Operational Reactor Safety
22.091/22.903

Professor Andrew C. Kadak
Professor of the Practice

Lecture 19
Three Mile Island Accident

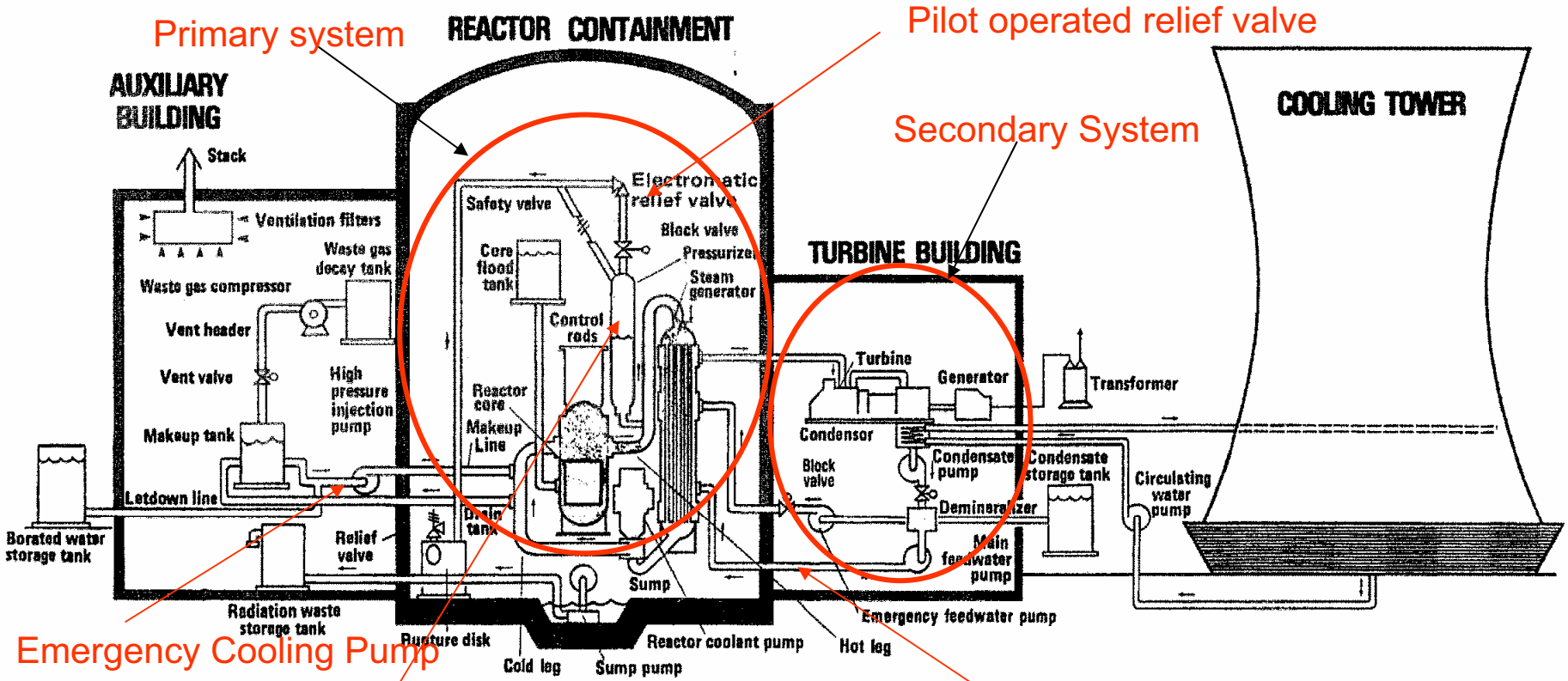
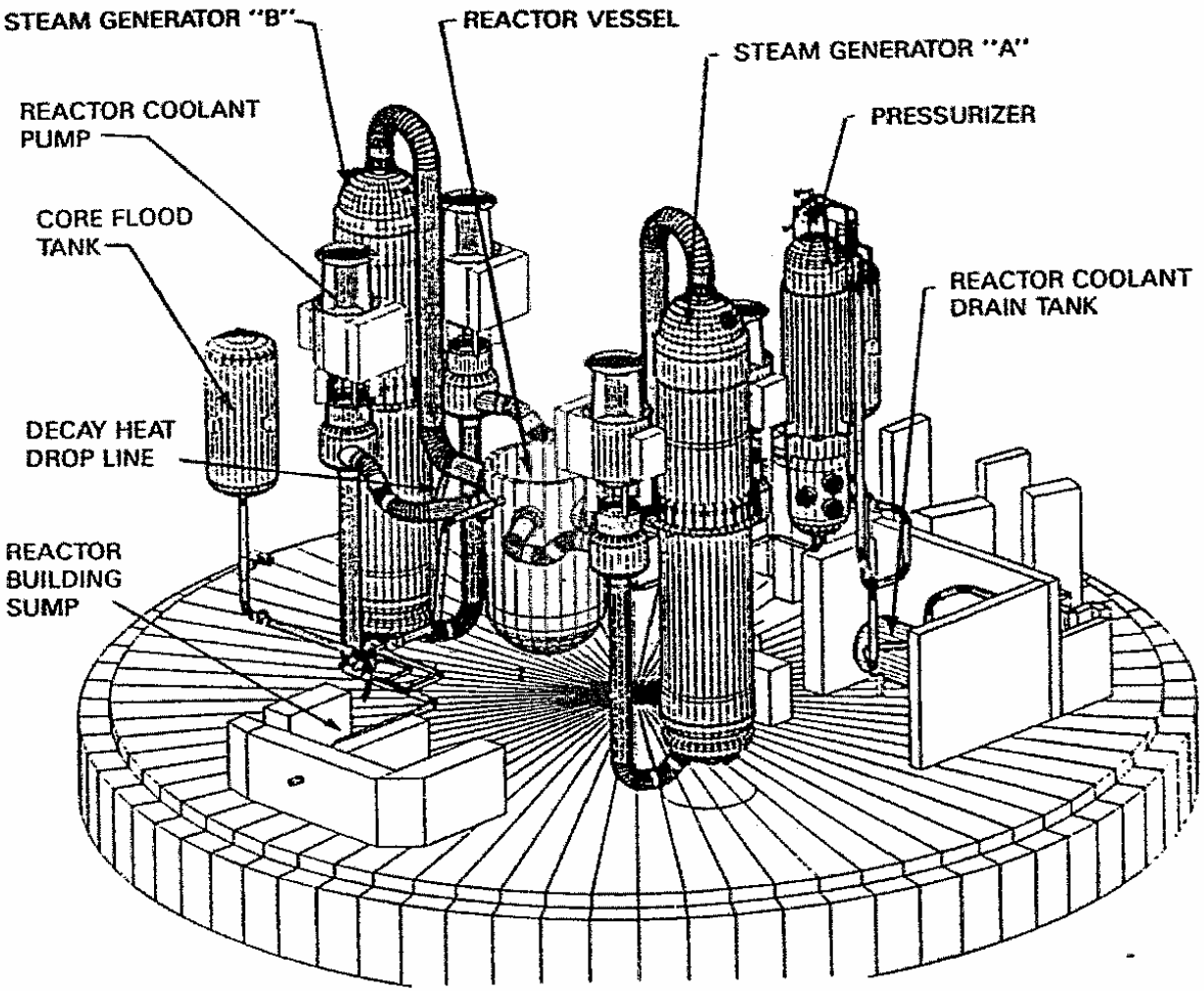
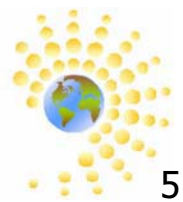


