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To: U. S. Nuclear Regulatory Commission
NRC: Generic Issues Program

PRE-GI-015,

HYDROGEN FIRES AND EXPLOSIONS IN NUCLEAR REACTORS, 11/29/2014

EXECUTIVE SUMMARY

In my opinion, the possibility of hydrogen explosions in nuclear reactors should be further considered with respect to safe nuclear reactor operations. Based on a new reactor fire and explosion theory that I invented, a nuclear reactor fire has been shown to be coincident to the reactor meltdown at Three Mile Island (TMI) and other piping explosions in offshore nuclear reactor facilities. Additionally, hydrogen fires and explosions at Chernobyl and Fukushima Daiichi are likely to have had similar causes. In other words, the United States, Soviet Union, and Japanese governments considered the risks of nuclear reactor meltdowns to be negligible since the possibilities of meltdowns were considered to be incredible, but each of these countries experienced reactor meltdowns, where explosions or fires also occurred. This new information for the hydrogen burn at Three Mile Island demands a stand-alone NRC safety evaluation through the Generic Issues Program. In addition to a safety evaluation, additional research is recommended to investigate the intricacies of reactor explosions and possible actions to prevent explosions in the event of a nuclear accident. As concluded in my ASME article on the Three Mile Island fire and meltdown, "If the causes of reactor explosions and fires were unknown for decades, the implications of this new theory are certainly not understood. Reactor explosions can be stopped to improve nuclear reactor safety, prevent deaths, and prevent environmental disasters."

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DISCUSSION

To document this opinion, I have written a technical article for the American Society of Mechanical Engineers (ASME), Mechanical Engineering Magazine, which was published in the December 2014 edition, titled "From water hammer to ignition, the spark that ignited Three Mile Island burst from a safety valve", by Robert A. Leishear (See Attachment 1). This article culminates the latest in a series of publications that I have written to present new theory to describe explosions in nuclear reactors and off-shore oil rigs. Recently my concern was partially addressed when I filed a concern through allegations@nrc.gov. NRC staff provided technical references that were used to write the referenced ASME magazine article. This article discusses my explosions and fire research, and the article focuses on the reactor accident at Three Mile Island, Pennsylvania. This theory is also applicable to accidental explosions in Brunsbuettel, Germany; and Hamaoka, Japan, See "A Hydrogen Ignition Mechanism for Explosions in Nuclear Facility Piping" (See Attachment 2 and NRC 2002-15). This theory can probably be related to the explosions at Fukushima Daiichi and Chernobyl, if more information were made available. See "Explosions: a fresh look at Chernobyl, Three Mile Island, Fukushima Daiichi and the Gulf Oil Spill" (See Attachment 3). Explosions can be stopped.

As discussed in the referenced ASME magazine article, fires and explosions are ignited in piping or pressure vessels when trapped gases are compressed by changing fluid flow rates that cause the gases to compress and autoignite, similar to ignition in a diesel engine. This ignition process is rather complicated in nuclear reactor systems, where trapped hydrogen and oxygen can ignite during fluid transients. For the Hamaoka and Brunsbuettel explosions, the transients were caused during system operations when flow rates suddenly changed and high pressures were induced. The Three Mile Island accident hydrogen fire occurred during water additions to the reactor system. The explosion at Fukushima occurred during water additions. The explosion at Chernobyl has been labeled a steam explosion, but more information may, in fact, disclose that water additions occurred at the time to cause that explosion. The common denominator for multiple reactor fires and explosions is the generation of hydrogen and / or oxygen coupled with fluid transients, i.e., optimal conditions for fires and explosions were present in each of these accidents. Issues of such consequence should be considered by the NRC.

SAFETY ISSUES

This issue of reactor fires and explosions may affect the public health, safety and environment. In particular, previous NRC issues were closed without benefit of this new information.

1. NUREG-0933: Safety analyses for the Three Mile Island accident did not include this new information, where slower reactor response following the accident could have caused an explosion rather than a fire in the reactor building. Specifically, the TMI fire could have led to an explosion if more hydrogen was released from the reactor meltdown or water hammer and ignition had occurred prior to homogeneous mixing of air with hydrogen in the reactor containment building. Risks to the public should also be evaluated in light of this new information.
2. NUREG-0933: Resolution of Generic Safety Issues: Item A-48: Hydrogen Control Measures and Effects of Hydrogen Burns on Safety Equipment (Rev. 1): The new information provided herein was unavailable at the time that this report oh hydrogen deflagration was issued, and this new information may affect the findings of NUREG-0933, where the possibility of a hydrogen explosion should be further considered
3. NRC Bulletin, BL 2011-01: This new information may affect mitigating strategies, since the “Events at the Fukushima - Daiichi Nuclear Power Station following the March 11, 2011, earthquake and tsunami highlight the potential importance of … mitigating strategies in responding to beyond design basis events.” According to the Tokyo Electric Power Co., “Fukushima Nuclear Accident Analysis Report”, 2012, the cause of ignition for reactor explosions was unknown, and in my opinion the research presented herein is likely pertinent to those explosions. Additionally, an explosion of unknown origin and location was also noted by TEPCO, where this ignition mechanism may have caused a reactor explosion.
4. NUREG-927: Water hammer events may be affected by hydrogen and oxygen accumulation in piping. In fact, past water hammer events could have very well been accompanied by hydrogen and oxygen explosions in reactor piping.

