A HYDROGEN IGNITION MECHANISM FOR EXPLOSIONS IN NUCLEAR FACILITY PIPING SYSTEMS
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ABSTRACT

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. 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 may occur. Pipe ruptures in nuclear reactor cooling systems were attributed to hydrogen explosions inside pipelines, i.e., Hamaoka, Nuclear Power Station in Japan, and Brunsbuettel in Germany (Fig. 1). Prior to these accidents, an ignition source for hydrogen was not clearly demonstrated, but these accidents demonstrated that a mechanism was, in fact, available to initiate combustion and explosion. A new theory to identify an ignition source and explosion cause is presented here, and further research is recommended to fully understand this explosion mechanism.

KEYWORDS

Hydrogen, explosions, nuclear facility, nuclear reactor, power plant safety, reactor safety, off shore drilling, oil drilling, Gulf oil spill / disaster, Three Mile Island, Chernobyl, Fukushima hydrogen explosions, fluid transients, water hammer, adiabatic compression.

SYMBOLS

a	sonic velocity in a pipe, meter / second (feet/second)
ft	feet
g	gravitational constant
k	ideal gas constant
m	meter
psi	pounds per square inch
$psig$	pounds per square inch, gauge
P_1	initial pressure, MPa (pounds / inch^2)
P_2	final pressure, MPa (pounds / inch^2)
T_0	ambient temperature, º C (º F)
T_1	initial temperature, º K (º R)
T_2	final temperature, º K (º R)
ΔV	change in velocity, meter / second (feet / second)
ΔP	change in pressure, MPa (pounds / inch^2)
ρ	mass density, kg / meter^3 (lbm / in^3)

INTRODUCTION

The autoignition of a flammable fluid coupled with the pressure surges associated with water hammer provides a probable mechanism for hydrogen detonations in closed pipes. 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 milliseconds (Kuo [1]). This paper demonstrates that water hammer may cause pressures of sufficient magnitude to ignite trapped hydrogen in pipe systems.

To date, the detonation mechanism presented here has not been fully discussed in the literature, but the elements of detonation may potentially be present in nuclear facility systems (Leishear [2]). 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 autoignition point, the hydrogen gas may detonate and explode. 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.

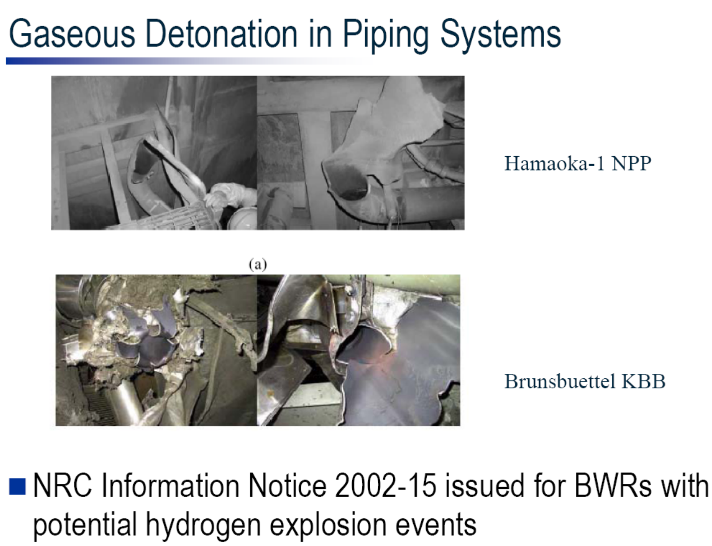

Figure 1: Hydrogen Explosion Damage in Nuclear Facilities (ASME, Task Group on Impulsively Loaded Vessels, 2009, Bob Nickell)

ANALYSIS

Autoignition

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 autoignition temperature. The time for hydrogen ignition and ignition temperature require further investigation.

The equations for the adiabatic expansion of a gas (John [4]) provide a relationship between pressure and temperature, such that

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

where T_1 and P_1 are the initial temperature (°K) and pressure (MPa); T_2 and P_2 are the temperature and pressure after compression of the gas; and k equals the ideal gas constant, which is a ratio of the constant pressure specific heat to the constant volume specific heat (k = 1.4 for hydrogen or air). Using this relationship in the presence of 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. Even though appreciable heat loss may occur through the pipe wall, the time for heat transfer through the wall is expected to minimize heat loss effects on gas temperature increases.

