INTRODUCTION TO THE PRESSURE WATER REACTOR

AND THE THREE MILE ISLAND ACCIDENT

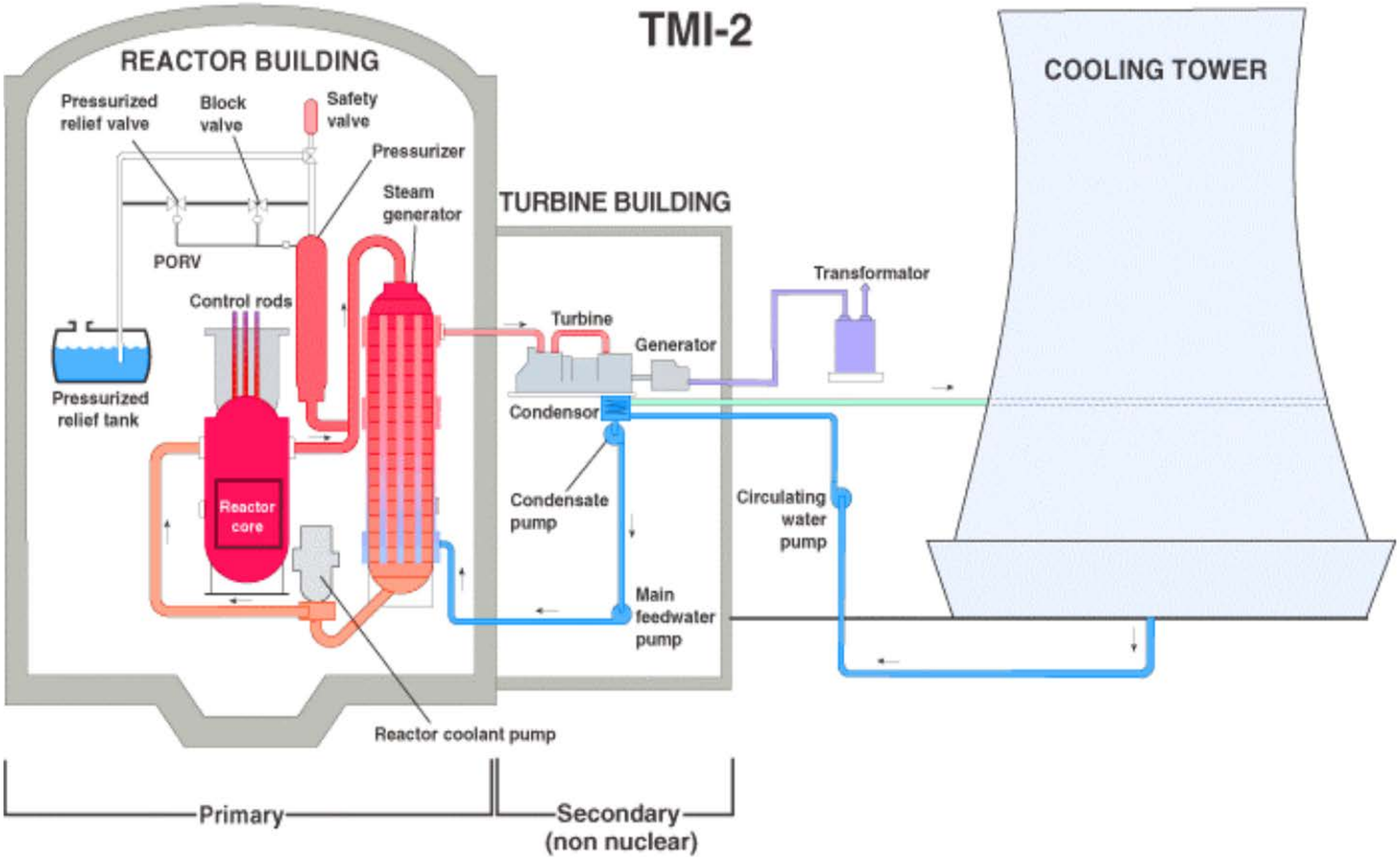
In 1979 at Three Mile Island nuclear power plant in USA a cooling malfunction caused part of the core to melt in the # 2 reactor. The TMI-2 reactor was destroyed.