Other NRC documents are also impacted, and a comprehensive review to determine all affected documents should be performed during a Generic Item investigation. When previous accident scenarios and damages were analyzed, risks were calculated using frequencies and consequences that have been affected by this new information.

RECOMMENDED RESEARCH

A brief review of NRC documents and the new information provided herein mandates the need for a Generic Item, but additional research should be considered to address several important issues.

1. Operator responses to prevent explosions during off-normal conditions need to be established. Slower addition of water to a reactor system during off-normal operations may prevent explosions in reactor piping.

2. Flow conditions to cause ignition require further analysis to assist fire and explosion prevention. The fundamental theory has been clearly defined, but different scenarios for condensate induced water hammer and valve closures during operations have not been fully evaluated.
3. Temperature and pressure conditions to induce ignition should be evaluated, since the autoignition temperature and ignition are affected by these parameters.
4. Hydrogen and oxygen quantities should be related to piping ruptures, i.e., how much trapped gas will explode the piping?
5. Hydrogen and oxygen may be vented and burned off before significant flammable accumulations occur, but the rate of gas generation and venting may need to be investigated during meltdowns or other off-normal operations. If flammable gases are hammered before adequate venting, explosions in the piping may occur.
6. Fukushima Daiichi explosions warrant further investigation with respect to this new information.
7. Chernobyl warrants further investigation with respect to this new information, but accident data is unavailable.
8. Of coincidental interest, water hammer should be investigated as a possible contributing cause to nozzle failures, where reflected pressure waves near the reactor will magnify the dynamic effects of the pressure waves in the coolant piping (See "Fluid Mechanics, Water Hammer, Dynamic Stresses and Piping Design" by R. A. Leishear, ASME Press 2013). Several NRC reports note nozzle failures, where thermal cycling is the cited cause of fracture. Water hammer, or explosions in piping systems cause pressure waves which travel at sonic velocities throughout the system. Where a transition in pipe diameter occurs at nozzle / pressure vessel interfaces, most of the pressure wave is reflected and the reflected pressure adds to double the pressure magnitude near the reactor. This phenomenon will exacerbate any thermal cycling stresses in the fatigue failure process of nozzles.

Comprehensive research has not been performed to date for this new information, since research and safety evaluations on this issue have not been supported. The Savannah River National Laboratory, a DOE contractor, referred me to the NRC. The NRC referred me to Grants.gov, where the National Science foundation (NSF) administers research funding. The NSF declined explosions research, and referred me to DOE. This research is also pertinent to explosions at off-shore oil rigs, where research has been declined by the Bureau of Science and Environmental Enforcement. Research to date has been performed on my own time at my own expense. I believe these issues to be significant, but all government contacts to date point to some other organization to fund research. In addition to further safety analysis in conjunction with a Generic Issue, additional research is imperative to fully understand reactor fires and explosions.

MD 6.4, GENERIC ISSUES COMPLIANCE, DT-09-14

In my opinion this new information meets the requirements to be evaluated by the Generic Issues program, where screening criteria are addressed below.

The GIP will address only those issues that meet the following criteria. A proposed GI or a GI that does not meet any of these criteria at any time will not be processed further by the GIP.

(a) The issue affects public health and safety, the common defense and security, or the environment.

The fact that reactor explosions were not understood until this new information on reactor fires and explosions was published certainly has potential impact on reactor safety and the environment, since risks were evaluated in the absence of this information.

(b) The issue applies to two or more facilities and/or licensees/certificate holders, or holders of other regulatory approvals.

This issue has potential application to many reactor facilities.

(c) The issue cannot be readily addressed through other regulatory programs and processes; existing regulations, policies, or guidance; or voluntary industry initiatives.

Existing NRC regulations have not addressed this new information

(d) The issue can be resolved by new or revised regulation, policy, or guidance.

Licensees can be directed to evaluate their facilities and safety analysis with respect to this identification of a new explosion hazard.

(e) The issue's risk or safety significance can be adequately determined (i.e., it does not involve phenomena or other uncertainties that would require long-term studies and/or experimental research to establish the risk or safety significance).

Uncertainties with respect to fires and explosions may be determined since TMI has been identified to have been a past explosion hazard. Additional research is recommended, but the issue is sufficiently defined for the NRC to take action. Generic Issues that have already been closed are called into question by this new information, and safety implications should be addressed.