Hydrogen Ignition Temperature. Temperatures for ignition, or deflagration, in a piping system have been shown to depend on pressures, as shown in Fig. 2, which was published following the 50 MPa (7250 psi) Hamaoka explosion investigation (Yamamoto [5]). Numerous other explosions were reported by Yamamoto at Japanese plant locations as indicated in Fig.3, and other hydrogen explosions have been reported due to various causes (Reference [3]). Some caution needs to be exercised here since full details of all explosions are unavailable, and claiming to fully understand each explosion is not claimed here. In fact, Yamamoto proposed a different explosion mechanism, which assumed that cold fusion caused ignition of hydrogen in pipelines. The plausibility of this assertion is not questioned here, but reported explosions typically occur during system start-ups, and the mechanism considered here is related to system start-up whereas cold fusion would be expected to be a random process. Accordingly, the primary purpose of this paper is to propose an explanation of a probable explosion mechanism at system start-up to understand safety implications.

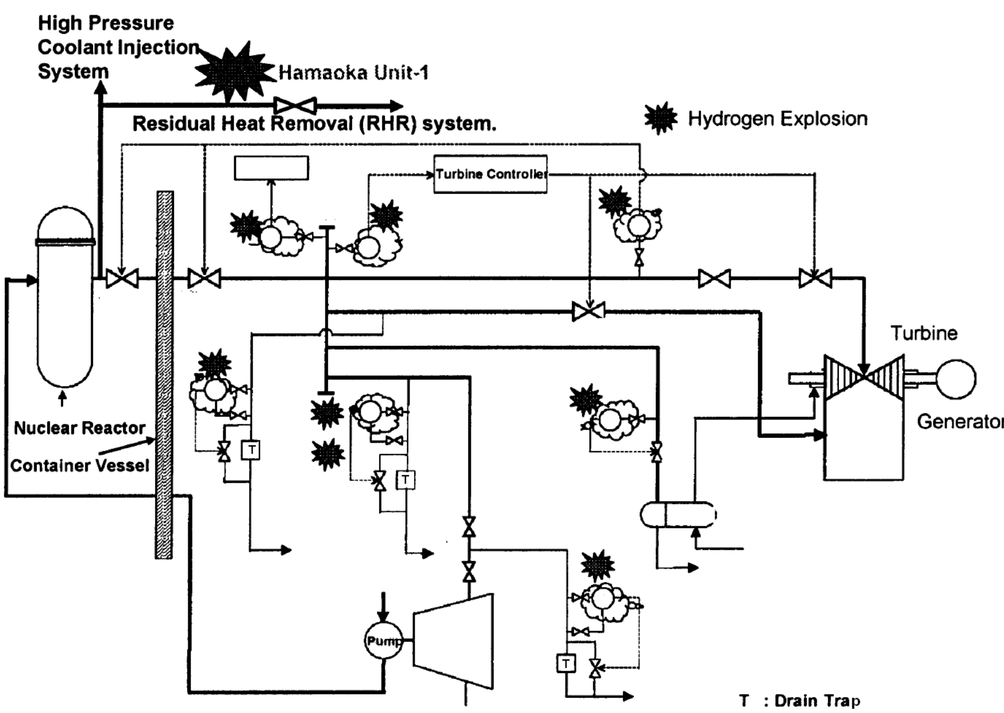

Figure 2: Reported Hydrogen Explosions in Japanese Nuclear Power Plants (Yamamoto [5])

