitted from the pipe. The steam is at all times confined within the containment structure, and even in the event of a relief valve lifting, which is not normally expected, the steam passes into a 55-gallon drum and under the surface of the water there. This container will act like a condenser for the steam. The condenser allows for safe disposal of the steam without the necessity to modify the laboratory infrastructure.

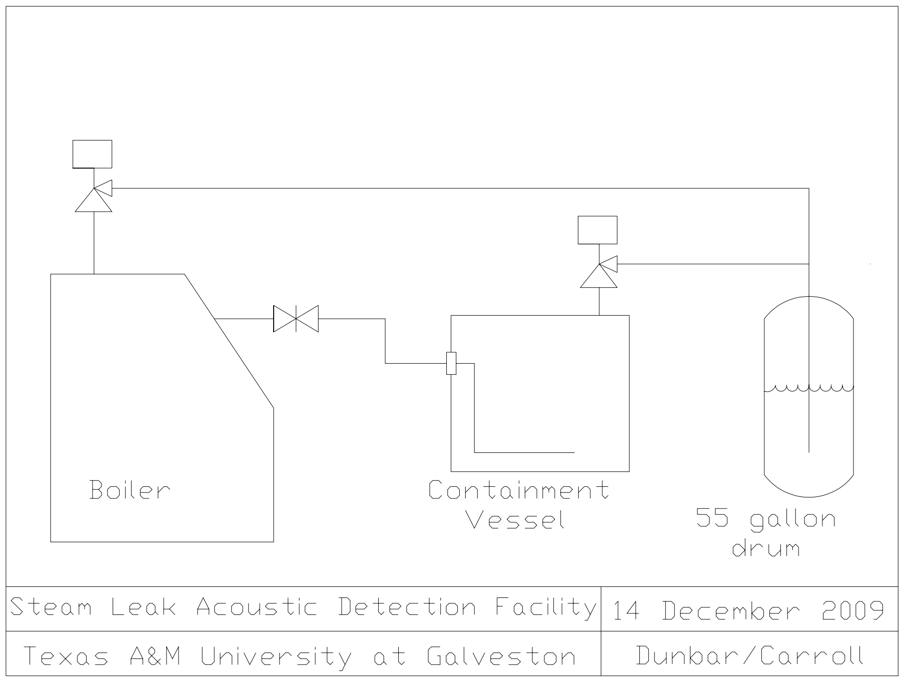

Figure 1: Layout – Steam Leak Acoustic Detection Facility

The containment vessel is sealed with a separate lid which will be bolted to the container, and the number and size of the bolts required for safe operation of the facility has been calculated as explained later in this paper. At the end of each experimental trial the main steam stop valve is shut and the containment vessel is allowed to cool to room temperature. The relief valves can be manually lifted to vent any remaining steam to the condenser if necessary. The piping specimen is then removed so that a new experimental trial may be conducted. To more accurately simulate acoustic attenuation conditions in a Kraft recovery boiler, it will also be possible to fill the containment vessel with other solids and fluids such as water, mud, and clay. Since the sensors are located on the bottom of the vessel, attenuated profiles may also be obtained to validate attenuation models previously developed by the researchers discussed earlier. Shovels and submersible pumps will be available to later remove this material from the vessel.

Design Calculations for the Facility

Some of the major design calculations for the facility included a thermal analysis of the passage of steam from the boiler, through the leaking pipes, and into the containment vessel, and the mechanical analysis of the number and size of the bolts required for the cover of the containment vessel.

One major question that needed to be resolved was whether the containment vessel needed to be designed for the same pressure as the boiler, or whether a lower design pressure was possible. Since the inlet line to the vessel is ¾” pipe, a limiting case was considered where the pipe breaks wide open and steam passes very rapidly through the open-ended pipe into the vessel. A large rapid steam leak into a vessel is hardly an orderly passage through equilibrium states as normally discussed in undergraduate thermodynamics courses; nevertheless it was possible to develop calculations based on the well-analyzed case of "choked flow" through the pipe opening. In "choked flow" the steam exhausts from the pipe at the speed of sound, and no further change in the outlet conditions will further increase the flow. The reader will note that outlet pressure conditions (a 10 psig boiler exhausting to atmospheric pressure for a pressure ratio of about 0.6) do not quite warrant the choked flow assumption, which would require a pressure ratio below 0.5283, but certainly the Mach number of the steam is very close to 1, and the errors are in the conservative direction. A more accurate analysis would involve Fanno flow calculations due to friction effects on the steam exiting the pipes and the pressure variation as steam enters the vessel, but these calculations generally involve graduate level sophistication, and the only requirement was that the general question be answered as to whether the containment vessel "fills up" fast enough to require boiler design pressure for the vessel as well.