(f) The issue is well defined, discrete, and involves a radiological safety, security, or environmental matter.

Safety and environmental impacts of an explosion versus a fire at TMI can be clearly defined.

(g) Resolution of the issue may potentially involve review, analysis, or action by the affected licensees, certificate holders, or holders of other regulatory approvals.

Review and analysis will be required by affected licensees.

ATTACHMENT 1: ASME, MECHANICAL ENGINEERING MAGAZINE, DECEMBER 2014.

Three Mile Island Nuclear Power Plant »

Unit 2 of the Three Mile Island power plant in Pennsylvania (below, left) suffered a partial meltdown and fire in 1979. The fire cause is attributed to water hammer, which caused compression and ignition of flammable gases. Unit 1 (right) has continued operations.

FROM WATER HAMMER

It can be hard to get even scientifically minded people to reexamine their conclusions; change is hard to hold on to.

I have been working toward acceptance of a new theory of mine concerning accidental combustion in nuclear facility and oil industry pipelines. The theory has safety implications for any pipeline where explosive gases can form in liquid filled systems, and is consistent with pipeline accidents in nuclear power plants, such as Three Mile Island. I suggest that this theory is certainly worthy of further study.

THE SPARK THAT IGNITED THREE MILE ISLAND BURST FROM A SAFETY VALVE.

TO IGNITION

BY ROBERT A. LEISHEAR

I wrote to the U.S. Nuclear Regulatory Commission and suggested that the theory had direct application to the hydrogen burn that followed a nuclear reactor meltdown in Unit 2 at Three Mile Island. The agency thanked me and politely said I was mistaken. They also sent me a report published under the designation GEND-INF-023, "Analysis of the Three Mile Island Unit 2 Hydrogen Burn." It was prepared for the Department of Energy by J.O. Henrie and A.K. Postma of the Electric Power Research Institute.

Studying this document convinced me that the chain of events proved my theory that accidental combustion in a pipeline caused a dangerous fire at Three Mile Island. The facts presented in the report support conclusions that water hammer and trapped gases in a pipeline ignited the hydrogen burn at TMI-2. In fact, different responses by reactor operators could have even resulted in an explosion at Three Mile Island.

The partial meltdown at TMI-2 began at about 4:00 a.m. on March 28, 1979. According to the Nuclear Regulatory Commission, a series of mechanical failures, design flaws, and human errors resulted in a loss of coolant to the reactor.

TMI-2 was one of two pressurized water reactors at Three Mile Island. In pressurized water reactors, the controlled nuclear reaction among the fuel rods heats water, which is pressurized to more than 2,300 pounds per square inch so that it does not boil.

The pressurized water circulates in a closed loop called the primary cooling system. The primary system transfers heat to the secondary system, another closed loop of circulating water, which converts water to steam to run the turbines.

A third system of circulating water cools the steam in the secondary system as it exits the turbines and condenses it to water, which is recycled to boil again. The third system is open to cooling towers and takes water from the river. At no point do the three systems share water with each other.

A meltdown may be defined as extreme overheating of fuel rods in a nuclear reactor core. In the case of TMI-2, cooling water flowed out of the reactor core through a valve, referred to as the pilot-operated relief valve, which was stuck in the open position. As the reactor core was uncovered, its shield of water boiled away, the zirconium cladding of the fuel rods ruptured, and fuel pellets wrapped in the cladding melted. Half the core melted at temperatures above 4,200 °F during the early stages of the accident, but an uncontrolled nuclear reaction or criticality accident did not occur.

During the meltdown, the primary reaction to form hydrogen occurred when zirconium cladding reacted with steam to form 126,000 cubic feet of hydrogen. At this time, there was not enough oxygen present to burn the hydrogen in the reactor, since four percent oxygen is required to maintain a flame in hydrogen, and free oxygen does not form in the zirconium-steam reaction.

The only reaction that formed oxygen for ignition inside the reactor was that due to radiolysis. During radiolysis, radioactivity separates water into oxygen and hydrogen molecules. There may, or may not, have been a minimal amount of oxygen in the reactor during the meltdown, but there were no reported indications of major fire or explosion in the reactor at that time.

The steam bubbling from the molten reactor core and the newly formed hydrogen increased the reactor system pressure. Due to the pressure increase, steam and most of the hydrogen were then vented from the reactor into the reactor building through a safety valve, which was distinct from the stuck valve that initiated the meltdown. Hydrogen and air then mixed in the building to create flammable conditions.

Later that morning, operators forced water into the reactor core, which cooled, stopping the meltdown and the formation of hydrogen from the zirconium. In less than three hours, the meltdown was under control even though operators were unaware that a meltdown was in progress.

