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HYDROGEN IGNITION MECHANISM FOR EXPLOSIONS IN NUCLEAR FACILITY PIPE SYSTEMS

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ABSTRACT

Hydrogen and oxygen generation due to the radiolysis of water is a recognized hazard in pipe systems used in the nuclear industry, where the accumulation of hydrogen and oxygen at high points in the pipe system is expected, and explosive conditions exist. Pipe ruptures at nuclear facilities were attributed to hydrogen explosions inside pipelines, in nuclear facilities, i.e., Hamaoka, Nuclear Power Station in Japan, and Brunsbuettel in Germany. Prior to these accidents an ignition source for hydrogen was questionable, but these accidents, demonstrated that a mechanism was, in fact, available to initiate combustion and explosion. Hydrogen explosions may occur simultaneously with water hammer accidents in nuclear facilities, and a theoretical mechanism to relate water hammer to hydrogen deflagrations and explosions is presented herein.

KEYWORDS

Hydrogen, explosions, nuclear facility, power plant safety

SYMBOLS

a	sonic velocity in a pipe, feet / second
g	gravitational constant, feet /second^2
k	ideal gas constant
psi	pounds per square inch
psig	pounds per square inch, gauge
P_1	initial pressure, pounds / inch^2
P_2	final pressure, pounds / inch^2
T_0	ambient temperature, º F
T_1	initial temperature, º F
T_2	final temperature, º F
V	velocity, feet / second
ΔP	change in pressure, pounds / inch^2
ρ	mass density, pound / feet^3

INTRODUCTION

The auto-ignition of a flammable fluid coupled with the pressure surges associated with water hammer provides an explanation of hydrogen detonation in a closed pipe. Similar to the ignition of fuel in a diesel engine, any flammable fluid will ignite when sufficiently compressed. The autoignition temperature is defined as the temperature at which a fluid will spontaneously ignite when left at that temperature for a period of time. For diesel fuel, that time is a few milli-seconds (Kuo [2]). This paper demonstrates that water hammer may cause pressures of sufficient magnitude to ignite trapped hydrogen in pipe systems.

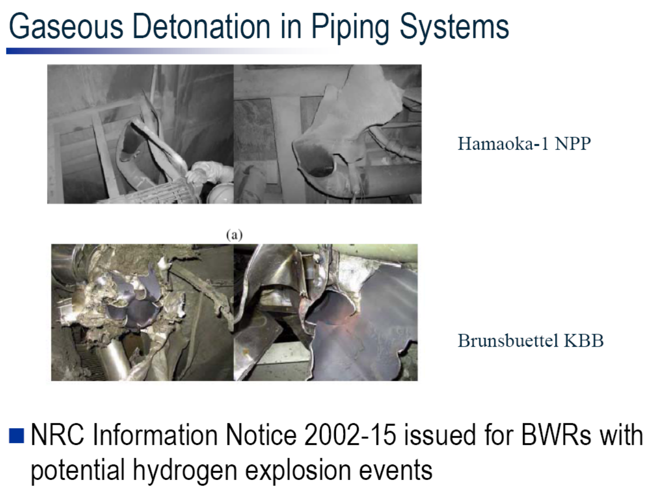

Figure 1: Hydrogen Explosion Damage in Nuclear Facilities (ASME, Task Group on Impulsively Loaded Vessels, Bob Nickell)

To date, the detonation mechanism discussed here has not been presented in the literature, but the elements of detonation are potentially present in nuclear facility systems. In nuclear facilities, the radiolysis of water generates hydrogen, which accumulates at high points in pipe lines. If water hammer occurs while hydrogen is trapped in the pipe, pressures and temperatures increase. If the temperature increases to the ignition point, the hydrogen gas may detonate and explode. The quantity of hydrogen required to initiate an explosion, rather than a deflagration, is outside the scope of this paper. A brief discussion of autoignition is followed here by consideration of pressure increases due to water hammer, and the resultant adiabatic temperature increase to the ignition temperature.

ANALYSIS

Autoignition

The time for hydrogen ignition and ignition temperature require further investigation, but the ignition temperature for hydrogen is approximately 1060º – 1170º F (Lindeburg [3], Kuo [2]). To demonstrate that explosions are probable, the primary requirement is to show that pressures are of sufficient amplitude to cause the gas to reach the ignition temperature.