The Three Mile Island power station is near Harrisburg, Pennsylvania. It had two pressurized water reactors. One PWR was of 800 MWe (775 MWe net) and entered service in 1974. It remains one of the best-performing units in USA. Unit 2 was a 906 MWe PWR (880 MWe net) and was almost brand new. The two reactors at Three Mile Island were designed by Babcock and Wilcox.

SECTION ONE; INTRODUCTION TO THE PRESSURIZED WATER REACTOR

A. **Pressurized water reactor**s (**PWR**s) comprise a majority of all western nuclear power plants. In a **PWR** the primary coolant (superheated water) is pumped under high pressure to the reactor core, then the heated water transfers thermal energy to a steam generator. The Nuclear Reactors at Three Mile Island are all **PWR,** types of reactors. The Westinghouse AP 1000 is a **PWR.**

SCHEMATIC OF THE PRESSURE WATER REACTOR AT THREE MILE ISLAND



B. PRESSURIZED WATER REACTOR OPERATION

1. The reactor core transfers the fission energy, primarily kinetic energy created by recoil of the fission fragments in the fuel rods into thermal energy of the water which is both the moderator and the cooling agent in a Light Water Reactor.
2. Pressurized-water in the primary coolant loop carries the heat to the steam generator.
3. Inside the steam generator heat from the primary coolant loop vaporizes the water in the secondary loop producing steam.
4. The steam line directs the steam to the main turbine causing it to turn the turbine which is connected to the generator to create electrical power.
5. The unused steam is condensed into water.
6. The resulting water is pumped out of the condenser with a series of pumps, reheated and pumped back to the steam generator.

C. NUCLEAR STEAM SUPPLY SYSTEM: Nuclear fuel in the reactor vessel is engaged in a fission chain reaction, which produces heat, heating the water in the primary coolant loop by thermal conduction through the fuel cladding. The hot primary coolant is pumped into a heat exchanger called steam generator, where heat is transferred across a set of tubes to the lower pressure secondary coolant, which evaporates to pressurized steam. The transfer of heat is accomplished without mixing the two fluids.

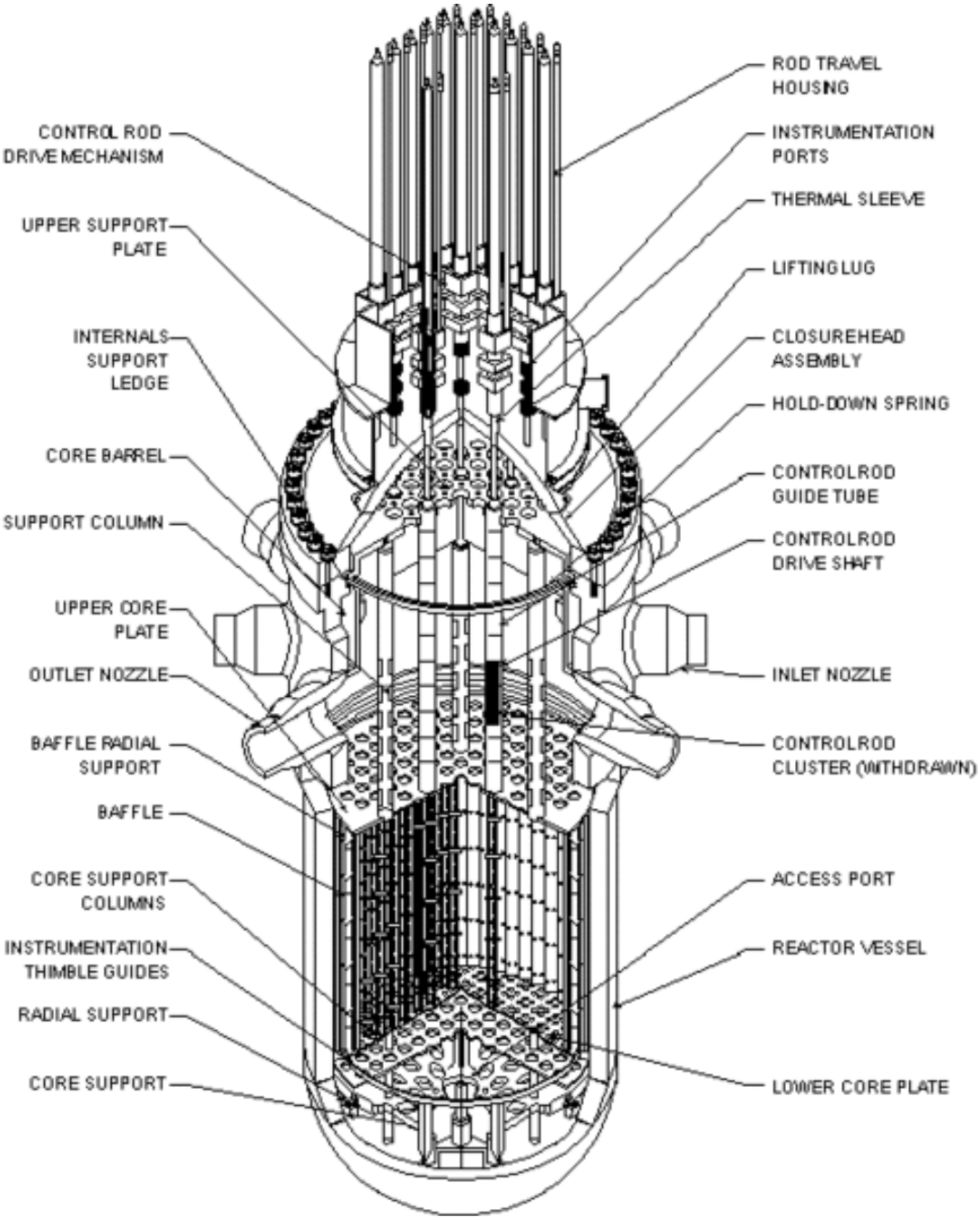
Two things are characteristic for the **pressurized water reactor** (**PWR**) when compared with other reactor types: coolant loop separation from the steam system and pressure inside the primary coolant loop. In a **PWR**, there are two separate coolant loops both filled with demineralized/deionized water. The pressure in the primary coolant loop is typically 15–16 megapascals (153 atmospheres, 2,250 psig), which is notably higher than in other nuclear reactors. As an effect of this, only localized boiling occurs.