FIGURE 15-2
Schematic layout of the TMI-2 reactor. (Reprinted, and adapted with permission of IEEE, from *IEEE Spectrum*, November 1979 issue, special report on Three Mile Island.)



Davis Besse Event: September 24, 1977 - 9:24 PM

- Power Level 9%
- Transient initiated - Loss of "feedwater" to steam generator
- Temperature increased in reactor
- Water level in pressurizer increased
- Pilot Operated Relief Valve (PORV) opened
- PORV did not close but stuck open
- Reactor Automatically Shutdown
- Emergency Feedwater pumps automatically started
- Primary coolant system cooled and shrunk



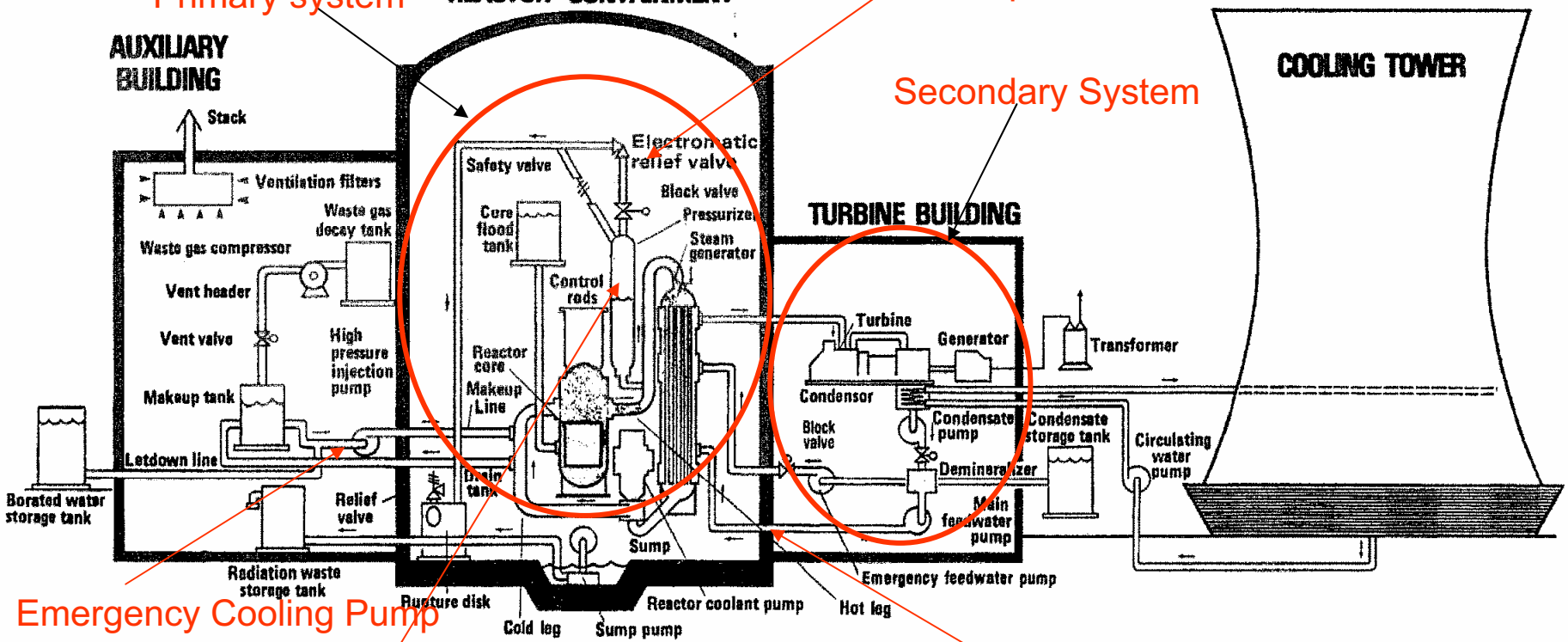


FIGURE 15-2
Schematic layout of the TMI-2 reactor. (Reprinted, and adapted with permission of IEEE, from *IEEE Spectrum*, November 1979 issue, special report on Three Mile Island.)

Event Sequence Continued

- Primary circuit pressure dropped rapidly
  - Coolant leakage out of PORV
  - Coolant shrinkage (cooldown)
- Emergency Core Cooling System (ECCS) automatically starts to provide more water
- Operators monitoring water level in pressurizer which was changing until with ECCS water level became normal.
- Operators shutdown ECCS cooling water system
- However PORV still open - “small break loss of coolant accident”

Event Sequence Continued

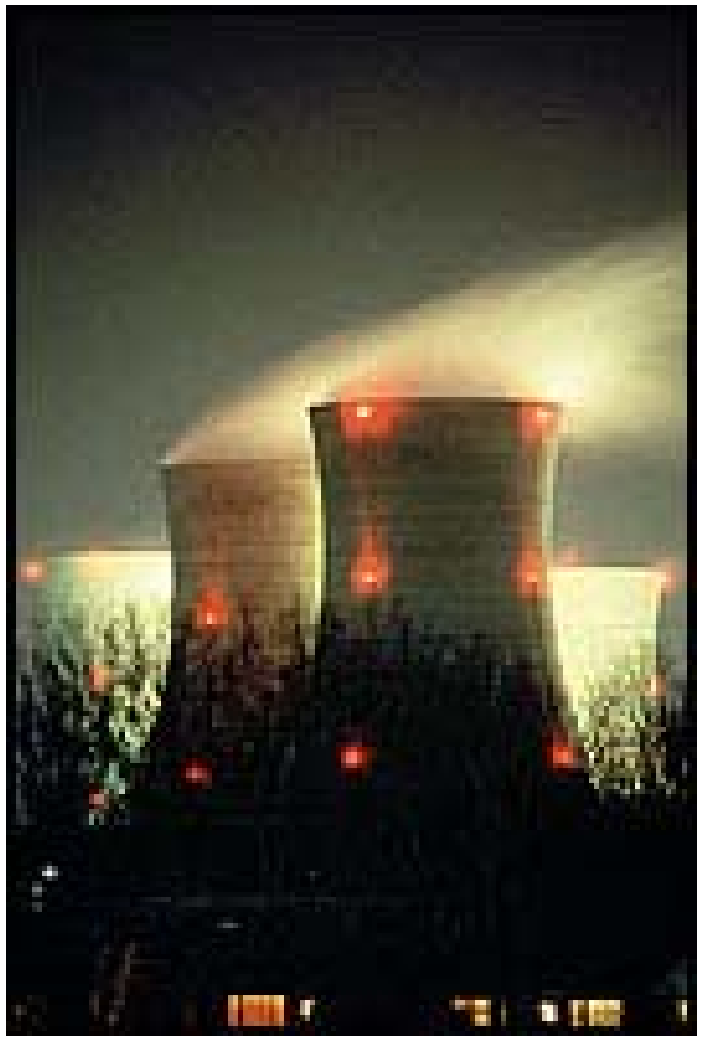
- Since PORV was open - pressure kept dropping reaching "saturation pressure" of coolant which allowed the water to boil - forming steam voids which caused the pressurizer water level to rise.
- 22 Minutes later, operators determined that there was a continuing primary coolant leak and closed the block valve downstream of the pressurizer.
- Operators then restored cooling water by ECCS and water make up system of reactor and returned reactor to normal shutdown condition.