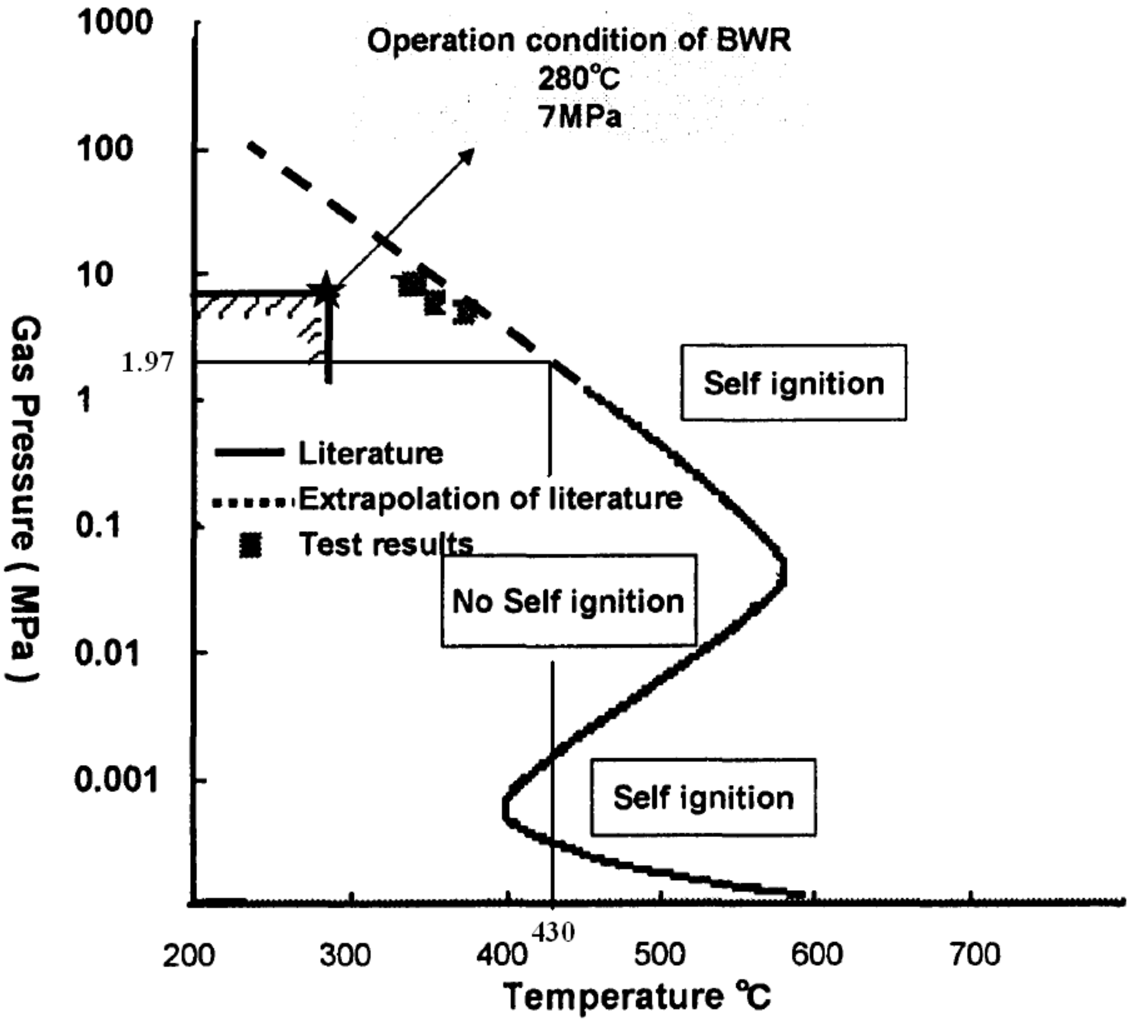

Figure 3: Self Ignition of Stoichiometric Hydrogen and Oxygen Due to Temperature Increases

(Yamamoto [5])

The quantity of hydrogen needed to initiate an explosion, rather than a deflagration, is outside the scope of this paper. In fact, further research is required to even understand the quantity, or cell size, that causes a detonation during fluid transients. Even so, Akbar, et al. [6] have investigated the cell size prerequisite to initiate hydrogen explosion for several combinations of hydrogen and other gases. When deflagration is initiated by a glow plug, a run-up length is required where a flame front progresses through a trapped gas and forms a shock wave at the limiting cell size required for detonation. Akbar et al. concluded that “Chemical kinetic models of the mixtures of interest have been compared to published experimental data and evaluated with respect to limits of validity. No mechanism has been shown to be valid for all the conditions necessary for detonation modeling, although a modified Miller and Bowman (1989) mechanism has been moderately successful". That is, even well controlled experiments have significant variability for the autoignition temperature, and autoignition coupled with fluid transients is even more complex. For the explosion mechanism discussed here, a run-up length is not expected to be applicable. In other work, Mogi, et al. [7] have shown that hydrogen oxygen gas mixtures will ignite when discharged through a tube to atmosphere at supersonic velocities.