A fire was waiting to happen. Air in the unoccupied reactor building had thoroughly mixed with 703 pounds of hydrogen released from the reactor for approximately seven hours after the meltdown was brought under control. All that was required was a flame to start the fire.

Henrie and Postma's report detailed the complex chain of events that resulted in the release and subsequent burning of hydrogen in the reactor building. Nearly ten hours after the accident started, a hydrogen fire occurred without explosion in the reactor containment building. The report did not, however, identify an ignition or spark source for the fire.

My ignition theory states that the sudden compression of trapped flammable gases due to fluid transients, or water hammer, in pipelines may heat the gases sufficiently to autoignite them, similar to the combustion of fuel with air compressed in a diesel engine. In other words, slugs of liquid squeeze an oxygenated combustible gas until it gets hot enough to burn or explode. I outlined the theory in a paper, "A Hydrogen Ignition Mechanism for Explosions in Nuclear Facility Piping Systems," published by the ASME *Journal of Pressure Vessel Technology* in 2013 (135(5), 054501).

TO VALIDATE MY THEORY SEVERAL CONDITIONS NEEDED TO BE PRESENT, AND THOSE CONDITIONS WERE, IN FACT, PRESENT AT THE TIME OF THE BURN.

1. Hydrogen and oxygen needed to be present in the piping. Henrie and Postma acknowledged that the radioactive breakdown of water, or radiolysis, occurred during the accident. Once the zirconium-hydrogen reactions stopped during meltdown, and the hydrogen was released to the reactor building, the only continuing source of hydrogen in the piping was radiolysis. Hydrogen and oxygen formed as the melted fuel pellets radioactively decomposed water in contact with the exposed reactor fuel. When radiolysis occurs, sufficient oxygen is formed to support a fire or explosion in the presence of an ignition source.

2. Water hammer had to occur in the piping. Flowing steam and water were simultaneously present in the primary system at the time of ignition. Conditions were right for water hammer. Condensate-induced water hammer occurs when water and steam flow together in piping systems. Steam vapor bubbles, or steam voids, collapse to induce sudden pressures of thousands of pounds per square inch as shock waves resonate the piping system. Water hammer behavior is detailed in my book, *Fluid Mechanics, Water Hammer, Dynamic Stresses, and Piping Design*, published by ASME Press.

3. Piping near the relief valve should increase in temperature as the hydrogen and oxygen in the piping burns or explodes. Henrie and Postma acknowledged this temperature increase.

4. The ignition source of the fire had to occur at the safety valve in the reactor building. Henrie and Postma stated that the fire started near the safety valve at the time that the safety valve opened.

In short, water hammer started a fire or explosion in the primary system piping by compressing hydrogen and oxygen. The piping near the safety valve increased in temperature immediately prior to the hydrogen burn, which is consistent with an explosion or fire in the piping. Increasing pressures then opened the safety valve to start the fire in the reactor building.

Approximately seven hours after the meltdown was brought under control, the safety valve opened at 13:49, and a flame front fired from the reactor piping into the reactor building. That is, a flame shot from the safety valve into the building filled with hydrogen and air. The resulting 1,400 °F fire was detected by pressure increases at 13:50; one minute after the safety valve opened. In other words, the safety valve opening was nearly coincident to the time that the burn started.

All of the reported facts are consistent with the new ignition theory. More than 35 years after the accident, the cause of the Three Mile Island fire has an explanation.

"WATER HAMMER IN PRIMARY SYSTEM PIPING IGNITED HYDROGEN AND OXYGEN. THE SAFETY VALVE THEN OPENED AND STARTED THE FIRE IN THE REACTOR BUILDING."

Hydrogen and Oxygen From Steam »

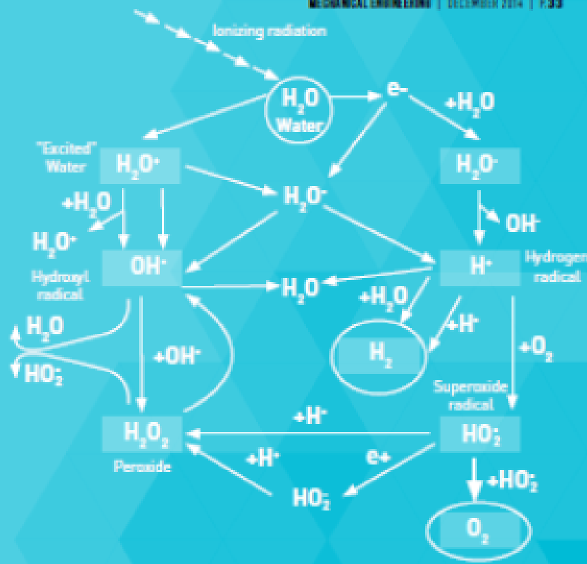
The oxidation of zirconium with steam was a principal source of the hydrogen that burned at Three Mile Island. According to an international Atomic Energy Agency document, IAEA-TECDECDOC-1661, the primary reaction to create 85 to 90 percent of the hydrogen during a meltdown is expressed by:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2\,H_2 + \Delta H,$$

where ΔH is the energy released during the chemical reaction.