Consequences

- Core damage accident avoided by timely operator action.
- NRC, Babcock and Wilcox and the utility investigated the incident
- Neither NRC nor the nuclear steam supplier - B&W shared this information with other B&W plants or the rest of the industry.
- 1975 Rasmussen (MIT Prof) Report analyzed probabilistic risks (PRA) of nuclear plants
  - Conclusion - small break LOCAs are dominant accident contributors
  - NRC and critics did not want to use PRA is safety determinations

18 MONTHS LATER

March 28, 1979



Courtesy of Three Mile Island Nuclear Power Station. Used with permission.

Three Mile Island
What Happened and Why ?

Courtesy of Three Mile Island Nuclear Power Station. Used with permission.

What Is Three Mile Island ?

- TMI is a two unit nuclear plant site in Middletown, Pennsylvania
- Unit 1- 792 Mwe: Unit 2 - 880 Mwe
- Babcock & Wilcox Designed PWR
- 2 Steam Generators - once through
- 4 Main Coolant Pumps
- Condensers cooled by Cooling Towers

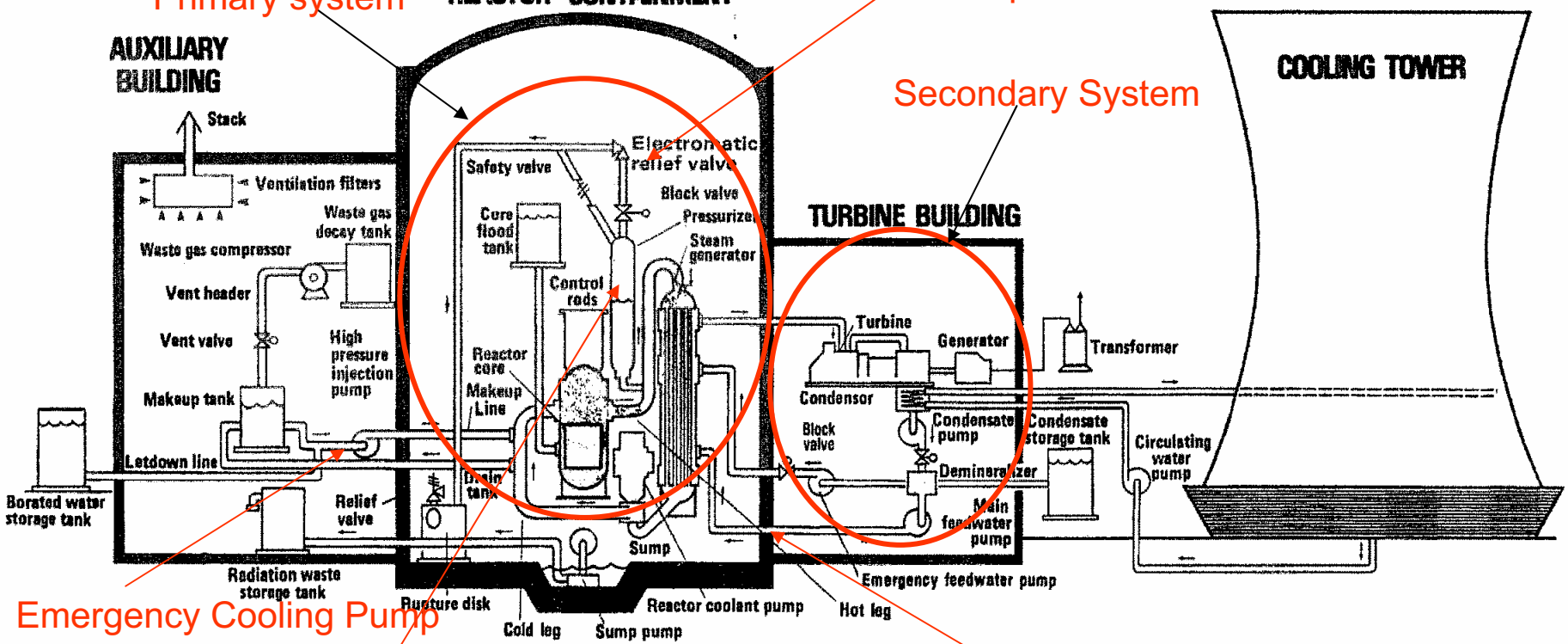


FIGURE 15-2
Schematic layout of the TMI-2 reactor. (Reprinted, and adapted with permission of IEEE, from *IEEE Spectrum*, November 1979 issue, special report on Three Mile Island.)

