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Disaster at Davis-Besse: What Might Have Been

Years of unbelievable neglect by the FirstEnergy Nuclear Operating Company (FENOC) and the Nuclear Regulatory Commission (NRC) resulted in a pineapple-sized hole in the metal lid on the vessel housing the reactor core at the Davis-Besse nuclear plant in Ohio. A thin stainless steel liner, installed to protect the metal lid from corrosion but never intended to retain pressure, is all that kept water cooling the reactor from escaping within seconds. In other words, luck rather than skill saved the day.

The ultimate discovery of the gaping hole itself involved more fortune than prowess. Workers at a sister nuclear plant in South Carolina found unexpected cracks and leaks in metal tubes passing through the reactor's lid. Nearly a year later, workers inspecting the metal tubes at Davis-Besse found similar cracks and leaks. While repairing one of the cracked tubes, workers stumbled – almost literally – onto the hole.

But what would have happened had the problems at the South Carolina reactor not been found or the hole at Davis-Besse overlooked for another year? Until recently, computer studies by FENOC and the NRC indicated the stainless steel liner would have remained intact against the pressure with plenty of margin to spare. But testing at the Oak Ridge National Laboratory now tells a different story. Two mock-ups of the damaged reactor's lid burst at lower pressure than predicted by the computer studies. In fact, one burst occurred at a pressure substantially lower than Davis-Besse's normal operating pressure.

Another problem discovered at Davis-Besse received little attention. The plant's containment sump – a vital part of the safety systems designed to protect the public in event of an accident – was determined to be unable to function as needed. Had the stainless steel liner failed, the containment sump problem would have prevented the backup safety systems from functioning. In other words, Davis-Besse walked a stainless steel tightrope without a safety net.

To outline what might have been, the Union of Concerned Scientists (UCS) developed the following scenario: Davis-Besse is operating at full power on August 14, 2003, with the pineapple-sized hole in its reactor lid still undetected. On that afternoon, a cascading disturbance caused a massive blackout of the electrical grid in the United States and Canada. The blackout hit Davis-Besse and, as we speculate, hit it very hard indeed. The following accounting is fictional, but it was luck and not skill on the part of FENOC or effectiveness on the part of the NRC that prevented it from being factual. While the scenario's initiation is speculative, the narrative of what would have happened during the postulated accident relied heavily on results from evaluations conducted by Davis-Besse's owner as described in the plant's Updated Safety Analysis Report and related documents cited at the end of this report.

The following account reports what likely would have happened at Davis-Besse had the damaged lid not been found before it broke. It also predicts what *will* happen at any one of the nation's 68 other nuclear power reactors like Davis-Besse should it experience a broken pipe without fixing the broken backup safety system – the containment sump – that has now been fixed at Davis-Besse. Finally, this report also recommends what **should** happen: the NRC, under pressure from Congress if necessary, must make all owners fix their impaired containment sumps as soon as possible.