RESULTS

Autoignition and Pressure Surges Due to a Sudden Valve Closure

The pressure surges due to a valve closure in a pipeline can be calculated, and the resulting temperatures can be compared to the autoignition temperature of a gas. To provide a typical example, a flow rate of 407.3 liters per minute (107.6 gallons per minute) was assumed in 0.076 meter (3 inch), stainless steel, Schedule 40 pipe. Arbitrary pipe dimensions were selected. A system description and a schematic are provided in Fig. 4. A fluid transient, or water hammer, was assumed to commence when an installed valve was suddenly closed.

Approximate pressure surges are frequently calculated for pipes flowing full of water ((Joukowski [8]), using

$$\Delta P = \rho \cdot a \cdot \Delta V / g \tag{2}$$

where ΔP is the change in pressure due to a sudden change in velocity, which may be caused by a valve closure a pump shut-down, or a vapor cavity collapse in a liquid; ΔV is the initial velocity in the pipe; and a is the wave speed. The wave speed, a, equals the sonic velocity in a pipe, which decreases as the pipe wall thickness increases to compensate the energy losses associated with expanding the pipe wall. That is, the shock wave loses energy and slows down, when energy is used to expand the pipe wall. For this example, the wave speed equals 1424 m/second (4673 feet / second) for the 0.076 meter (3 inch) diameter, Schedule 40 pipe.

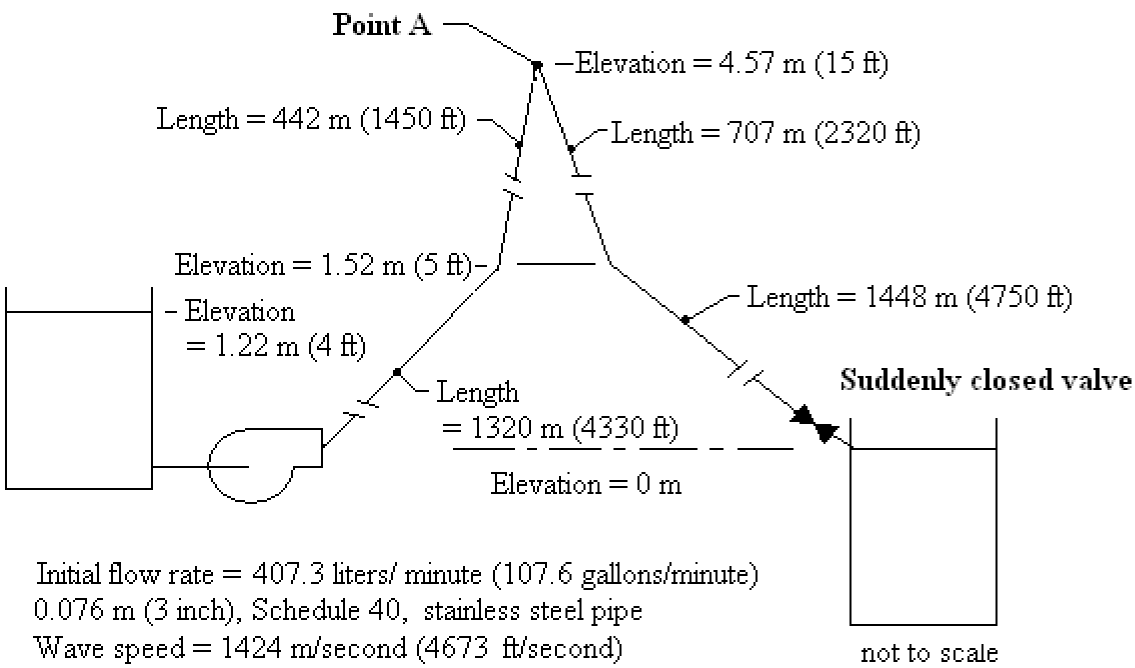

Figure 4: Pipe Schematic

However, calculations were performed here for both a pipe nearly full of water with 14.7 liters (0.52 cubic feet) of gas at a high point in the system at point A, using TFSIM (G. Schohl [9]). The TFSIM model is a computer program based on the method of characteristics, which is a widely accepted and experimentally validated simulation technique for fluid transients in liquid filled systems (Wylie and Streeter [10]). The method of characteristics is a technique used to transform partial differential equations into total differential equations that are, in turn, transformed into finite difference equations to be numerically solved using computer codes. Boundary conditions may then be introduced into the codes to represent closed end pipes, pumps, operating valves, and trapped vapors or gases.