Steam Generators

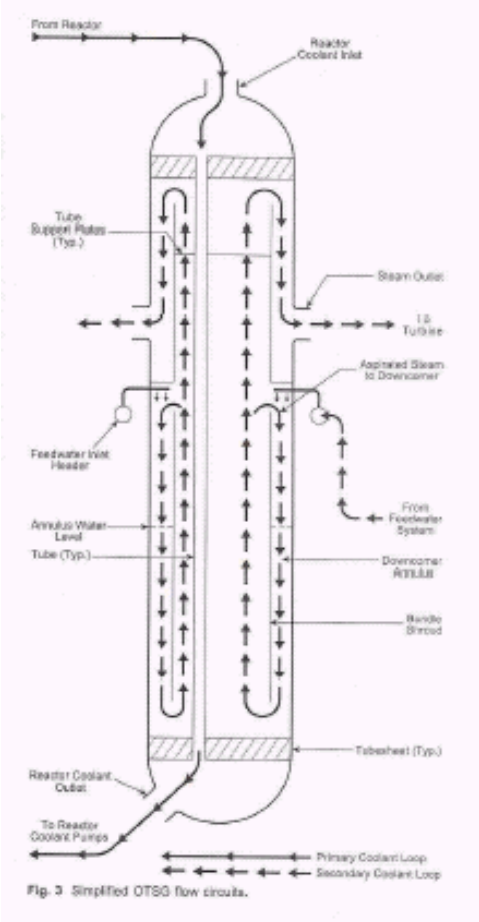


Fig. 3 Simplified OTSG flow circuits.

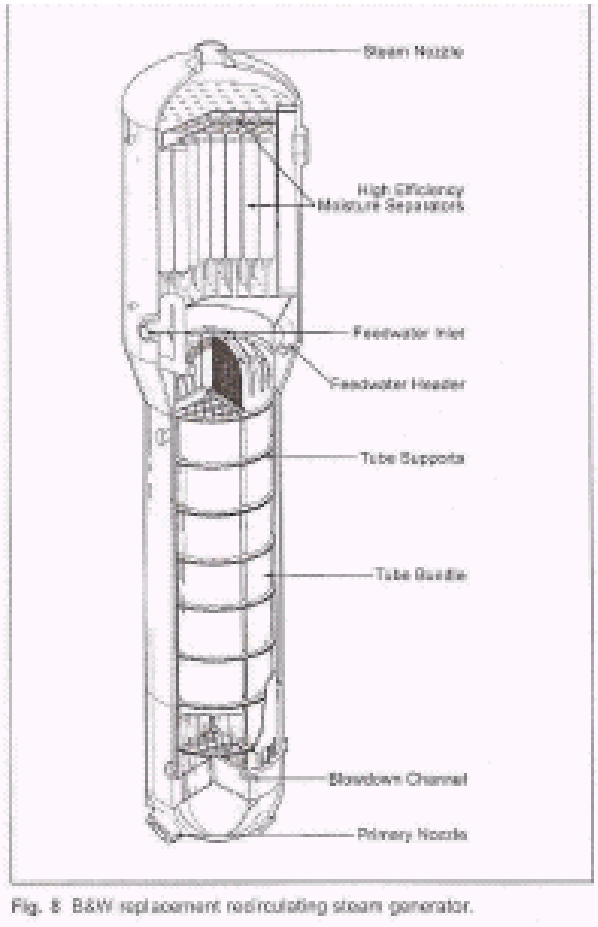


Fig. 8 B&W replacement recirculating steam generator.

B&W Once Through Steam Generator

Recirculating U Tube Steam Generator

Courtesy of Three Mile Island Nuclear Power Station. Used with permission.

Reactor Shutdown Signals

- Overpower
- High Temperature Outlet
- High Pressure
- Reactor Building Pressure
- Low Pressure
- Power imbalance/flow
- Reactor Coolant Pumps
- ARTS - anticipatory reactor trip system

  (not at TMI) - for feedwater and turbine trip for Integrated Control System)

Precursors

- TMI Unit 2 - Newest Unit on Site
- Small coolant leak in the pressurizer relief valve raises temperature downstream of valve which drains into the drain tank
- Operators unaware that two valves on emergency feedwater valves were closed following maintenance (were supposed to be open).
- Small blockage in a transfer line for demineralizer resins which could not be cleared.