The remaining 10 to 15 percent of hydrogen may be caused by oxidation of steel in the core. The IAEA study was rather uncertain on this point.

Radiolysis is considered to be a minor initiator of hydrogen during and after pressurized water reactor meltdowns. However, radiolysis is the only identified initiator of free oxygen inside the reactor. The reactions during radiolysis are rather complex, but are shown at right. Essentially, water plus radiation yields hydrogen plus oxygen.



A complex series of reactions produces the end result of radiation splitting water into hydrogen and oxygen.

Why is further research required? The NRC documented extensive actions to improve reactor safety after the Three Mile Island accident, but this new ignition theory has yet to be fully evaluated with respect to off-normal reactor operations in the U.S. and abroad. Several nuclear reactor fires and explosions warrant consideration.

This fire-and-explosion theory is consistent with past piping explosions at nuclear reactors in Brunsbuettel, Germany, and Hamaoka, Japan, where eight-inch diameter steel pipes shredded like paper firecrackers. When my theory was first published, the causes of German piping explosions were unknown, but later reports concluded that water hammer probably caused the explosions. The Japanese piping was removed from service.

With respect to Three Mile Island, there was no explosion in the containment building during the accident, since 99.4 percent of the hydrogen had already burned. Only half of the reactor core was affected by the meltdown. Slower reaction times by operators could have destroyed the entire core and more than doubled the hydrogen in the reactor building. This additional hydrogen may have been sufficient to cause an explosion rather than a fire. Following the TMI-2 accident, unburned hydrogen was safely vented from the reactor building to the atmosphere by reactor operators. The hydrogen burn was contained in the reactor building.

Hydrogen burns were not so well contained, however, at Fukushima Daiichi in Japan. Several hydrogen explosions accompanied meltdown caused by a tsunami that damaged nuclear reactors. During this reactor accident, radioactive clouds blasted into the air from hydrogen explosions that devastated nuclear reactor buildings.

Mild winds then dispersed the radioactive contamination across the surrounding Japanese countryside, where 300,000 residents were evacuated. Some accident details of these Japanese explosions are available from the Tokyo Electric Power Co. (*Fukushima Nuclear Accident Analysis Report*, 2012), and the conditions to apply this new ignition and combustion theory to these explosions were present. Specifically, for two of the reactors, at the time of explosions sea water was abruptly added to reactor cores experiencing meltdown accidents. That is, water hammer was potentially applied to hydrogen in the pipelines to ignite flames, which in turn could have entered the reactor buildings to initiate explosions of hydrogen. If the sea water had been added at a slower rate, perhaps the explosions could have been prevented.

The Japanese report neglected the ignition source of the explosions. Neither the Tokyo Electric Power Co., the International Atomic Energy Agency, nor the Japanese Atomic Energy Agency answered correspondence with respect to this nuclear safety and environmental concern.

Nuclear reactor accidents deserve further investigation, since reactor fires and explosions were ignited by sources that were reported to be unknown. This new theory confirms a source of ignition.

If the causes of reactor explosions and fires were unknown for decades, the implications of this new theory are certainly not understood. Reactor explosions can be stopped to improve nuclear reactor safety, prevent deaths, and avoid environmental disasters. ME

ROBERT A. LEISHEAR, an ASME Fellow, is a fellow engineer at Savannah River National Laboratory, and a member of the ASME B31.3 Process Piping Design Committee. His book, *Fluid Mechanics, Water Hammer, Dynamic Stresses, and Piping Design*, was published by ASME Press in 2013.

ATTACHMENT 2: ASME JOURNAL OF PRESSURE VESSEL TECHNOLOGY, SEPT. 2013.

A HYDROGEN IGNITION MECHANISM FOR EXPLOSIONS IN NUCLEAR FACILITY PIPING SYSTEMS PVT-11-1024

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ABSTRACT

Hydrogen explosions may occur simultaneously with fluid transients accidents in nuclear facilities, and a theoretical mechanism to relate fluid transients 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. A similar explosion mechanism is also possible in oil pipelines.

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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, fluid transients , 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, ° C (° F)
T_1	initial temperature, ° K (° R)
T_2	final temperature, ° K (° 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 fluid transients provides a probable mechanism for flammable gas 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 fluid transients may cause pressures of sufficient magnitude to ignite trapped hydrogen in pipe systems, and also briefly discusses a similar condition in oil pipelines.

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 fluid transients occurs while hydrogen is trapped in the pipe, gas 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 fluid transients, and the resultant adiabatic temperature increase to the ignition temperature.