Variations in the air volume, flow rates, and elevations in the pipe system significantly affect the dynamic response of the air volume. For the given conditions, model results are shown in Figs. 5 and 6. Figure 5 shows the pressure history in the pipe for the highest elevation at point A, and Fig. 6 shows the volume change of the gas in the pipe at that point. The calculated maximum gas pressure is 1.97 MPa (286 psig) in the pipe. How does this gas pressure increase affect temperature?

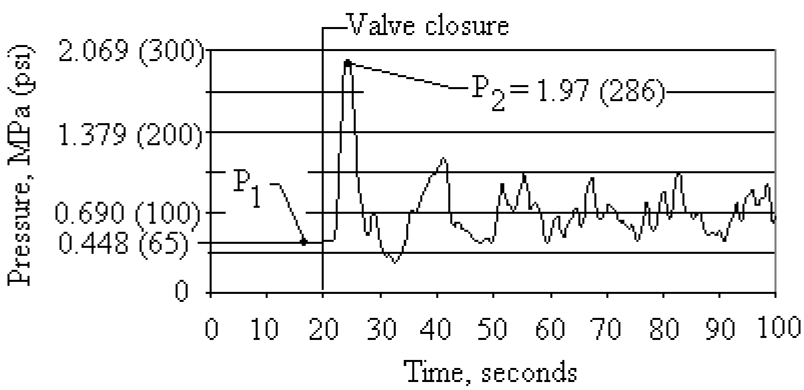

Figure 5: Pressure Surges at Point A Due to Valve Closure in a Pipe With Gas Accumulation

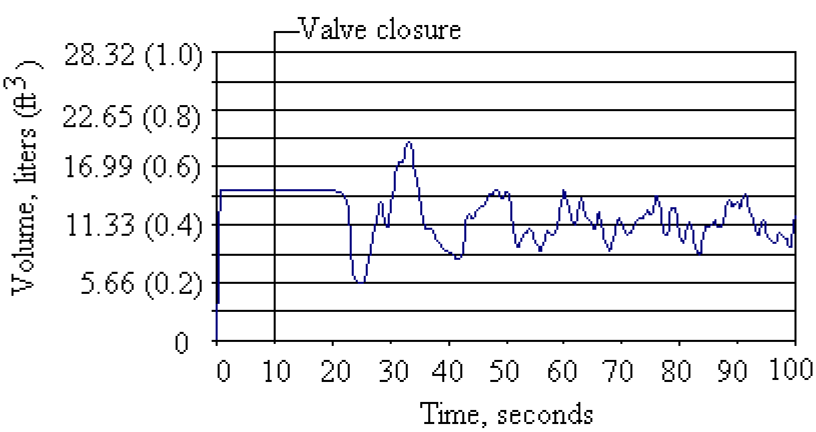

Figure 6: Gas Volume at Point A Due to Valve Closure in a Pipe With Gas Accumulation

Temperature increase due to a suddenly closed valve in an open loop pipe system. Continuing this example, and considering the sudden pressure increase from 0.448 MPa (65 psig) to approximately 1.97 MPa (286 psig), the adiabatic temperature increase can be found as follows. The absolute temperature equals

$$T_1 = 273°K + T_0 \tag{3}$$

and P_1 is the initial pressure shown in Fig. 5 plus atmospheric pressure, such that

$$P_1 = 0.101MPa + 0.448MPa = 0.549MPa(14.7\,psi + 65\,psi = 79.7\,psi) \tag{4}$$

T_1 is an assumed initial temperature of 21.1° C (294.1° K), and P_2 is the final pressure in the pipe shown in Fig. 5 plus atmospheric pressure, where

$$P_2 = 1.97+0.101=2.071\ MPa = (14.7+286 = 300.7\ psi) \tag{5}$$

Then the final temperature of the gas equals

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 294.1°K \cdot \left(\frac{2.071MPa}{0.549Mpa}\right)^{\frac{0.4}{1.4}} = 429.8°K = 156.8°C \tag{6}$$

