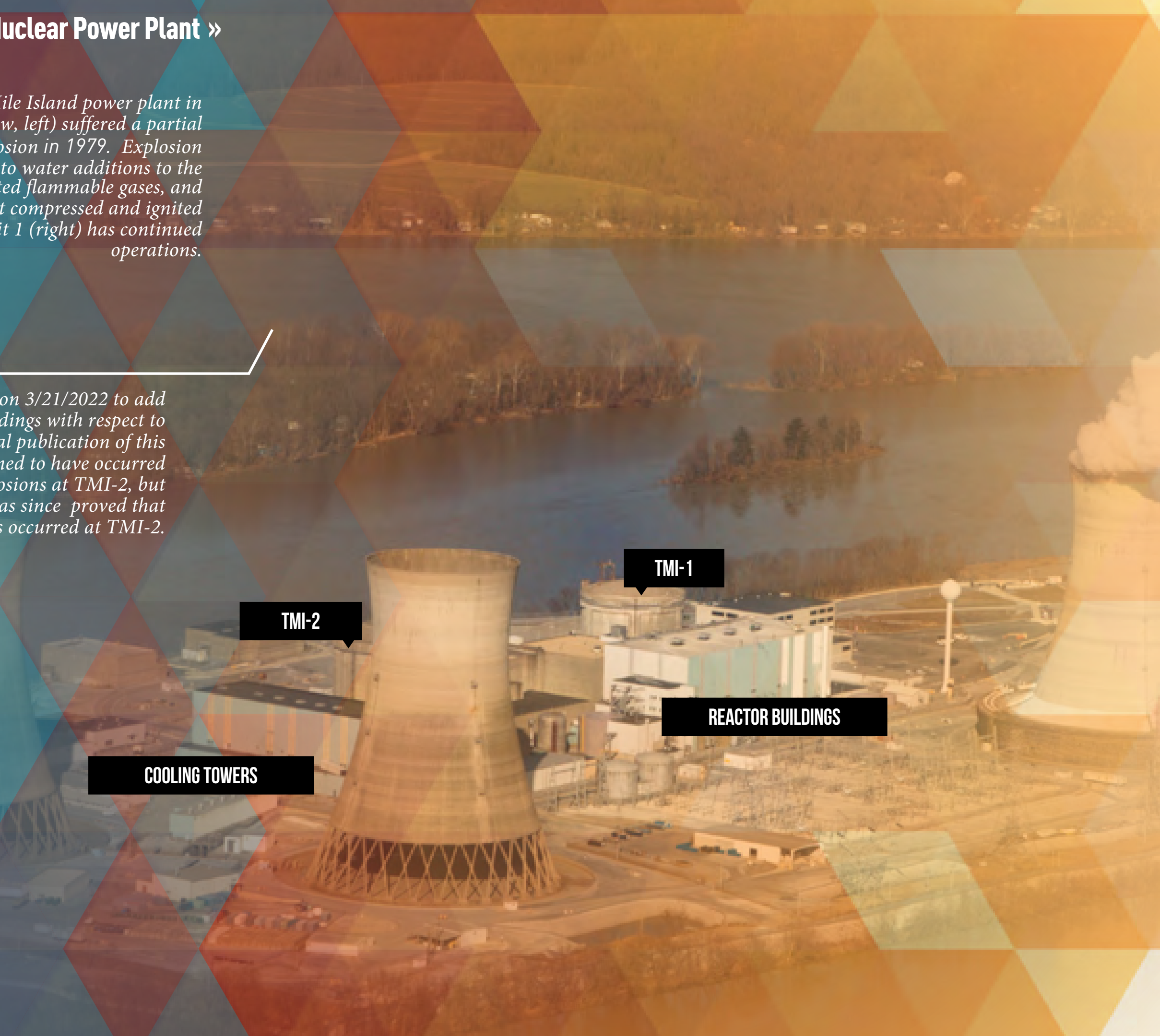
Three Mile Island Nuclear Power Plant »

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 assumed to have occurred rather than explosions at TMI-2, but additional research has since proved that several explosions occurred at TMI-2.



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.

TO IGNITION

BY ROBERT A. LEISHEAR

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

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 at TMI-2. In fact, different responses by reactor operators could have even prevented an explosion at Three Mile Island, but technology was not yet invented.

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

Hydrogen and Oxygen From Steam »

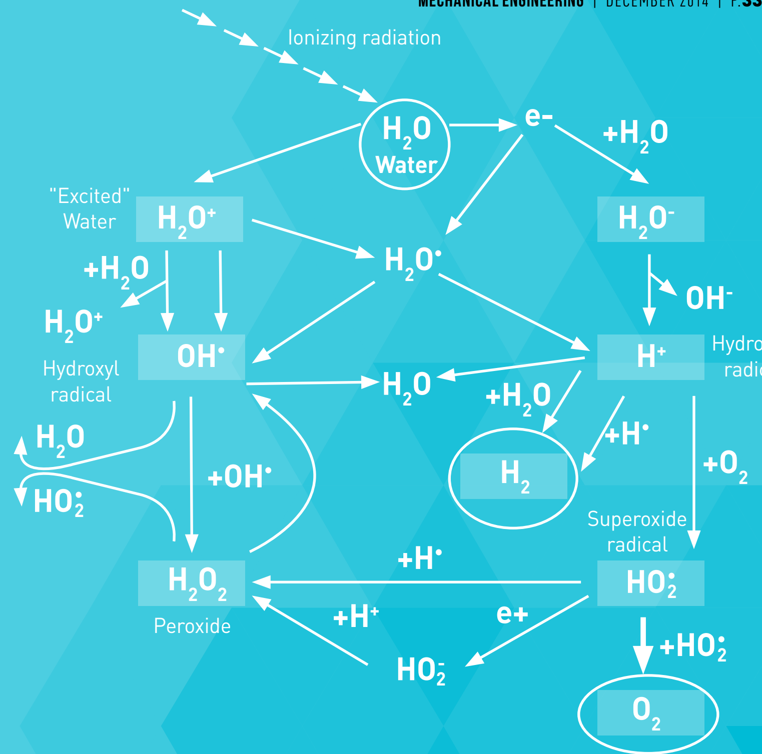
The oxidation of zirconium with steam was a principal source of the hydrogen that burned at Three Mile Island. According to an international Atomic Energy Agency document, IAEA-TECDECDOC-1661, the primary reaction to create 85 to 90 percent of the hydrogen during a meltdown is expressed by:

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

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, several explosions occurred in the containment building during the accident, and 99.4 percent of the hydrogen 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 was 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 explosions were contained in the reactor building.

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 sea water was abruptly added to reactor cores experiencing meltdown accidents. That is, water hammer was applied to hydrogen in the pipelines to ignite explosions, which in turn exploded into the reactor buildings to initiate large explosions of hydrogen. If the sea water had been added at a slower rate and reactors were vented, 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 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. 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 Leishear Engineering, LLC, 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.