D. CONTROL SYSTEM FOR PRESSURIZED WATER REACTOR: Reactor power is controlled via two methods: by inserting or withdrawing control rods and by adjusting the concentration of Boron (called a chemical shim) in the primary cooling circuit. Positioning (withdrawing or inserting) control rods is the normal method for controlling power when starting up a **PWR**. As control rods are withdrawn, neutron absorption decreases in the control material and increases in the fuel, so reactor power increases. As control rods are inserted, neutron absorption increases in the control material and decreases in the fuel, so reactor power decreases.

In **PWR**s reactor power can be viewed as following steam (turbine) demand due to the reactivity feedback of the temperature change caused by increased or decreased steam flow. Boron and control rods are used to maintain primary system temperature at the desired point. In order to decrease power, the operator throttles shut turbine inlet valves. This would result in less steam being drawn from the steam generators. This results in the primary loop increasing in temperature. The higher temperature causes the reactor to fission less and decrease in power.

The operator could then add boric acid and/or insert control rods to decrease temperature to the desired point.

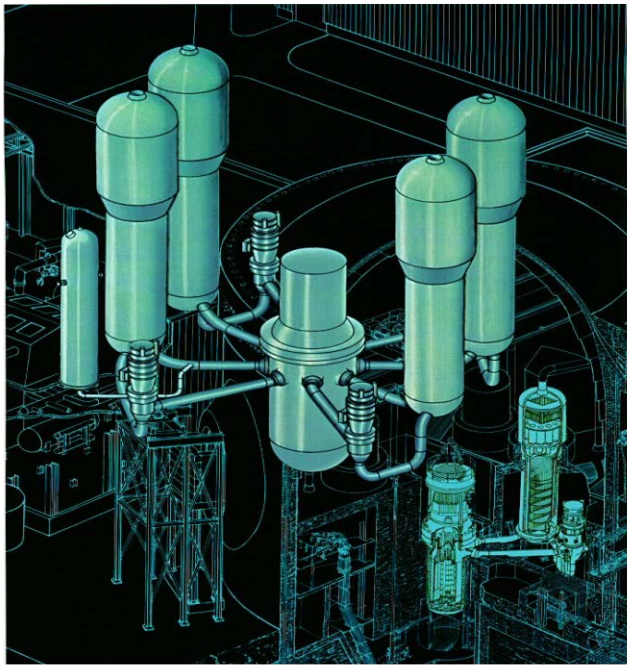
PRESSURIZED WATER REACTOR: REACTOR PRESSURE VESSEL