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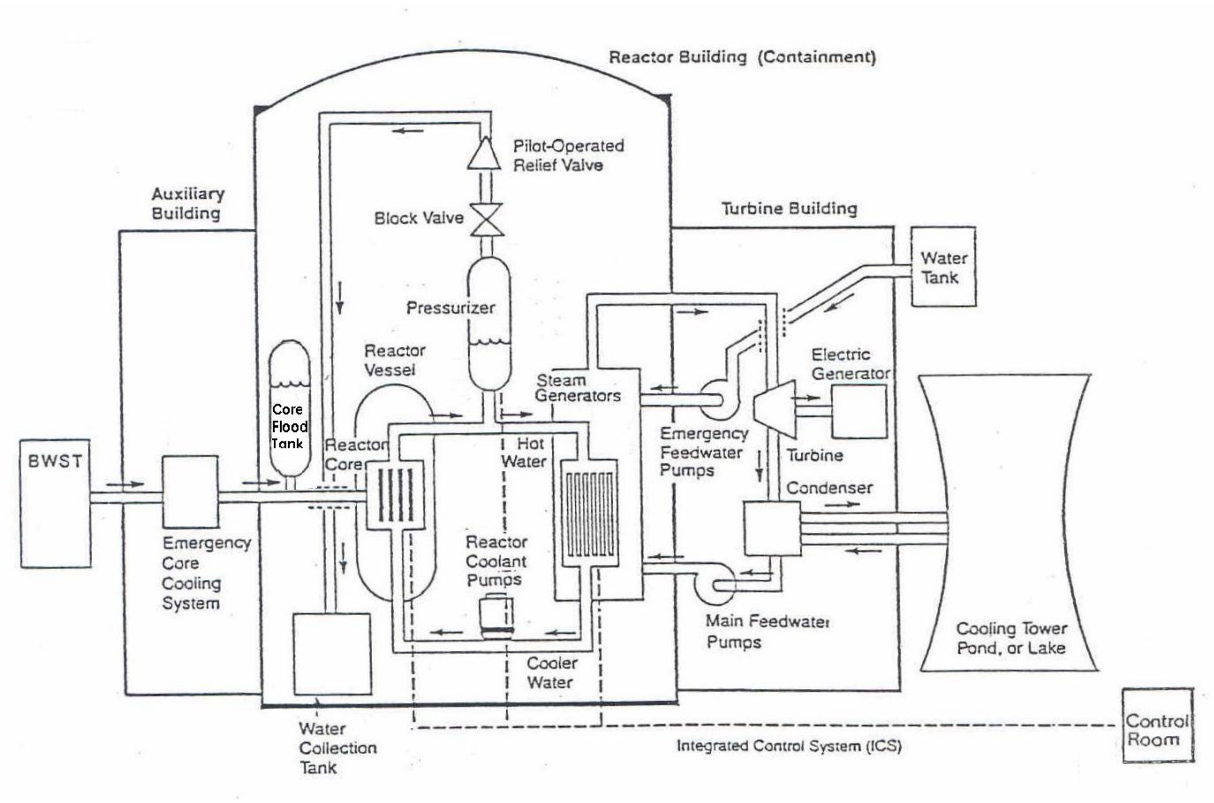
Background

The Davis-Besse reactor core has 177 fuel assemblies forming a cylinder roughly 12 feet tall and 11 feet in diameter. The reactor core contains about 84 metric tons of uranium fuel. The NRC licensed Davis-Besse for a maximum output of 2,772 megawatts of thermal energy (Mwt). When the plant operates at full power, nearly 23 million gallons of water cycles back and forth between the reactor vessel and two steam generators every hour to cool the reactor core. This water is heated to 608°F by the reactor core but does not boil because it is kept at nearly 2,200 pounds per square inch pressure. The very hot, pressurized water enters the steam generators where it flows inside tubes. Heat passes through the tubes' thin walls to boil water outside the tubes. The water exits the tubes at about 557°F and returns to the reactor vessel helped along by the reactor coolant pumps.

The steam from the water boiling outside the tubes within the steam generators passes through large pipes to spin blades within the turbine. The turbine is connected to an electrical generator providing nearly 900 megawatts of electricity (Mwe) to the grid when Davis-Besse operates at full power.

The steam leaving the turbine enters a large box called the condenser. Tubes inside the condenser circulate water drawn from the lake between the condenser and the cooling tower. The steam is cooled down until it turns back into water. The main feedwater pumps return the water to the steam generators. The Davis-Besse plant is only one-third efficient. For every watt of electricity produced, nearly two watts of waste heat are discharged to the environment.

When Davis-Besse is operating, the emergency core cooling system and the emergency feedwater pumps are in standby mode for use in event of an accident.



What happens on August 14, 2003?