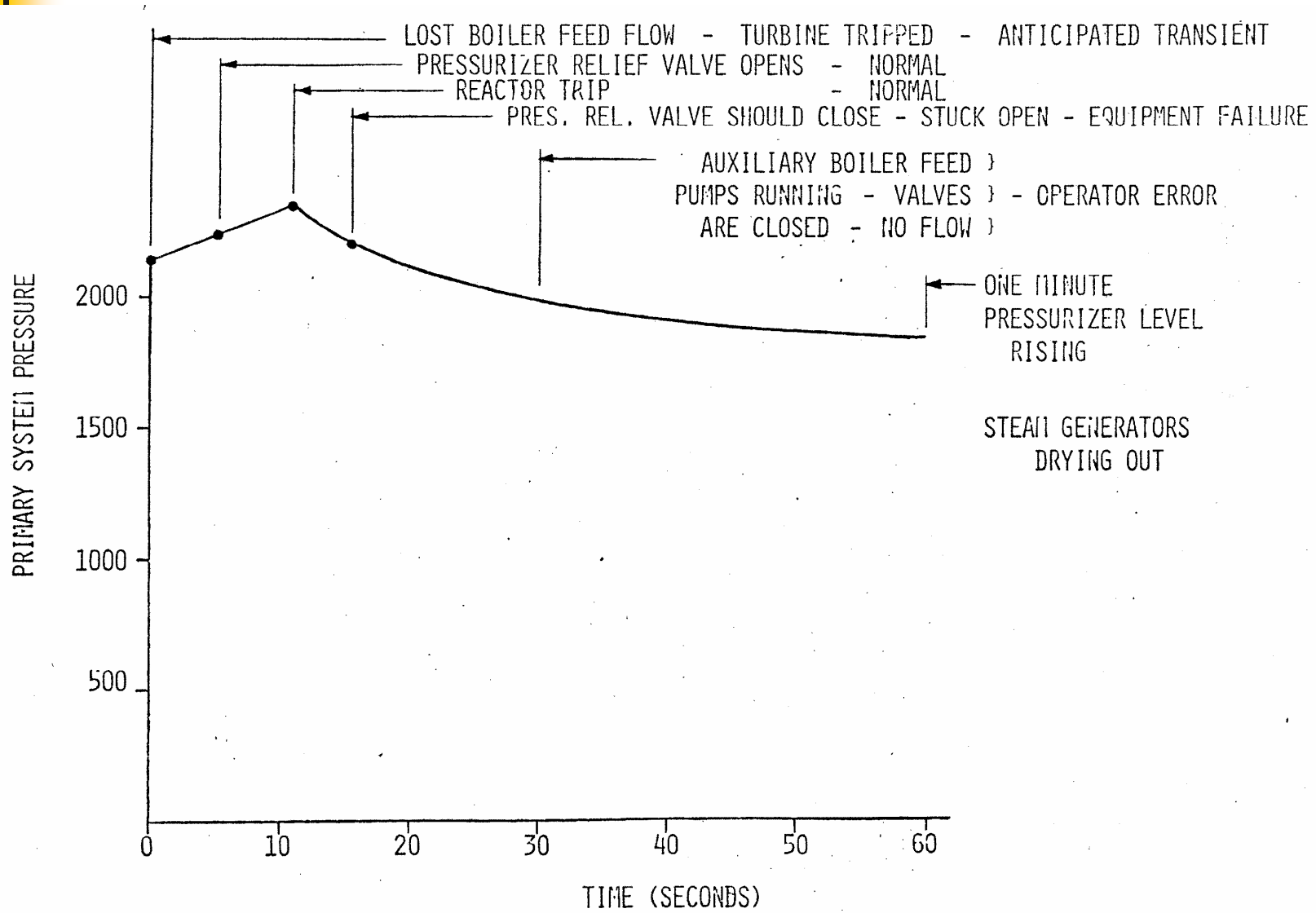
Initiation

- Plant operating normally at 97% power
- 4:00:37 (AM) loss of condensate flow due to a condensate pump trip (shutdown).