The equations for the adiabatic expansion of a gas provide this relationship between pressure and temperature, such that

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \qquad (1)$$

where T_1 and P_1 are the initial temperature and pressure; T_1 and P_2 are the temperature and pressure after compression of the gas; and k equals the ideal gas specific heat ratio (k = 1.4 for hydrogen or air). Using this relationship and pressure transients due to water hammer, the temperature increase during a water hammer event can be estimated. Heat losses through the pipe wall and cooling due to the fluid in the pipe are neglected.

RESULTS

Pressure Surges Due to a Sudden Valve Closure

The pressure surges due to a valve closure in a pipeline can be calculated. To provide a typical example, a flow rate of 107.6 gallons per minute was assumed in 3 inch, stainless steel, schedule 40 pipe. Arbitrary pipe dimensions were selected. A system description and a schematic is provided in Fig. 2. A fluid transient, or water hammer, is assumed to commence when an installed valve is suddenly closed.

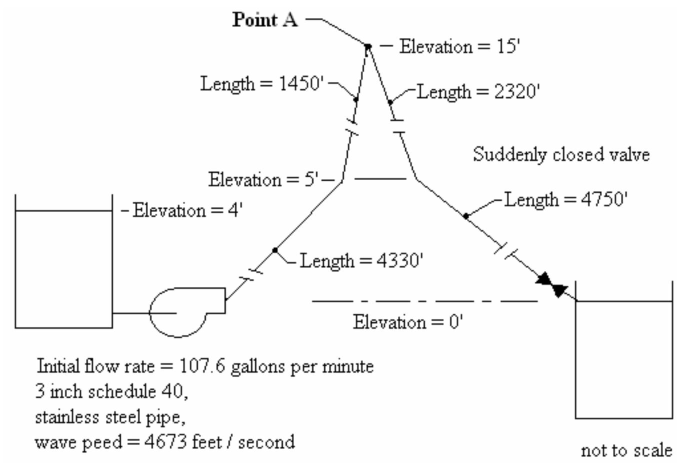

Figure 2: Pipe Schematic

Approximate pressure surges are frequently calculated for pipes flowing full of water, using

$$\Delta P = \frac{\rho \cdot a \cdot V}{g} \qquad (2)$$

where ΔP is the change in pressure due to a sudden change in velocity, V is the initial velocity in the pipe, g is the gravitational constant, and a is the wave speed, which is 4673 feet / second for the 3 " pipe of this example.

However, calculations were performed here for both a pipe full of water and a pipe with 0.52 cubic feet of gas at a high point, point A, in the system, using TFSIM (G. Schohl [4]). Model results are shown in Figs. 3 – 5. Figure 3 and 4 show the pressure history in the pipe at point A, and Fig. 5 shows the volume change of the gas in the pipe. The maximum gas pressures are 286 psig in the pipe regardless of gas volume. How does this gas pressure affect temperatures?

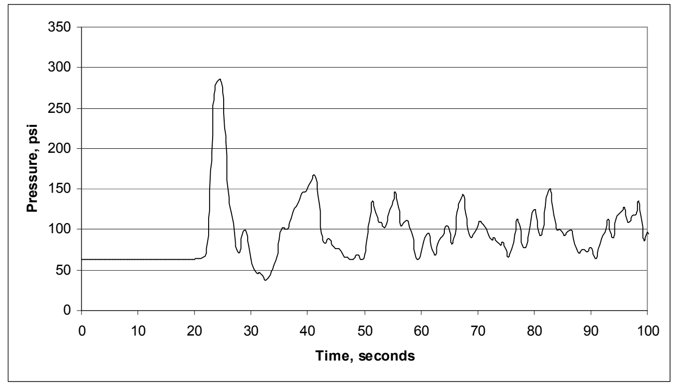

Figure 3: Pressure Surges at Point A Due to a Valve Closure in a Pipe Without Gas Accumulation

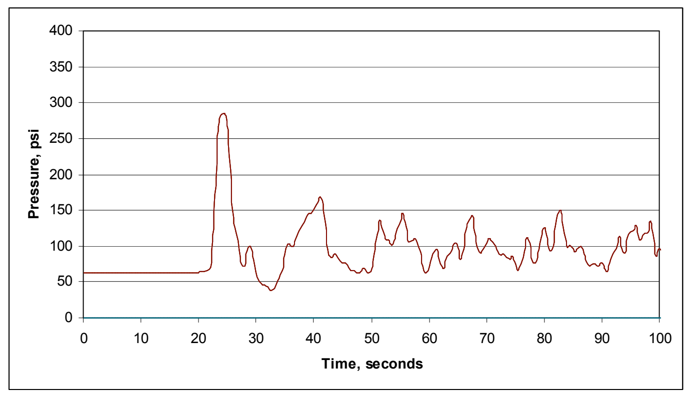

Figure 4: Pressure Surges at Point A Due to Valve Closure in a Pipe With Gas Accumulation