Hence, the standard "choked flow" formula [6] was used to determine the mass flow rate of steam entering the vessel:

$$\text{mass flow rate} = A^{*}P_0 g_C (k/Rg_cT_0)^{1/2} \quad (2)$$

A^* = flow area
P_0 = stagnation pressure
T_0 = stagnation temperature
g_c = 32.174 lbm-ft/s^2 lbf (unit conversion constant for English units = 1)
k = ratio of specific heats
R = individual gas constant for air

Rates of flow for the steam for this condition were determined for a number of different containment vessel sizes. For the ¾" pipe used in the design, the flow rate is 0.3017 lbm/s.

The rise in temperature and pressure within the vessel over time were then determined using an energy balance whereby the hot entering steam transfers its energy to the cooler air (which is assumed to be at room temperature at the start of the experimental trial). Several different vessel sizes were considered, and results for both vessel temperature and vessel pressure are shown in the following figures:

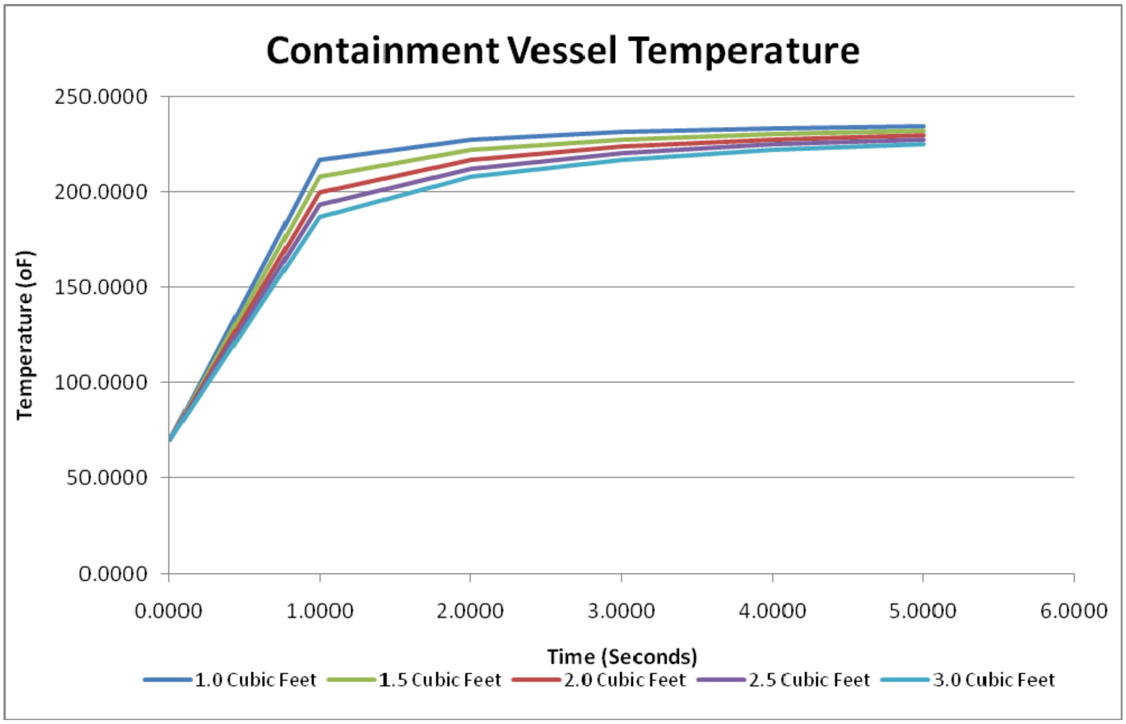

Figure 2: Containment Vessel Temperatures – Wide Open Steam Leak

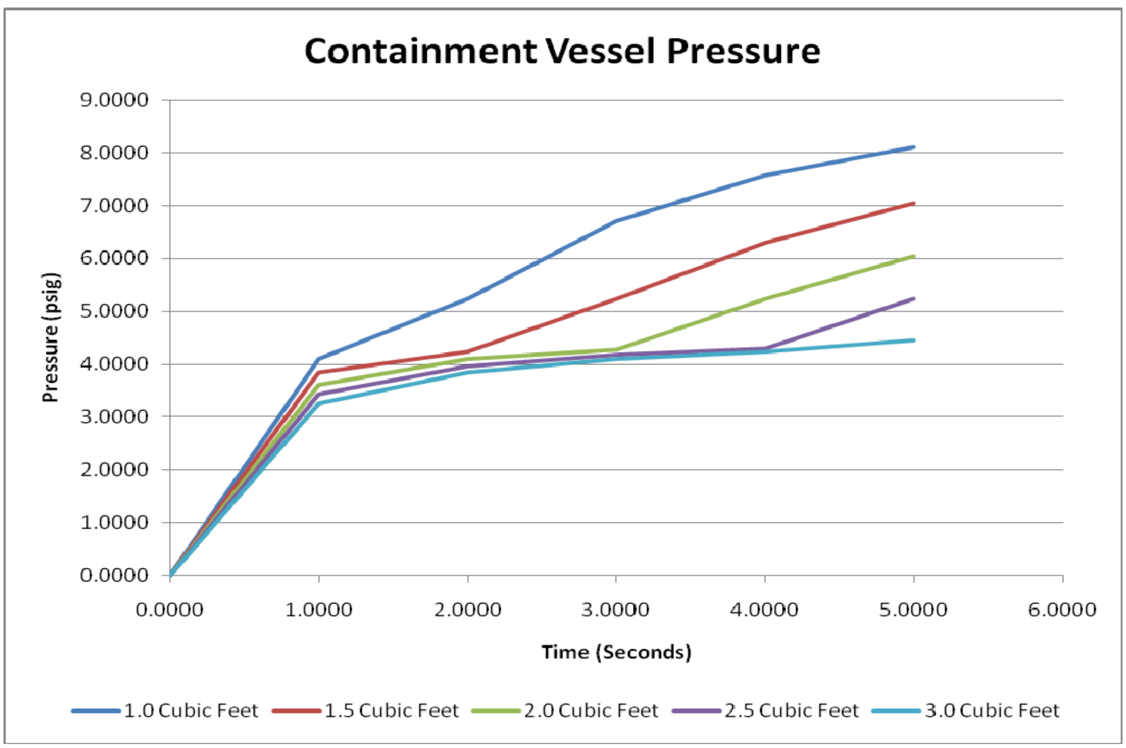

Figure 3: Containment Vessel Pressures – Wide Open Steam Leak

It was found that temperatures and pressures in the vessel rise very rapidly, and that they will approach steam temperature and pressure long before the data acquisition phase is completed for each experimental trial. Hence the decision was made to design the containment vessel to accommodate full boiler temperatures and pressures. It was also determined that for the first few seconds, pressure was primarily controlled by air temperature; later, the saturation pressure of the steam at the vessel temperature was the dominating factor.

Inspection of the graphs also helped the authors determine the optimum size for the containment vessel. The minimum size needed to be such that data acquisition could be performed before equalization of pressures (which would certainly not be expected to occur in the much larger space of a Kraft recovery boiler), but small enough to fit on the cart and to prevent uncovering of the heating elements in the boiler due to excessive steam leakage. From these considerations a volume of approximately two cubic feet was chosen for the containment vessel.