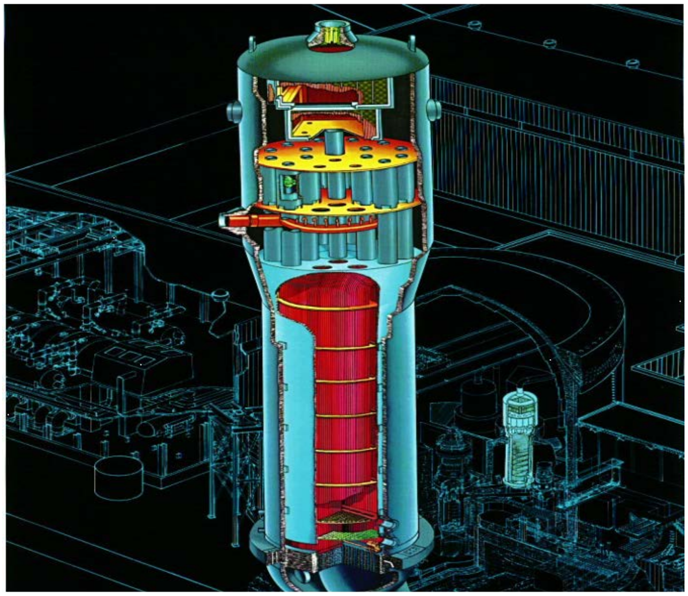
PRESSURIZED WATER REACTOR: REACTOR PRESSURE VESSEL

DETAILS OF A WESTINGHOUSE REACTOR VESSEL

CONFIGURATION OF REACTOR AND STEAM GENERATORS IN PRESSURIZED WATER REACTOR



STEAM GENERTOR IN WESTINGHOUSE PRESURIZED WATER REACTOR



Pressure in the primary circuit is maintained by a pressurizer, a separate vessel that is connected to the primary circuit and partially filled with water which is heated to the saturation temperature (boiling point) for the desired pressure by submerged electrical heaters. To achieve a pressure of 155 bar, the pressurizer temperature is maintained at 345 °C, which gives a sub-cooling margin (the difference between the pressurizer temperature and the highest temperature in the reactor core) of 30 °C. Thermal transients in the reactor coolant system result in large swings in pressurizer liquid volume, total pressurizer volume is designed around absorbing these transients without uncovering the heaters or emptying the pressurizer. Pressure transients in the primary coolant system manifest as temperature transients in the pressurizer and are controlled through the use of automatic heaters and water spray, which raise and lower pressurizer temperature, respectively.

To achieve maximum heat transfer, the primary circuit temperature, pressure and flow rate are arranged such that subcooled nucleate boiling takes place as the coolant passes over the nuclear fuel rods.

The coolant is pumped around the primary circuit by powerful pumps, which can consume up to 6 MW each. After picking up heat as it passes through the reactor core, the primary coolant transfers heat in a steam generator to water in a lower pressure secondary circuit, evaporating the secondary coolant to saturated steam — in most designs 6.2 MPa (60 atm, 900 psia), 275 °C (530 °F) — for use in the steam turbine. The cooled primary coolant is then returned to the reactor vessel to be heated again.

Pressurized water reactors, like all thermal reactor designs, require the fast fission neutrons to be slowed down (a process called moderation or thermalization) in order to interact with the nuclear fuel and sustain the chain reaction. In **PWR**s the coolant water is used as a moderator by letting the neutrons undergo multiple collisions with light hydrogen atoms in the water, losing speed in the process. This "moderating" of neutrons will happen more often when the water is denser (more collisions will occur). The use of water as a moderator is an important safety feature of PWRs, as any increase in temperature causes the water to expand and become less dense; thereby reducing the extent to which neutrons are slowed down and hence reducing the reactivity in the reactor. Therefore, if reactivity increases beyond normal, the reduced moderation of neutrons will cause the chain reaction to slow down, producing less heat. This property, known as the negative temperature coefficient of reactivity, makes PWR reactors very stable.