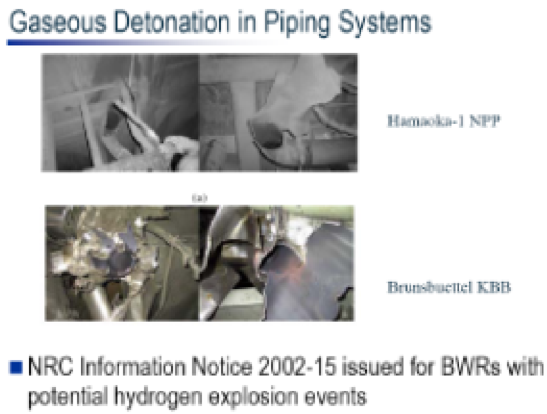

Figure 1: Hydrogen Explosion Damage in Nuclear Facilities (ASME, Task Group on Impulsively Loaded Vessels, 2009, Bob Nickell)

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 hydrogen autoignition temperature. The time to reach hydrogen autoignition and the dynamic effects on the autoignition 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

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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 fluid transients, the temperature increase during a fluid transient 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.

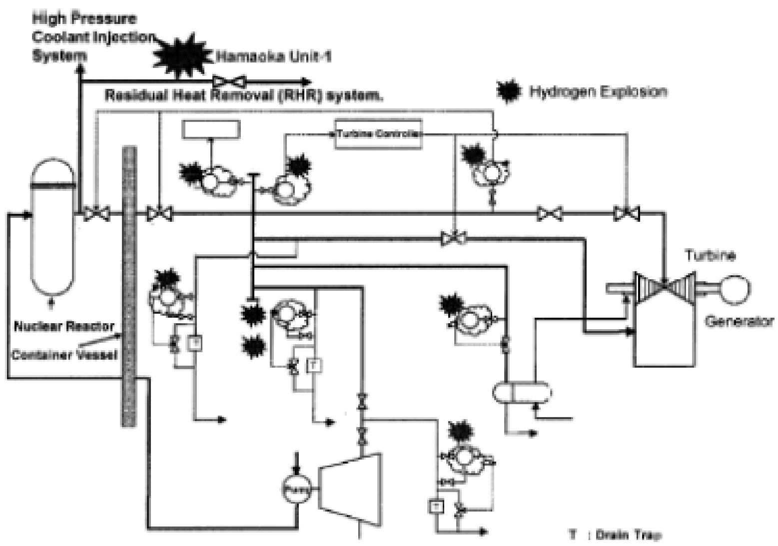

Figure 2: Reported Hydrogen Explosions in Japanese Nuclear Power Plants (Yamamoto [5])

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.

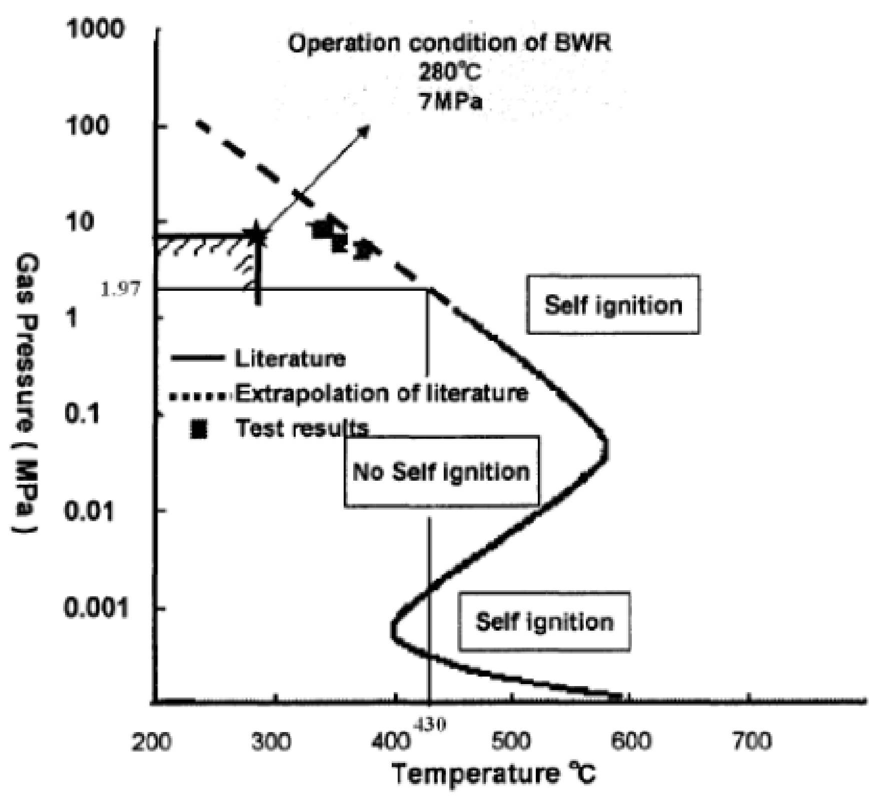

Figure 3: Self Ignition of Stoichiometric Hydrogen and Oxygen Due to Temperature Increases

(Yamamoto [5])

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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. In short, thereare numerous complexities associated with hydrogen autoignition.