The authors were also interested in how this leak rate compared with the design steam flow rate of the boiler, i.e. the steady rate at which the boiler could supply steam over an extended period of time. To determine this, the design heating load for the boiler was divided by the change in enthalpy of the steam in passing from the subcooled liquid state at room temperature to the vapor state at 10 psig:

$$\text{design steam flow rate} = Q/\Delta h \quad (3)$$

Q = design heating load for boiler (= 30,000 Btu/hr)
Δh = change in enthalpy (at P = 15 psig = 29.696 psia, 30 psia was actually used)

The common approximation [6] for a subcooled liquid was used to determine the enthalpy of the water at room temperature:

$$h_{in} = h_{sat\ liq\ @\ 70\ F} + v_{sat\ liq\ @\ 70\ F}\,(P - P_{sat}) \quad (4)$$

h_{in} = enthalpy of water entering the boiler (subcooled liquid at room temperature)
$h_{sat\ liq\ @\ 70\ F}$ = enthalpy of saturated liquid at 70°F
P_{sat} = saturation pressure for a saturation temperature of 70°F

For inlet and outlet enthalpies of 38.177 Btu/lbm and 1165.89 Btu/lbm, respectively, a design steam flow rate of 26.6 lbm/hr was determined. This was compared to the leak rate of 0.3017 lbm/s = 1086 lbm/hr which was over 40 times the design rate. The authors therefore concluded that the boiler could definitely not keep up with a steam leak on a continuing basis!

The containment vessel design pressure was also used to determine the number of 5/8" bolts required to properly secure the containment vessel lid during the experimental trials. The standard formula shown below, learned by the student authors in the lecture portion of the Senior Capstone Design course and similar to formulas presented in Reference [7], was used:

$$n(S_pA_t - F_i) / CP > 1 \quad (5)$$

S_p = proof strength divided by safety factor
A_t = thread area
F_i = preload force on bolt
C = fraction of external load P carried by bolt
P = external tensile load
n = number of bolts required

The requirement that $n > 1$, so that the bolt stress is less than the proof strength divided by an appropriate safety factor, resulted in a determination that at least 14 5/8" bolts would be required.