PWRs are designed to be maintained in an under-moderated state, meaning that there is room for increased water volume or density to further increase moderation, because if moderation were near saturation, then a reduction in density of the moderator/coolant could reduce neutron absorption significantly while reducing moderation only slightly, making the void coefficient positive. Also, light water is actually a somewhat stronger moderator of neutrons than heavy water, though heavy water's neutron absorption is much lower. Because of these two facts, light water reactors have a relatively small moderator volume and therefore have compact cores. One next generation design, the supercritical water reactor, is even less moderated. A less moderated neutron energy spectrum does worsen the capture/fission ratio for ^{235}U and especially ^{239}Pu, meaning that more fissile nuclei fail to fission on neutron absorption and instead capture the neutron to become a heavier non-fissile isotope, wasting one or more neutrons and increasing accumulation of heavy transuranic actinides, some of which have long half-lives.

In a nuclear power station, the pressurized steam is fed through a steam turbine which drives an electrical generator connected to the electric grid for distribution. After passing through the turbine the secondary coolant (water-steam mixture) is cooled down and condensed in a condenser. The condenser converts the steam to a liquid so that it can be pumped back into the steam generator, and maintains a vacuum at the turbine outlet so that the pressure drop across the turbine, and hence the energy extracted from the steam, is maximized. Before being fed into the steam generator, the condensed steam (referred to as feed-water) is sometimes preheated in order to minimize thermal shock.

SECTION TWO: THE THREE MILE ISLAND NUCLEAR POWER PLANT ACCIDENT

In 1979 at Three Mile Island nuclear power plant a cooling malfunction caused part of the core to melt in the # 2 reactor. The TMI-2 reactor was destroyed. Some radioactive gas was released a couple of days after the accident, but not enough to cause any dose above background levels to local residents. There were no injuries or adverse health effects from the Three Mile Island accident.

A. **PREAMBLE:** The Three Mile Island power station is near Harrisburg, Pennsylvania. It had two pressurized water reactors. One PWR was of 800 MWe (775 MWe net) and entered service in 1974. It remains one of the best-performing units in USA. Unit 2 was of 906 MWe (880 MWe net) and almost brand new.

The accident to unit 2 happened at 4 am on 28 March 1979 when the reactor was operating at 97% power. It involved a relatively minor malfunction in the secondary cooling circuit which caused the temperature in the primary coolant to rise. This in turn caused the reactor to shut down automatically. Shut down took about one second. At this point a relief valve failed to close, but instrumentation did not reveal the fact, and so much of the primary coolant drained away that the residual decay heat in the reactor core was not removed. The core suffered severe damage as a result.

The operators were unable to diagnose or respond properly to the unplanned automatic shutdown of the reactor. Deficient control room instrumentation and inadequate emergency response training proved to be root causes of the accident

B. **THE CHAIN OF EVENTS DURING THE ACCIDENT:** Within seconds of the shutdown, the pilot-operated relief valve (PORV) on the reactor cooling system opened, as it was supposed to. About 10 seconds later it should have closed. But it remained open, leaking vital reactor coolant water to the reactor coolant drain tank. The operators believed the relief valve had shut because instruments showed them that a "close" signal was sent to the valve. However, they did not have an instrument indicating the valve's actual position.

Responding to the loss of cooling water, high-pressure injection pumps automatically pushed replacement water into the reactor system. As water and steam escaped through the relief valve, cooling water surged into the pressurizer, raising the water level in it. (The pressurizer is a tank which is part of the primary reactor cooling system, maintaining proper pressure in the system. The relief valve is located on the pressurizer. In a PWR like TMI-2, water in the primary cooling system around the core is kept under very high pressure to keep it from boiling.)

Operators responded by reducing the flow of replacement water. Their training told them that the pressurizer water level was the only dependable indication of the amount of cooling water in the system. Because the pressurizer level was increasing, they thought the reactor system was too full of water. Their training told them to do all they could to keep the pressurizer from filling with water. If it filled, they could not control pressure in the cooling system and it might rupture. Steam then formed in the reactor primary cooling system. Pumping a mixture of steam and water caused the reactor cooling pumps to vibrate. Because the severe vibrations could have damaged the pumps and made them unusable, operators shut down the pumps. This ended forced cooling of the reactor core. (The operators still believed the system was nearly full of water because the pressurizer level remained high.) However, as reactor coolant water boiled away, the reactor’s fuel core was uncovered and became even hotter. The fuel rods were damaged and released radioactive material into the cooling water.