The electrical grid failure on August 14, 2003, includes the region where Davis-Besse is located. All nuclear power plants within that region operating at the time of the blackout automatically shut down. Davis-Besse is no different – at least initially. The electrical grid failure causes the turbine, electric generator, and reactor core to automatically shut down. With both the main generator and the electrical grid de-energized, the only electrical power sources remaining at Davis-Besse are large banks of batteries and two emergency diesel generators. These provide power to emergency equipment needed to cool the reactor core and not much else.

Among the equipment losing power are the main steam isolation valves. These valves do not appear in the drawing but are located in the piping between the steam generators and the turbine. The "fail-safe" position for these valves is closed and the valves close upon loss of power. As the main steam isolation valves close, the flow of energy from the reactor core to the steam generators to the turbine to the generator/cooling tower abruptly stops. Although the grid failure triggered the reactor core to go to its "fail-safe" position, shut down, the reactor's rapid shut down is not fast enough to prevent pressure from spiking high as a result of the sudden interruption in the energy flow. Within the reactor vessel, the pressure jumps towards the design pressure of 2,500 pounds per square inch.

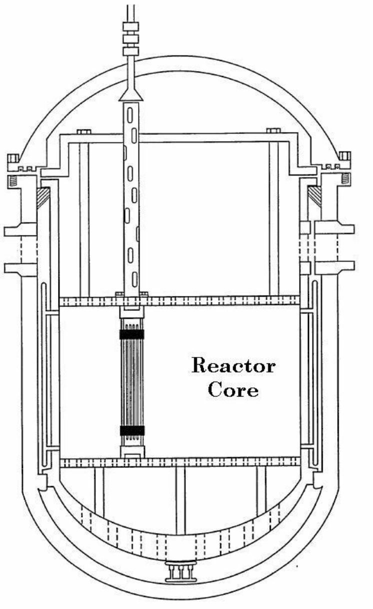
The pressure spike forces the stainless steel liner, already cracked and bulging outward under normal pressure, to break wide open causing in a loss of coolant accident (LOCA). The ensuing LOCA has four distinct phases: (1) blowdown, (2) refill, (3) reflood, and (4) recirculation.

During the blowdown phase, the reactor vessel rapidly depressurizes as water jets out through the large hole in the reactor's lid into the containment. The hot water flashes to steam as its pressure drops upon exiting the hole. The blowdown phase ends within tens of seconds when the pressure inside the containment rises to balance that inside the emptied reactor vessel. The surface temperature of the fuel rods inside the reactor core nearly doubles during the blowdown phase to about 1,200°F.

Even though the reactor core automatically shut down within seconds of the blackout, it continues to generate considerable amounts of heat. Thirty minutes after shut down, the reactor emits nearly two (2) percent of the heat it generated at full power. Two percent may not sound like much, but it's around 180,000,000 British Thermal Units (BTUs) per hour. A single BTU is defined as the heat needed to increase the temperature of one pound of water by one degree Fahrenheit at atmospheric pressure. Two percent of Davis-Besse's rated output can heat one million pounds of water from 32°F to 212°F in an hour. Even twenty (20) hours after the blackout, the reactor produces nearly 60,000,000 BTU per hour. The reactor's decay heat must be removed to protect the nuclear fuel from damage caused by overheating.

As pressure inside the reactor vessel plummets during the blowdown phase, three parts of the emergency core cooling system (ECCS) automatically engage: (1) the core flood tanks, (2) the high pressure injection (HPI) pumps, and (3) the low pressure injection/decay heat (LPI/DH) pumps. The core flood tanks provide the first response. The HPI and LPI/DH responses are delayed by the time needed for idle pumps to start up and move stagnant water from the Borated Water Storage Tank to the reactor vessel.