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.

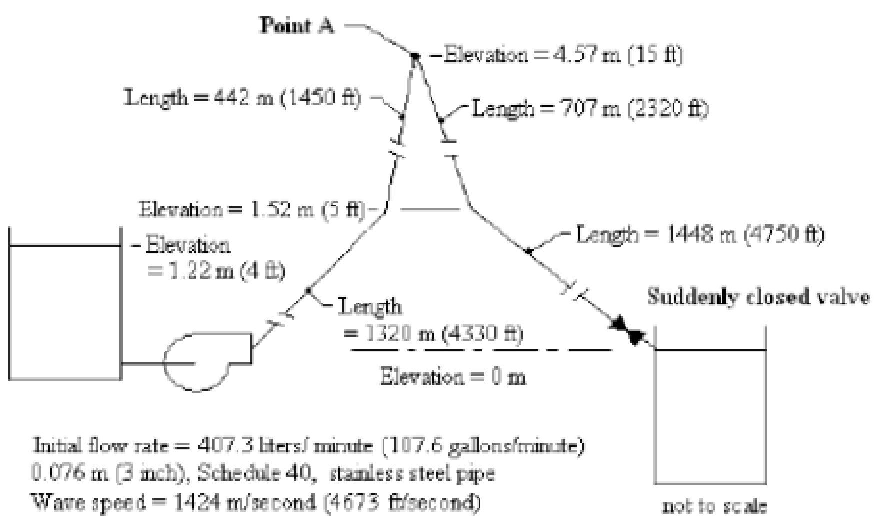

Figure 4: Pipe Schematic

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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?

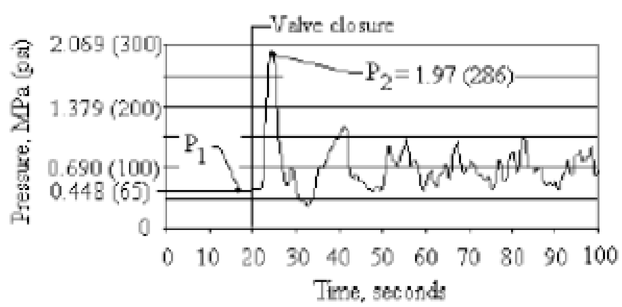

Figure 5: Pressure Surges at Point A Due to Valve Closure in a Pipe With Gas Accumulation

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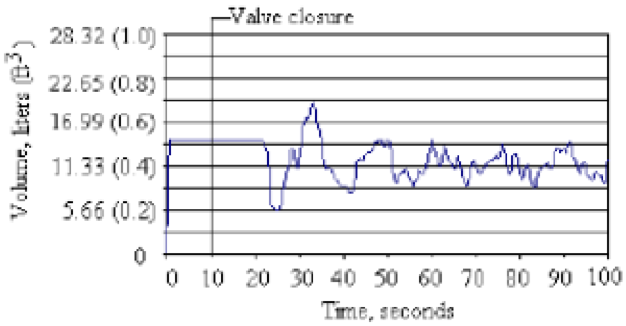

Figure 6: Gas Volume at Point A Due to Valve Closure in a Pipe With Gas Accumulation

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

$$T_1 = 273°K + T_0$$

(3)

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

$$P_1 = 0.101MPa + 0.448MPa = 0.549MPa(14.7psi + 65psi = 79.7psi)$$

(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

$$P_2 = 1.97+0.101=2.071\ MPa = (14.7+286 = 300.7\ psi)$$

(5)

Then the final temperature of the gas equals

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

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(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

$$T_2 = 156.8° \text{ C} < 430 ° \text{ C} < 571 ° \text{ C} \quad (7)$$

The calculated maximum temperature is below the autoignition 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. In short, all fluid transients will not induce explosions, but some conditions can cause explosions.

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 fluid transient 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 to assess system pressures during fluid transients. 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

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

$$T_2 = 710.2°\,C > 571°\,C > 430\,°\,C \tag{9}$$

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 and explosion, 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, the amount of hydrogen consumed by other reactions in the system, and the final energy of explosive source. All of these factors require further research.

Preventing Fluid Transients 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 autoignition. 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 fluid transients. While the bypass valve is operated, downstream valves are opened to blowdown 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. If fluid transients are 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 fluid transients were not considered.