At 6:22 am operators closed a block valve between the relief valve and the pressurizer. This action stopped the loss of coolant water through the relief valve. However, superheated steam and gases blocked the flow of water through the core cooling system.

Throughout the morning, operators attempted to force more water into the reactor system to condense steam bubbles that they believed were blocking the flow of cooling water. During the afternoon, operators attempted to decrease the pressure in the reactor system to allow a low pressure cooling system to be used and emergency water supplies to be put into the system.

C. **COOLING RESTORED:** By late afternoon, operators began high-pressure injection of water into the reactor cooling system to increase pressure and to collapse steam bubbles. By 7:50 pm on 28 March, they restored forced cooling of the reactor core when they were able to restart one reactor coolant pump. They had condensed steam so that the pump could run without severe vibrations. Radioactive gases from the reactor cooling system built up in the makeup tank in the auxiliary building. During March 29 and 30, operators used a system of pipes and compressors to move the gas to waste gas decay tanks. The compressors leaked, and some radioactive gas was released to the environment.

D. **THE HYDROGEN BUBBLE:** When the reactor's core was uncovered, on the morning of 28 March, a high-temperature chemical reaction between water and the zircaloy metal tubes holding the nuclear fuel pellets had created hydrogen gas. In the afternoon of 28 March, a sudden rise in reactor building pressure shown by the control room instruments indicated a hydrogen burn had occurred. Hydrogen gas also gathered at the top of the reactor vessel. From 30 March through 1 April operators removed this hydrogen gas "bubble" by periodically opening the vent valve on the reactor cooling system pressurizer. For a time, regulatory (NRC) officials believed the hydrogen bubble could explode, though such an explosion was never possible since there was not enough oxygen in the system.

E. **COLD SHUTDOWN:** After an anxious month, on 27 April operators established natural convection circulation of coolant. The reactor core was being cooled by the natural movement of water rather than by mechanical pumping. The plant was in "cold shutdown".

SECTION THREE: PUBLIC CONCERN AND CONFUSION:

Many of the concern about the accident were generated as a direct result of the production of the movie **“The China Syndrome”.** The film was released on 16 March 1979, 12 days before the Three Mile Island nuclear accident in Dauphin County, Pennsylvania. Coincidentally, in the film, physicist Dr. Elliott Lowell (Donald Hotton) says that the China Syndrome would render "an area the size of Pennsylvania" permanently uninhabitable.

A. **DOE HISTORY OF THE ACCIDENT:** When the TMI-2 accident is recalled, it is often in the context of what happened on Friday and Saturday, March 30-31. The drama of the TMI-2 accident-induced fear, stress and confusion on those two days. The atmosphere then, and the reasons for it, are described well in the book "*Crisis Contained, The Department of Energy at Three Mile Island*," by Philip L Cantelon and Robert C. Williams, 1982. This is an official history of the Department of Energy's role during the accident.

"Friday appears to have become a turning point in the history of the accident because of two events: the sudden rise in reactor pressure shown by control room instruments on Wednesday afternoon (the "hydrogen burn") which suggested a hydrogen explosion? became known to the Nuclear Regulatory Commission [that day]; and the deliberate venting of radioactive gases from the plant Friday morning which produced a reading of 1,200 millirems (12 mSv) directly above the stack of the auxiliary building.

"What made these significant was a series of misunderstandings caused, in part, by problems of communication within various state and federal agencies. Because of confused telephone conversations between people uninformed about the plant's status, officials concluded that the 1,200 millirems (12 mSv) reading was an off-site reading. They also believed that another hydrogen explosion was possible, that the Nuclear Regulatory Commission had ordered evacuation and that a meltdown was conceivable.

"Garbled communications reported by the media generated a debate over evacuation. Whether or not there were evacuation plans soon became academic. What happened on Friday was not a planned evacuation but a weekend exodus based not on what was actually happening at Three Mile Island but on what government officials and the media imagined might happen. On Friday confused communications created the politics of fear."

Throughout the book, Cantelon and Williams note that hundreds of environmental samples were taken around TMI during the accident period by the Department of Energy (which had the lead sampling role) or the then-Pennsylvania Department of Environmental Resources. But there were no unusually high readings, except for noble gases, and virtually no iodine. Readings were far below health limits. Yet a political storm was raging based on confusion and misinformation.