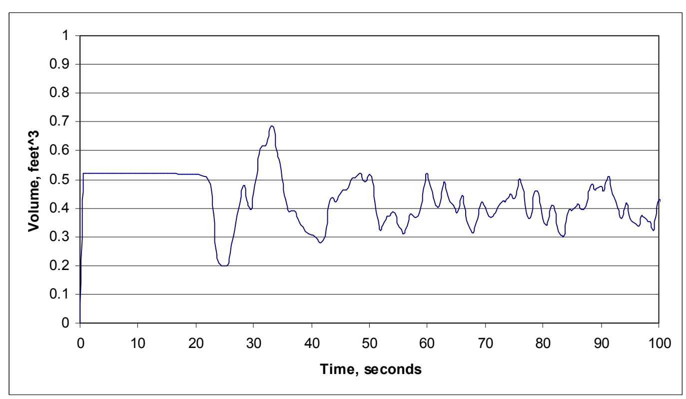

Figure 5: Gas Volume at Point A Due to Valve Closure in a Pipe With Gas Accumulation

Temperature increase due to suddenly closed valves in open loop pipe systems. Continuing this example, and considering only the sudden pressure increase to approximately 286 psig, the temperature increase can be found, such that

$$T_1 = 459 + T_0 \tag{3}$$

$$P_1 = 14.7 \tag{4}$$

where T_0 is an assumed initial temperature of 70º F, neglecting the pressure at the highest point in the pipe, P_1 is the atmospheric pressure

$$P2 = 14.7 + 315 \tag{5}$$

Then

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 529 \cdot \left(\frac{329.7}{14.7}\right)^{\frac{0.4}{1.4}} \tag{6}$$

$$T_2 = 1253º\ R = 794º\ F < 1060º\ F \tag{7}$$

For this example of flow in and an open end, or open loop pipe system subjected to sudden valve closure, pressure surges will not cause pressures sufficient to ignite hydrogen. This calculated temperature is well below the ignition point, and ignition is not expected. Common operating conditions for pipe designs are 6 – 10 feet per second flow rates. At these flow rates, hydrogen ignition is not expected in most open loop systems.

Closed loop pipe systems. However, in closed loop systems, pressure surges may double to cause sufficient pressures for ignition. The situation is different for closed loop systems. When a resonant pipe length exists, the pressures may double the expected pressures for a straight, open loop pipe. This phenomenon has been referred to as rebound, and further discussion is available (Leishear [5]).

Doubling the pressures of the above example,

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 529 \cdot \left(\frac{586.7}{14.7}\right)^{\frac{0.4}{1.4}} \tag{6}$$

$$T_2 = 1517º\ F > 1058º\ F \tag{8}$$

The ignition temperature is exceeded, and detonation is possible.

Dead end branches in pipe systems. Also, branches in pipes provide conditions conducive to ignition. Consider a dead end pipe. For example, consider a tee with a blanked end to prevent flow through the branch, which is connected at the high point of the pipe system used as an example here. As the water compresses, the trapped air compresses, and the pressures are assumed to be comparable in the liquid and the gas. For dead end pipes, the reflected pressure wave may double the incident pressure wave, depending on the length of the pipe (Streeter [6]). Consequently, Eq. 8 also describes the maximum temperature increase for a dead end pipe.

Steam Systems

Condensate induced water hammer in steam systems has been shown to induce pressures in excess of 1000 psi. Condensate induced water hammer occurs when condensate is present in a system, and steam vapor is introduced. The steam moving over the condensate induces waves, which form collapsing vapor bubbles. This vapor collapse results in pressure shock waves throughout that part of the system containing liquid. Also, slugs of liquid may be propelled through the pipe system. Either of these phenomena can result in pressure surges in excess of 1000 psig. Assume a 1000 psig pressure surge in a 150 psig saturated steam system, where the initial condensate pressure and temperature are ambient. Equation 1 becomes

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 529 \cdot \left(\frac{1014.7}{14.7}\right)^{\frac{0.4}{1.4}} = 1774 \tag{9}$$

$$T_2 = 1774^o\ F > 1060^o\ F \quad (10)$$

As another example, consider the H Canyon water hammer incident at a DOE Hanford facolity [7], which occurred in the early 1990's. Although hydrogen was not present in this system, a thorough analysis of the incident was performed and records are available. Pressures were calculated to vary between 1000 and 3000 psig.

