

Three Mile Island Nuclear Power Plant »

Unit 2 of the Three Mile Island power plant in Pennsylvania (below, left) suffered a partial meltdown and explosion in 1979. Explosion causes are attributed to water additions to the molten core that ignited flammable gases, and water hammers that compressed and ignited flammable gases. Unit 1 (right) has continued operations.

This paper was revised on 3/21/2022 to add important new findings with respect to explosions. In the initial publication of this article, fires were incorrectly assumed to have occurred rather than explosions at TMI-2, but additional research has since proved that several explosions occurred at TMI-2. The long-term cover up of explosions resulted in several errors in the initial publication of this article by the ASME Mechanical Engineering Magazine. The TMI-2 cover up is documented in "Nuclear Power Plants Are Not So Safe: Fluid Transients/Water Hammers, Autoignition, Explosions, Accident Predictions and Ethics". ASME declined an offer to publish these new findings.



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.

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

TO IGNITION

BY ROBERT A. LEISHEAR

in the TMI-2 piping and reactor building. Furthermore, an initial explosion occurred at the reactor core prior to final explosions, which occurred outside of the reactor pressure vessel.

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 over-heating 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

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 explosion 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 and explosion

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 largest reaction to form hydrogen occurred when zirconium cladding reacted with steam to form 126,000 cubic feet of hydrogen. Later, the only oxygen present to burn the hydrogen was formed when water was added to the core to ignite, where four

percent oxygen is required to maintain a flame in hydrogen, and free oxygen does not form in the zirconium-steam reaction.

That is, the only reaction that formed significant oxygen for ignition inside the reactor was that due to thermolysis. During thermolysis, high temperatures separate water into oxygen and hydrogen molecules. Oxygen and hydrogen form from thermolysis at the reactor core during water additions following a meltdown to ignite an explosion at the reactor core along with a possible steam explosion.

Newly formed hydrogen and steam - and an explosion in the molten reactor core - increased the reactor system pressure. Due to this 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, and stopped the meltdown and formation of hydrogen from zirconium. In less than three hours, the meltdown was under control even though operators were unaware that a meltdown was in progress.

An explosion 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 ignite the explosion.

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. Several hydrogen explosions occurred in the reactor containment building. The report did not, however, identify an ignition or spark source. However, recent ignition theory explains these power plant explosions.

Specifically, my ignition theory states that:

1) The sudden compression of trapped flammable gases due to fluid transients, or water hammers, in pipelines heat flammable 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 explode inside pipes and act as an ignition source for the reactor building. I detailed the theory in a paper, "The Autoignition of Nuclear Reactor Power Plant Explosions," published by the *ASME Journal of Nuclear Engineering and Radiation Science* in 2019.

2) Water additions to molten fuel during reactor meltdowns ignite explosions (Water Hammers Exploded the Nuclear Power Plants at Fukushima Daiichi, *ASME Journal of Nuclear Engineering and Radiation Science* in 2022, R. A. Leishear.).



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 radiolysis but not thermolysis occurred during the accident, where both processes are a radioactive breakdown of water.

The extent of hydrogen and oxygen generation from thermolysis compared to radiolysis is undetermined. However, radiolysis is assumed to be negligible with respect to thermolysis for TMI-2.

Prior to piping and building explosions, hydrogen and oxygen formed as the melted fuel pellets thermolytically and radioactively decomposed water in contact with the exposed reactor fuel. When thermolysis occurred, sufficient oxygen was formed to support an explosion in the presence of an ignition source. An initial explosion(s) at the core would have depended on the rate at which fuel initially entered water in the reactor pressure vessel, and an explosion(s) ignited when water was later added to the core, where steam may have exploded simultaneously at the core. Subsequent explosions in the piping due to unburned oxygen and hydrogen from thermolysis depended on water hammer.

Following water-fuel explosions and piping explosions, hydrogen from zirconium-hydrogen reactions at the core released hydrogen to the reactor building for subsequent detonations.

2. Water hammer had to occur in the piping. In addition to hydrogen and oxygen, 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 more than a thousand 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 explodes. Henrie and Postma acknowledged this temperature increase.

4. The ignition source had to occur at the safety valve in the reactor building.

Henrie and Postma stated that a fire started near the safety valve at the time that the safety valve opened, however, this research proved that an explosion occurred at the safety valve.

In short, water hammer started an 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 explosion, which is consistent with an explosion in the piping. Increasing pressures then opened the safety valve, and exiting heated gas ignited the residual gas in the 36 inch diameter safety valve piping. The ignited hydrogen and oxygen in the piping then blasted down the piping and out through a ruptured safety valve in a connected drain tank that was emptied from previous explosions. The hydrogen then flamed into the reactor building to ignite the large volume of hydrogen waiting to be ignited. Essentially, the spark blasted from the safety valve to ignite the explosion.