To compare this temperature to the autoignition temperature, a range of approximate autoignition temperatures for hydrogen was obtained as 571° C to 632.2° C (1060° F - 1170° F) (Kuo [1]). Also, note from Fig. 2 that the autoignition temperature for a stoichiometric mixture of hydrogen and oxygen is approximately 430° C (806° F) at 1.97 MPa. Depending on the volumes of the two gases, stratification of hydrogen and oxygen may cause the autoignition temperature to vary between these values (430° C to 571° C). Water vapor may also affect the autoignition temperature. Further research is recommended, but the two values of 430 and 571 are used to assess autoignition, such that

$$T_2 = 156.8^{\circ}\ \mathrm{C} < 430\ ^{\circ}\mathrm{C} < 571\ ^{\circ}\mathrm{C} \tag{7}$$

The calculated maximum temperature is below the ignition point, and ignition is not expected for this example. For this example of flow in an open end, or open loop, pipe system subjected to sudden valve closure, pressure surges should not cause pressures sufficient to ignite hydrogen. However, for other combinations of pressure and temperature, the autoignition temperature may be exceeded in liquid filled systems.

Steam Systems

Condensate induced water hammer (condensate water hammer) in steam systems has been shown to induce pressures well in excess of 1000 psi, and may create conditions conducive to autoignition if a flammable gas is present. For example, consider the H Canyon water hammer incident at a DOE Hanford facility (Green [12]), which occurred in the early 1990's. Although hydrogen was not present in this example system, a thorough analysis of the incident was performed and records are available. Pressures were calculated to vary between 1000 and 3000 psig, due to slug flow in the system.

Condensate water hammer occurs when condensate is present in a system, and steam vapor is introduced. Two types of condensate water hammer are discussed here. First, 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. Second, slugs of liquid may be propelled through the pipe system. Either of these phenomena can result in pressure surges in excess of 6.9 MPa (1000 psig).

As an example of autoignition, assume a 6.9 MPa pressure surge due to slug flow in a steam system containing condensate, water vapor, and trapped hydrogen and oxygen at initial atmospheric conditions. As steam is introduced to pressurize the system, water vapor condenses, and the pressure is exerted on the gas volume. Neglecting some dynamic effects, Equation 1 then becomes

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} = 294.1°K \cdot \left(\frac{6.9MPa}{0.101MPa} \right)^{\frac{0.4}{1.4}} = 983.2°K = 710°C \tag{8}$$

$$T_2 = 710.2^{o}\ C > 571^{o}\ C > 430\ ^{o}\ C \tag{9}$$

Autoignition is expected for this example. However, the dynamic effects of slug impact on the vapor space can affect the temperature increase as the air volume compresses and expands. The quantities of gas and steam vapor in the pipe at start-up will also affect pressure magnitudes. With respect to hydrogen generation, the amount of hydrogen and oxygen dissociated from water in a closed pipe depends on the amount of water present, the time of exposure to a radioactive source, and the energy of that source. All of these factors require further research.

Preventing Water Hammer in Steam Systems

Pressure surges of large magnitude should not occur if steam systems are completely drained to remove condensate prior to pressurization. If, however, a steam system is not completely drained, conditions may 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. Blow down 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. If water hammer is prevented, ignition of gases will be prevented.

Explosions in Reactor Facilities

The accidents at Hamaoka and Brunsbuettel both occurred during the startup of steam systems. For Brunsbuettel a report is not readily available, but an English translation of a Hamaoka report is available (Naitoh [13]). A maximum pressure was calculated for the Hamaoka incident, which resulted in calculated hydrogen temperatures lower than hydrogen ignition temperatures. However, gas temperature increases and gas ignition due to water hammer were not considered.

Water hammer is a possible 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. 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.

FUTURE WORK

Proof of Principle

Research needs to be performed to experimentally demonstrate the explosion mechanism discussed here.

1. Although the basic physics of an explosion mechanism has been clearly demonstrated, the complexities of the explosion process need validation and further study.
2. The effects of fluid transients on hydrogen compression processes in a pipe also require investigation.
3. To further understand the transient process, autoignition temperatures as a function of the compression cycle time and hydrogen volume also require investigation.