Assume a 1400 psi pressure surge occurred in a system, which was originally at ambient conditions. Then,

$$P_1 = 14.7 \quad (11)$$

$$P_2 = 1414.7 \quad (12)$$

Then,

$$T_2 = 1491^o\ F \quad (13)$$

If hydrogen had been present in this system, the autoignition temperature of 1060º F to 1170º F would have been theoretically exceeded.

Pressure surges of these magnitudes should not occur if steam systems are completely drained prior to pressurization to remove condensate. If, however, a steam system is not completely drained, conditions exist for ignition. Steam traps are inadequate protection to prevent condensate induced water hammer.

A common practice to restart steam systems consists of several steps. Typically a pressure regulator controls steam admission to the piping during routine operations. During restart, a smaller bypass valve around the regulator is used to gradually bring the system up to temperature and prevent water hammer. While the bypass valve is operated, downstream valves are opened to blow down the system. Blowdown consists of closing each downstream valve when condensate no longer issues from the valve. Valves are sequentially closed until the valve at the end of each pipe is closed. This technique ensures that large volumes of steam are prevented from inducing vapor collapse throughout the system.

Explosions in Reactor Facilities

The accidents at Hamaoka and Brunsbuettel both occurred during the startup of steam systems. For Brunsbuttel a report is not readily available, but an English translation of a Hamaoka report is available (Naitoh [8]). A maximum pressure was calculated for the Hamaoka incident, which resulted in calculated hydrogen temperatures lower than hydrogen ignition temperatures. However, gas temperature increases due to water hammer were not considered.

Water hammer is a probable cause of the explosion. Water was observed in the pipe following the explosion, at a location where it was expected if water hammer occurred. Water hammer was dismissed as a contributor to the event, since traps were installed on the system. From the report, blowdown was not apparently performed. Since the Hamaoka pipe line in question was removed from service, further evaluation to compare their calculations with the present work may be impossible. However, pressures in excess of 1000 - 3000 psig can be expected in steam system water hammer events, and pressures of this magnitude may result in hydrogen ignition, depending on initial conditions. One of the assumptions of the Hamaoka investigation was that condensate was drained by traps in the system. However, as noted above condensate accumulation is common place in steam systems, unless blow down of the pipe system is performed. Since blow down was not mentioned in the reports, the assumption that condensate was available to induce water hammer is reasonable, and the theory presented here is consistent with observations, where pressures exceeding 1000 psi may occur.

CONCLUSIONS

Can water hammer in liquid filled systems cause hydrogen explosions? There are numerous cases where water hammer can initiate temperatures sufficient to ignite hydrogen gas, although in many cases the answer is no. Temperatures to ignite hydrogen can be generated in both water filled systems and steam systems when condensate is present during startup, if sufficient hydrogen is present in the pipe.

Research is yet required, but an autoignition mechanism for hydrogen explosions has been established for pipe systems in nuclear facilities, where radiolytically generated hydrogen is present in the pipes. Water hammer increases the pressure in the pipe; hydrogen at flammable concentrations heats as it adiabatically expands to its autoignition temperature, and then ignites. The relationship between water hammer mechanisms, the autoignition point of hydrogen in fluid filled pipes, and the quantity of hydrogen needed for detonation require further investigation to fully understand this explosion process.

REFERENCES

1] "Recurring Events", 2003, Nuclear Energy Agency, Committee on Safety of Nuclear Installations, NEA/CSNI/R, 13.
2] Kuo, K. K., "Principles of Combustion", Wiley and Sons, pp. 736 - 742.
3] Lindeburg, 2006, "Mechanical Engineering Reference Manual", Professional Publications, Belmont, California, p. 22-8.
4] Schohl, G., 1998, "User's Manual for Locksim", Tennessee Valley Authority, pp. 1 – 179.
5] Leishear, R. A., "Water Hammer Damage in HTF Chromate Water Cooling Systems", WSRC-TR-2003-00181, pp. 1 – 65.
6] Wylie, B. E., Streeter, V. L., 1993, "Fluid Transients in Systems", Prentice Hall, Upper Saddle River, New Jersey, pp. 1.1 - 4.5.
7] Green, D. J., 1993, "Technical Evaluation: 300 Area Steam Line Valve Accident, Hanford, Richland Washington, pp. 8.1 - 8.22.
8] Naitoh, 2003, "Analysis of Pipe Rupture of Steam Condensing Line at Hamaoka-1", Journal of Nuclear Science and Technology.