Fluid transients were a possible cause of the explosion. Water was observed in the pipe following the explosion, at a location where it was expected if fluid transients occurred. Fluid transients were 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 condensate 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 blowdown of the pipe system is performed. Since blowdown was not mentioned in the reports, the assumption that condensate was available to induce fluid transients are reasonable, and the theory presented here is consistent with observations, where pressures exceeding 1000 psi may have occurred.

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 and explosive force 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 and oxygen needs to be present for autoignition?

4. How much oxygen is consumed during other reactions, and what effect does the percentage of oxygen have on the autoignition temperature?
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 following earthquake and Tsunami damages 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 partially related to this explosion mechanism. This mechanism was unknown when these accidents were analyzed, and was therefore not considered. However, internet reports note that condensate induced fluid transients and hydrogen were both present when explosions occurred during those accidents, although it is not clear from reports if fluid transients and explosions were simultaneous. The coincidence of explosive conditions and observed explosions bears further consideration.

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. A more appropriate response would be to add cooling water at a slower rate following a reactor accident, but this addition rate (or valve opening speed) requires further investigation for different operating conditions.

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

Also, explosions at off shore oil well drilling platforms may be consistent 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. Flammable 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).

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 fluid transients in liquid filled systems cause hydrogen explosions? There are numerous cases where fluid transients can initiate temperatures sufficient to ignite flammable gas, although in many cases the answer is no. Temperatures to ignite flammable gas can be generated if sufficient flammable gas 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. fluid transients 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 fluid transient 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 was also extended here to possible explosion mechanisms in oil pipelines and major nuclear reactor accidents. That is, this explosion mechanism may 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 investigate and experimentally demonstrate the discovery of this theory.

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ATTACHMENT 3: MENSA WORLD JOURNAL, DECEMBER 2013.

mensa world journal

EXPLOSIONS: *a fresh look at Chernobyl, Three Mile Island, the Gulf Oil Spill and Fukushima Daiichi*

by Robert A. Leishear, PhD, P. E.

There is a probable relationship between explosions in pipelines during well publicized industrial accidents, which include, but are not limited to, Chernobyl, Three Mile Island, Fukushima Daiichi, and the Gulf Oil Spill (the Macondo Well). To relate these accidents in nuclear reactor facilties and deep sea oil pipelines, a new theory was invented to explain explosions in industrial pipe systems.

This innovative fluid dynamics theory was first presented at the 2010, American Society of Mechanical Engineers (ASME), Pressure Vessels and Piping Division Conference and published in more detail in the August, 2013, ASME Mechanical Engineering Magazine ("Pipeline Explosions, A New Theory", 2013, R. A. Leishear) and in the October, 2013, ASME, Journal of Pressure Vessel Technology ("A Hydrogen Ignition Mechanism for Explosions in Nuclear Facility Pipe Systems", R. A. Leishear). The theory states that if a pipe contains a flammable gas, and that if there is an inrush of liquid into the piping or gas filled space, the gas can compress and heat up to its auto-ignition point (similar to a diesel engine). Then the gas ignites and may explode if there is a sufficient quantity of gas.

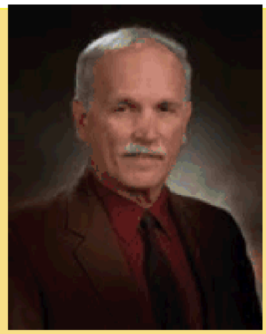
Accordingly, numerous industrial explosions share several common factors: 1) Fluid transients were known to occur, 2) Trapped flammable gases were known to collect in the piping, 3) Fluid transients can cause sudden pressure changes to above 1000 psi which are sufficient to auto-ignite flammable gases, and 4) Explosions in pipelines occurred with causes that are not yet well understood. In short, conditions at each of these accidents were consistent with this new theory, and the theory provides probable explanations for explosions that occurred during these accidents and many other less publicized fires and explosions.

For example, during explosions in nuclear reactor cooling systems, flammable hydrogen gas first forms in the piping systems. Then, a fluid transient due to intentional flooding of the system, or another cause, can compress the gas to ignition and explosion. One method to prevent this type of explosion is to change the rate of water addition. By adding cooling water more slowly to a gas-laden piping system, the pressures and temperatures may be reduced to prevent gas ignition.

During explosions in oil pipelines, flammable natural gas may be compressed to ignition between slugs of oil piped from below the sea floor to oil rigs at the surface, where slugs of oil traveling at different flow rates trap and compress the flammable gases.

"Swish, run, boom" is a common refrain reported by oil rig personnel during fires and explosions. "Swish" describes the sound heard from oil accelerating up toward an oil rig after ignited, exploding gas propels the oil slug upward in the pipeline. "Run" describes the time available to the operators to escape before the fiery explosion "Booms" at the oil rig.

Significant safety and environmental implications of this new theory warrant additional research. Even though financial support for research is presently unavailable, this discovery of major threats to public safety and the environment certainly demands further investigation and prevention.



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