Once the mechanism for autoignition is validated, other factors need consideration to investigate the explosion process.

1. What temperatures, pressures are required for autoignition?
2. How does the rate of pressure change affect the autoignition temperature?
3. How much hydrogen needs to be present for autoignition?
4. How much hydrogen needs to be present for deflagration to detonation transition?
5. What is the maximum pressure achieved following detonation?

Possible Cause of Other Reactor Explosions

In addition to providing a probable cause for explosions at the Hamaoka and Brunsbuettel reactors, there are other potential applications of this theory to explosions at reactors. This mechanism may be related to pipe explosions at the Fukushima Daiichi disaster (2011), but investigations are still on-going for that facility. In fact, internet reports state that hydrogen was formed in the reactor cooling system piping following reactor meltdown, and the system was then flooded with water, which are two of the conditions needed to cause detonation (a fluid transient and trapped flammable gas). Even the nuclear accidents at Three Mile Island (1979) and Chernobyl (1986) may be related to this explosion mechanism. This mechanism was unknown when these accidents were analyzed, and was therefore not considered. However, internet reports available through Wikipedia note that condensate induced water hammer and hydrogen were both present when explosions occurred during those accidents. When reactor accidents occur, the intuitive response is to flood the system and reduce temperatures. However, this action may lead to detonation of trapped gases (according to the theory presented here), while a slower addition of cooling water could prevent a sudden temperature increase of the trapped gas to autoignition. In other words, the response to overheating may have been the cause of explosions. Again, conditions to cause the explosions were present (a fluid transient and trapped flammable gas), and theory presented here may explain the cause of those explosions.

Possible Cause of Explosions and Fires at Off-shore Oil Drilling Platforms

Also, explosions at off shore oil well drilling platforms may be explained with this theory. During off-shore drilling, explosions frequently occur in pipe lines, and this theory provides a reasonable explanation of explosions and fires at oil drilling platforms. Natural gas bubbles of significant size occasionally fill pipeline sections at the time of explosions. Consistent with the theory presented here, if oil comes up the pipe behind the bubble, the bubble can compress, heat up, ignite, and explode under some conditions. That is, the slug of oil in front of the bubble slows down as the slug behind the bubble speeds up to compress the gas. "Swish, Run, Boom" is the operator response for explosions and fires according to internet reports. Swish is the sound that would be heard if there was an explosion in the pipe under water as liquid rushes through the pipe toward the platform. The operators would have had little time to run before the exploding gas pushed the oil out of the pipeline up to the platform where the operators were stationed. At the drilling platform explosive shock waves can form at the pipe exit as the flaming gas exits onto the platform. This mechanism is a possible cause of the explosion at the Gulf oil spill disaster (2010) and hydrogen explosions at Fukushima reactors following earthquakes and reactor damages. As an analogy, consider two moving vehicles. If the engine is turned off on only the vehicle in front, the other vehicle will strike it from behind, and the further apart they are at the time of turning off the engine, the more violent the impact. For the case of oil slugs in a pipe, one slug is pressurized by the well, while the other can slow down. The trapped gas between the slugs will act as a spring as the two slugs converge and pressurize the gas. Depending on the change in flow rates, autoignition may be reached. Further research is recommended to investigate the discovery of this new theory.

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 if sufficient hydrogen is present in the pipe in both water filled systems during transients and steam systems during start-up. If sufficient flammable gas has accumulated in the system at the time that a fluid transient occurs, gas detonation is probable.

Research is yet required, but an autoignition mechanism for hydrogen explosions has been established here for pipe systems in nuclear facilities, when radiolytically generated hydrogen may be 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 and may explode. The relationship between water hammer mechanisms and gas volumes, the autoignition point of hydrogen in fluid filled pipes, and the quantity of hydrogen or gas needed for detonation require further investigation to fully understand this explosion process. This discovery of an explosion mechanism in pipe systems may even be related to explosions in the Gulf oil spill disaster, the Three Mile Island nuclear accident, Fukushima Daiichi explosions, and the

Chernobyl nuclear accident. Given the significant safety implications of this new theory, further research is warranted to further investigate and experimentally demonstrate the discovery of this theory.

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