B. RADIOLOGICAL HEALTH EFFECTS: The Three Mile Island accident caused concerns about the possibility of radiation-induced health effects, principally cancer, in the area surrounding the plant. Because of those concerns, the Pennsylvania Department of Health for 18 years maintained a registry of more than 30,000 people who lived within five miles of Three Mile Island at the time of the accident. The state's registry was discontinued in mid 1997, without any evidence of unusual health trends in the area. Indeed, more than a dozen major, independent health studies of the accident showed no evidence of any abnormal number of cancers around TMI years after the accident. The only detectable effect was psychological stress during and shortly after the accident.

The studies found that the radiation releases during the accident were minimal, well below any levels that have been associated with health effects from radiation exposure. The average radiation dose to people living within 10 miles of the plant was 0.08 millisieverts, with no more than 1 millisievert to any single individual. The level of 0.08 mSv is about equal to a chest X-ray, and 1 mSv is about a third of the average background level of radiation received by U.S. residents in a year.

In June 1996, 17 years after the TMI-2 accident, Harrisburg U.S. District Court Judge Sylvia Rambo dismissed a class action lawsuit alleging that the accident caused health effects. The plaintiffs have appealed Judge Rambo's ruling. The appeal is before the U.S. Third Circuit Court of Appeals. However, in making her decision, Judge Rambo cited:

- Findings that exposure patterns projected by computer models of the releases compared so well with data from the TMI dosimeters (TLDs) available during the accident that the dosimeters probably were adequate to measure the releases.
- That the maximum offsite dose was, possibly, 100 millirem (1 mSv), and that projected fatal cancers were less than one.
- The plaintiffs' failure to prove their assertion that one or more unreported hydrogen "blowouts" in the reactor system caused one or more unreported radiation "spikes", producing a narrow yet highly concentrated plume of radioactive gases.

Judge Rambo concluded: "The parties to the instant action have had nearly two decades to muster evidence in support of their respective cases.... The paucity of proof alleged in support of Plaintiffs' case is manifest. The court has searched the record for any and all evidence which construed in a light most favorable to Plaintiffs creates a genuine issue of material fact warranting submission of their claims to a jury. This effort has been in vain."

More than a dozen major, independent studies have assessed the radiation releases and possible effects on the people and the environment around TMI since the 1979 accident at TMI-2. The most recent was a 13-year study on 32,000 people. None has found any adverse health effects such as cancers which might be linked to the accident.

SECTION FOUR: THE TMI-2 CLEANUP:

The cleanup of the damaged nuclear reactor system at TMI-2 took nearly 12 years and cost approximately US$973 million. The cleanup was uniquely challenging technically and radiologically. Plant surfaces had to be decontaminated. Water used and stored during the cleanup had to be processed. And about 100 tonnes of damaged uranium fuel had to be removed from the reactor vessel -- all without hazard to cleanup workers or the public.

A. CLEANUP PLAN: A cleanup plan was developed and carried out safely and successfully by a team of more than 1000 skilled workers. It began in August 1979, with the first shipments of accident-generated low-level radiological waste to Richland, Washington. In the cleanup's closing phases, in 1991, final measurements were taken of the fuel remaining in inaccessible parts of the reactor vessel. Approximately one percent of the fuel and debris remains in the vessel. Also in 1991, the last remaining water was pumped from the TMI-2 reactor.

The cleanup ended in December 1993, when Unit 2 received a license from the NRC to enter Post Defueling Monitored Storage. Early in the cleanup, Unit 2 was completely severed from any connection to TMI Unit 1. TMI-2 today is in long-term monitored storage. No further use of the nuclear part of the plant is anticipated. Ventilation and rainwater systems are monitored. Equipment necessary to keep the plant in safe long-term storage is maintained.

Defueling the TMI-2 reactor vessel was the heart of the cleanup. The damaged fuel remained underwater throughout the defueling. In October 1985, after nearly six years of preparations, workers standing on a platform atop the reactor and manipulating long-handled tools began lifting the fuel into canisters that hung beneath the platform. In all, 342 fuel canisters were shipped safely for long-term storage at the Idaho National Laboratory, a program that was completed in April 1990. TMI-2 cleanup operations produced over 10.6 megalitres of accident-generated water that was processed, stored and ultimately evaporated safely.