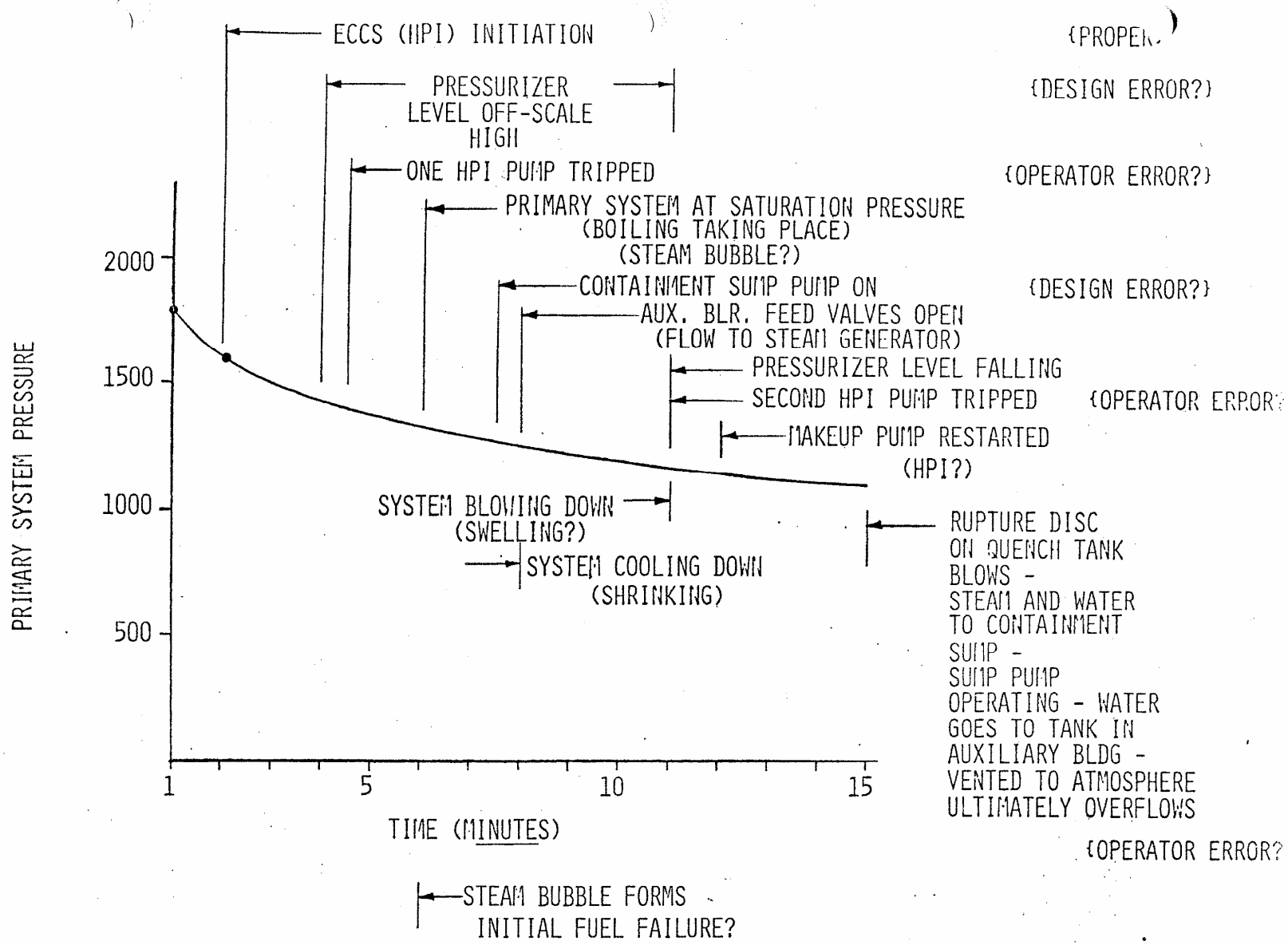
Key Sequence of Events

Approximate time	Event
	Wednesday March 28 [Day 0]
04:00:37	Main feedwater pump trips with simultaneous turbine trip
04:01 [3 s]	Primary pressure reaches relief-valve set point; valve opens
[8 s]	Reactor trips
[13 s]	Pressure drops below relief-valve set-point; valve remains open
[14 s]	Emergency feedwater pumps reach normal discharge pressure
[38 s]	Emergency feedwater directed to steam generators, but flow prevented by closed block valves
04:03 [2 min]	High-pressure injection ECCS starts automatically
	Drain tank relief valve lifts
04:06–04:08 [3–5 min]	Operators throttle high-pressure injection ECCS
04:08 [7 min]	Coolant transfer from containment to auxiliary building begins
04:09 [8 min]	Block valves on emergency feedwater lines are opened
04:16 [15 min]	Drain tank rupture disk lifts
05:14 [73 min]	Main coolant pumps in Loop A are tripped off line
05:40 [100 min]	Main coolant pumps in Loop B are tripped off line
05:30–07:30 [90–210 min]	Uncovered core heats up; zirconium-water reactions lead to fuel-assembly damage and hydrogen evolution