The two core flood tanks are partially filled with water and the remaining space is filled with nitrogen gas pressurized to about 800 pounds per square inch (psi). When reactor vessel pressure falls below 800 psi during the blowdown phase, the nitrogen gas pressure "pushes" the water from the core flood tanks into the reactor vessel. In the latter moments of the blowdown phase and early moments of the refill phase of the LOCA, the water entering the emptied reactor vessel from the core flood tanks refills its lower domed area. Throughout the refill phase, the reactor core receives very little cooling as the water from the core flood tanks runs down the sides of the vessel to its bottom. The uncovered reactor core sits and bakes – the fuel rods experience near adiabatic heat-up (meaning the reactor's decay heat goes into the fuel rod with very little heat going elsewhere). As the fuel rods' temperature rises above 1,400°F, a chemical reaction between the zirconium metal of the fuel rod and the water vapor occurs. This reaction is exothermic, meaning it produces heat to "boost" the fuel rods' temperature closer to its melting point of over 2,200°F.



When the water level inside the reactor vessel reaches the bottom of the reactor core, the reflood phase of the LOCA begins. As the rising water level recovers the exposed reactor core, decay heat boils some of the water. The steam cools the exposed upper regions of the reactor core.[1] The reflood phase stops the temperature rise of the fuel rods as the water or steam removes the decay heat being produced by the reactor core. The fuel rods' temperature reached approximately 2,100°F, retaining a small but sufficient margin to the 2,200°F melting point. At this temperature, the fuel rods may be a little blistered from the heat, but they are largely intact.

After the reactor core is once again covered and the reactor vessel refilled with water, the reflood phase of the accident ends. Until now, the water entering the reactor vessel to compensate for the lost inventory came from the core flood tanks and the Borated Water Storage Tank (BWST) via the high pressure inspection and/or low pressure injection/decay heat pumps. The water lost from the reactor vessel drained down into the bottom of the containment building. The first 200,000 gallons or so of the spilled water fills nooks and crannies in the basement to the point where water starts spilling over into the containment sump.

The BWST is a large tank containing 500,100 gallons of water. As the level inside the BWST drops to only nine (9) feet remaining, automatic alarms warn the operators in the control room. At this level, more than 360,000 gallons of water have been transferred from the BWST into the reactor vessel and through the hole in its lid to the containment, flooding the building two (2) feet above the top of the sump. By procedure, the operators respond to the warning by flipping switches that remotely open valves in the auxiliary building to permit the HPI and LPI/DH pumps to draw water from the containment sump instead of the BWST. As the containment sump valves open, the BWST valves automatically close as the recirculation phase of the accident begins.

In theory, the recirculation phase features the LPI pumps taking the water expelled from the reactor vessel and collected in the containment sump and returning it to the reactor vessel. In practice, this essential function is soon lost at Davis-Besse. The thousands of gallons of water sprayed through the reactor vessel's lid during the blowdown phase of the accident scoured piping and components in its path ripping away insulation, layers of paint, and other protective coatings. Debris falls to the containment floor and is carried by the water draining to the containment sump. Only a very small percentage of the debris generated during the blowdown phase needs to make it to the containment sump to clog the mesh screens covering the sump. The debris blocks the containment sump screens, depriving the HPI pumps, the LPI pumps, and the containment spray pumps of water they need.

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[1] Steam cooling is not an intuitive concept but recall that the fuel rods at this point are greater than 1,200°F and the steam temperature at this point is around 250°F.

The operators know about the trouble. Plenty of gauges, chart recorders, and alarms in the control room tell them about the water shortage problem plaguing the emergency core cooling system pumps. At the same time, the BWST is empty or very nearly so. What are their options?

They cannot send anyone inside the containment to clean the containment sump screens because of the high temperature, pressure, and radiation conditions. Even if someone makes a suicide run, once the flow of water through the cleaned screens resumes, the water carries more debris in to re-block the screens. On to Plan B.