That is, 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. Subsequent to the explosions, a resulting 1,400 °F temperature of burned gases was detected by the next measured pressure increase 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 explosion blasted into the reactor building.

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 »

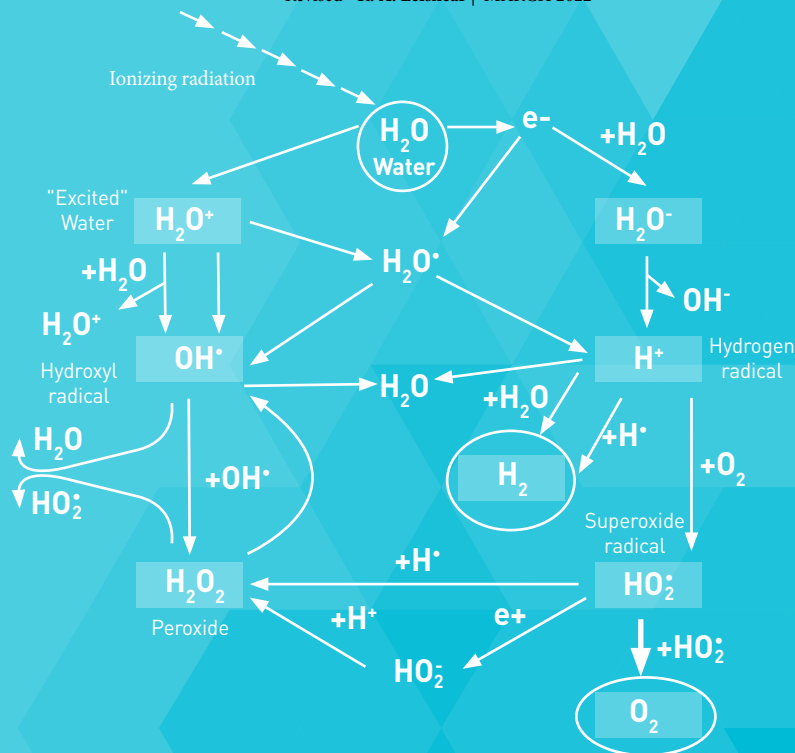
The oxidation of zirconium with steam was a principal source of the hydrogen that burned at Three Mile Island. According to an international Atomic Energy Agency document, IAEA-TECDOC-1661, the primary reaction to create 85 to 90 percent of the hydrogen during a meltdown is expressed by:



where ΔH is the energy released during the chemical reaction.

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

Radiolysis is considered to be a smaller initiator of hydrogen during and after pressurized water reactor meltdowns, where radiolysis is one identified initiator of free oxygen inside the reactor. The reactions during radiolysis are complex, and are shown at right, where combustion and thermolysis are complicated. Essentially, water plus radiation yields hydrogen plus oxygen for both radiolysis and thermolysis, where a combination of these processes occurs when water is added to molten fuel. At present, thermolysis, is considered to be the primary explosive source during water additions. 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 explosion theory is consistent with past piping explosions at nuclear reactors in Brunsbüttel, Germany, and Hamaoka, Japan, where six-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, several explosions occurred in the containment building during the accident, and 99.4 percent of the hydrogen burned. This additional hydrogen was sufficient to cause an explosion rather than a fire.

Only half of the reactor core was affected by the meltdown. Slower reaction times by operators could have destroyed the entire core, could have more than doubled the hydrogen in the reactor building, and could have caused damages similar to the damages at Fukushima Daiichi.

Following the TMI-2 accident, unburned hydrogen was safely vented from the reactor building to the atmosphere by reactor operators. The hydrogen explosions were contained in the reactor building and reactor core.

Hydrogen explosions were not so well contained, however, at Fukushima Daiichi in Japan. Several hydrogen explosions accompanied meltdowns 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 three of the reactors, at the time of explosions water was abruptly added to reactor cores experiencing meltdown accidents to cause those explosions. Subsequently, water hammers ignited another hydrogen explosion, or explosions, which in turn exploded into the reactor buildings to initiate large atmospheric explosions of hydrogen. If the water had been added at a slower rate and reactors were vented, 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 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 were unknown for decades, the implications of this new theory are certainly not understood. Are nuclear reactors safe if those responsible for nuclear safety do not know that explosions have been going on for decades? Is such a discovery not the very definition of a Potential Inadequacy in the Safety Analysis for each and every reactor in the worldwide fleet? Why are no actions - other than this research - underway to address this major safety concern? Reactor explosions can be stopped to improve nuclear reactor safety, prevent deaths, and avoid environmental disasters!

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