Containment Tank Drawing

As stated earlier, it was determined that the containment tank should be approximately 2 cubic feet in volume, and that the lid should be secured by at least 14 bolts. Connections were also required for the incoming steam and an 11 psig relief valve, as well as an opening for the wiring to the acoustic sensors. Based on these considerations, the vessel was designed as shown below:

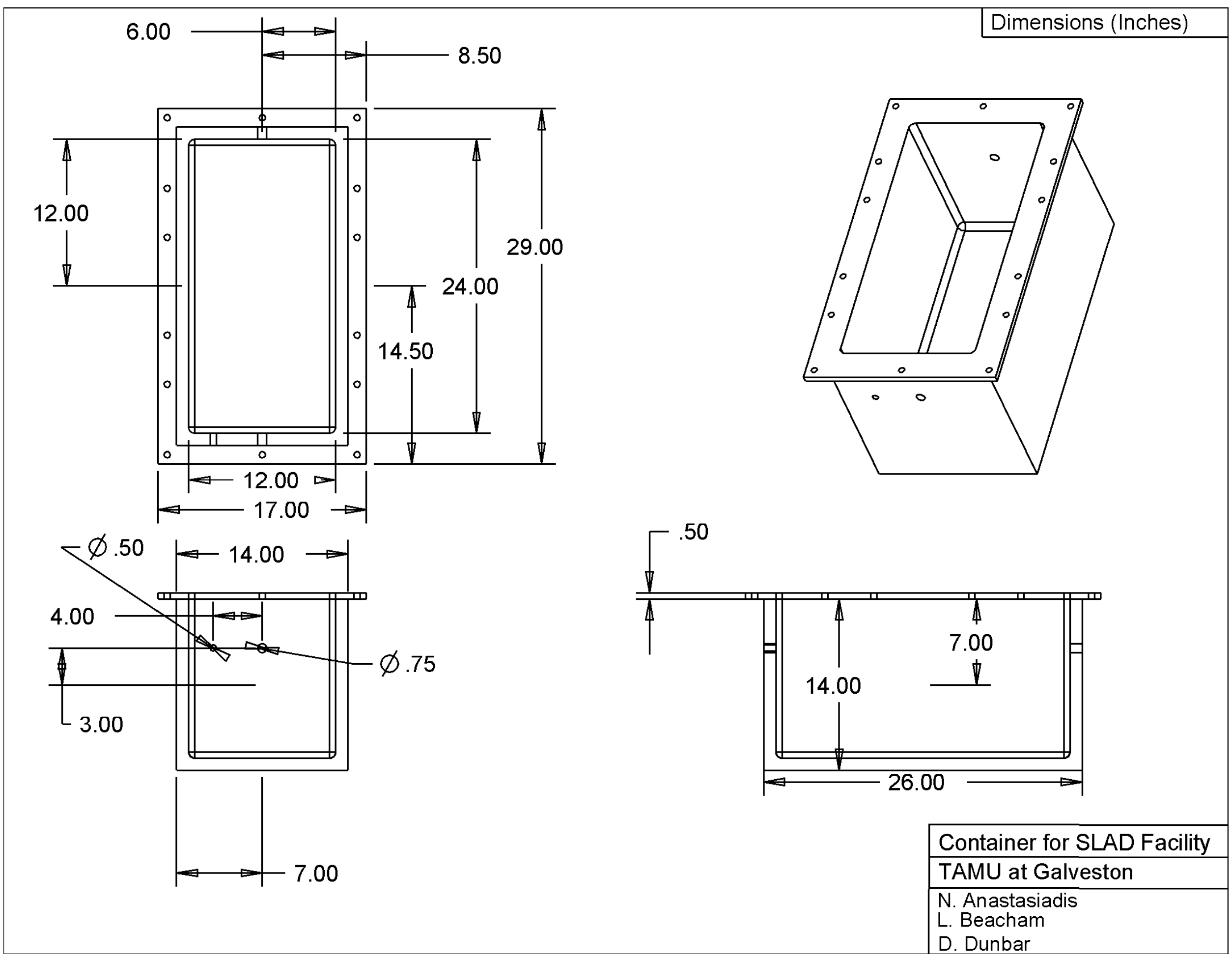

Figure 4: Containment Vessel Drawing

Conclusion

It is hoped that once the acoustic profile of a steam leak is determined using this facility, information will be provided to help engineers in the pulp and paper industries create safety systems to quickly and reliably identify steam leaks and shut down Kraft recovery boilers in the event of these leaks before a major pipe rupture and the resultant damage to the boilers occur, thus preventing financial loss to these industries and, perhaps in extreme cases, human injury as well.

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