There's a fairly large lake nearby. The operators use it to refill the BWST, then they swap the pumps back to taking water from it. It works fine – for awhile. Davis-Besse was designed to accommodate the amount of water inside containment from the BWST, a flood level of a couple of feet above the containment sump. Pumping Lake Erie into the containment carries a toll of about 8 pounds per gallon. Every 125,000 gallons of lake water entering containment adds one million pounds of weight and increases the flood level by nearly a foot. What gives way first? Does containment structure fail due to the added weight? Or does vital electrical equipment stop working because the flood submerged it?

It's a rhetorical question. Either answer being 'yes' causes the premature end of the recirculation phase of the accident and the unexpected arrival of a fifth phase: meltdown. Once the jury-rigged, lake-aided recirculation flow ends, the meltdown clock starts. The water inside the reactor vessel boils away and drops closer and closer to uncovering the reactor core.

The good news is it takes time, maybe 2 to 5 hours, to boil off enough water to uncover the core and allow fuel rod temperatures rise to the melting point. The bad news is the delay does not allow sufficient time to protect the people in harm's way. The blackout that started the sequence of events leading to reactor meltdown also affected activities outside the plant's fences. The emergency sirens intended to warn of impending disaster stand mute, lacking the power needed to sound an alarm. Even if the sirens are made to wail, people in hearing range turn on televisions to black screens and radios to dead air. The much-needed word about whether to evacuate or to shelter can neither be sent nor received.

Radioactivity released from the meltdown at Davis-Besse cannot be seen or tasted, but its visits can soon be felt. People in the path of the radioactive cloud may experience dizziness and nausea. Lacking potassium iodide pills to take, they inhale radioactive iodine that is absorbed by their thyroid glands. Particles falling from the sky onto exposed skin may produce a reddish rash-like reaction. Few people die the day of the accident or shortly thereafter, except for some of the Davis-Besse workers. Outside the plant's fences, the radioactivity is not concentrated enough to cause immediate fatalities. But the radioactive cloud is nevertheless lethal. Hundreds, perhaps thousands, of people exposed to the cloud develop cancer and other radiation-induced illnesses and die in the next few years. Even some of those exposed to the cloud but lucky enough to avoid cancer still become victims of the accident. Radiation damage to their chromosomes produces genetic defects in their children.

Aftermath

In a series of post-mortem inquiries, Congress presses the NRC for answers to questions like: Why wasn't backup power required for the emergency sirens? Why weren't alternative notification methods available? Why weren't the emergency plans crafted to account for realistic situations like power outages? Why wasn't potassium iodide provided to limit the damage to thyroids, particularly in young children? Why was Davis-Besse allowed to operate for so long with so many safety problems, some known and others suspected? Why has the NRC allowed pressurized water reactors like Davis-Besse to operate for decades with containment sumps known to be impaired? Congress allocates barrels of money to the NRC to finance all the reforms needed to reassure the American public that it won't happen again. Congress also authorizes millions, perhaps billions, of dollars to compensate victims of the nuclear disaster after the Price-Anderson liability coverage is depleted.

But why must the Congress wait for a disaster to seek the reforms NRC so desperately needs today? Whatever measures that Congress deems prudent and necessary after the next nuclear plant accident would seem to be even more vital now. After all, taking those steps **now** could prevent the next meltdown, leaving us one meltdown ahead in the safety race. And even if a meltdown occurred, at least members of Congress could tell their surviving constituents that they'd taken every reasonable step to protect them – something they could not claim today.

Among the first steps that Congress must ensure NRC takes is the expeditious resolution of the containment sump problem at pressurized water reactors. Had this vital safety equipment not been broken at Davis-Besse, the failure of the reactor lid's stainless steel liner would not likely have damaged the reactor core or caused the significant release of radioactivity to the atmosphere. Davis-Besse fixed this key safety system, but 68 other pressurized water reactors operating in the United States today have not yet done so. These reactors are one broken pipe away from turning this narrative into a tragic prophecy. Congress must ensure this clear and present danger is removed before our collective luck runs out.

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