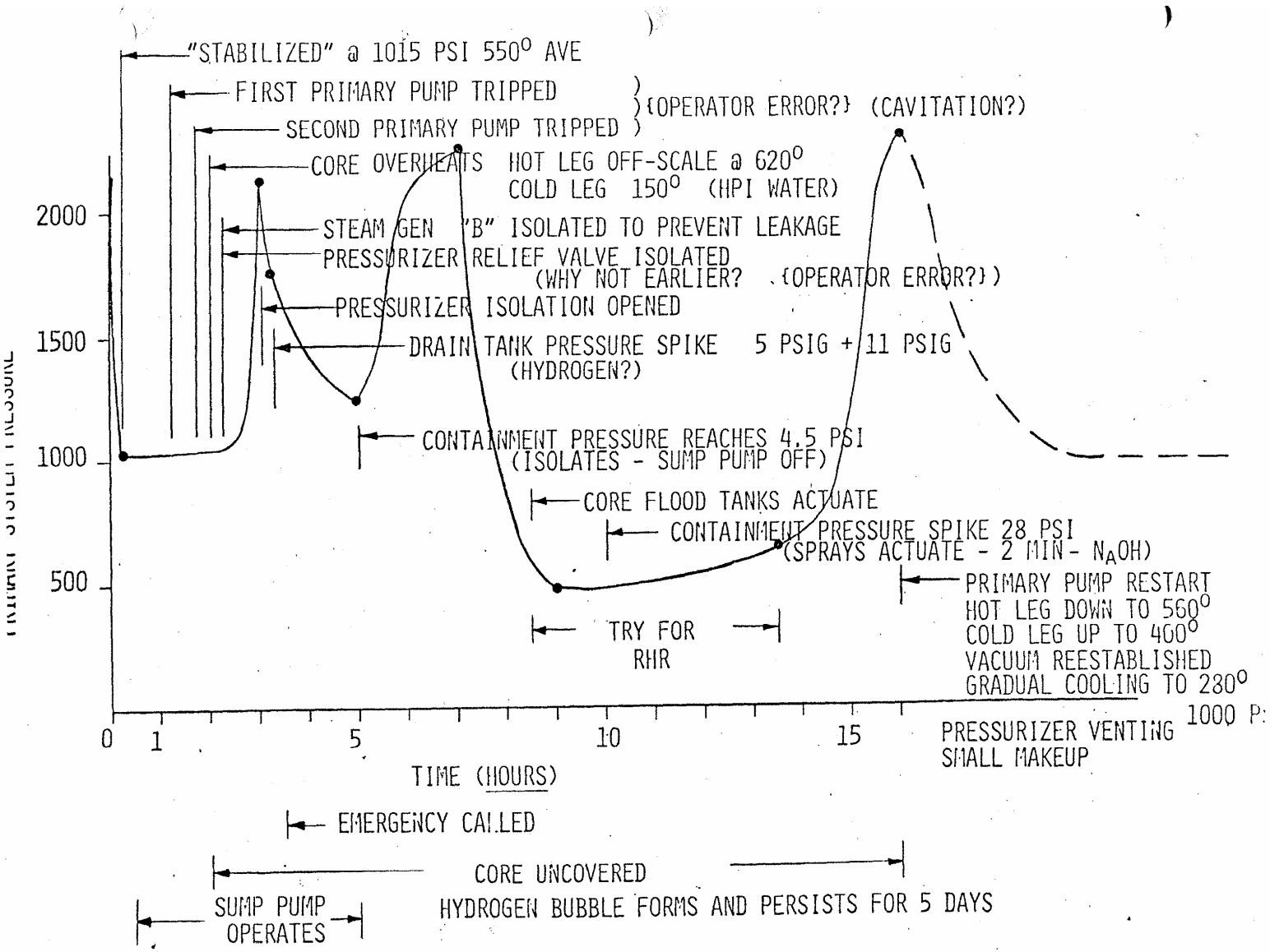
06:22 [142 min]	Block valve on pressurizer drain line is closed
06:30 [150 min]	In-core thermocouple readings go off scale
06:54 [174 min]	Operation of a coolant pump causes extensive clad damage
07:00 [180 min]	Site emergency declared
07:20 [200 min]	HPI operation re-covers core
07:30 [210 min]	General emergency declared
07:44–07:46 [224–226 min]	Molten fuel from core relocates to reactor vessel lower head*
09:00 [300 min]	Coolable core geometry established
	Associated Press news service reports declaration of general emergency with no radioactivity releases
13:30 [9.5 h]	Hydrogen detonation in reactor building produces pressure spike
20:00 [16 h]	Main coolant pumps in Loop A restart to restore forced cooling



Courtesy of Three Mile Island Nuclear Power Station. Used with permission.



Courtesy of Three Mile Island Nuclear Power Station. Used with permission.



Courtesy of Three Mile Island Nuclear Power Station. Used with permission.

Approximate time	Event
	Thursday March 29 [Day 1]
	Friday March 30 [Day 2]
08:00	Misinterpreted radiation reading above vent stack is followed by recommendation from Governor of Pennsylvania for sheltering within 10 mi
12:30	Governor recommends school closings and evaluation of pregnant women and pre-school children within 5 mi
Day	Majority of 144,000 spontaneous evacuations and school closings occur
Evening	Heavy media coverage emphasized "fearful and dramatic aspects"
	Saturday March 31 [Day 3]
	Discussion of possibility of a hydrogen bubble and an in-vessel explosion
	Sunday April 1 [Day 4]
	Visit to TMI-2 by the President of the United States
	Tuesday April 3 [Day 5]
	Plant stable, threat of hydrogen explosion discounted
	Saturday April 7 [Day 9]
	Closed schools outside of 5-mi radius began planning to reopen
	Monday April 9 [Day 11]
	Evacuation lifted

Bubble Trouble

- Hydrogen Production
  - Due to zirconium water reaction
- Oxygen generation due to
  - Radiolysis
  - Boiling
- Possible explosive mixture ?
  - Why or why not ?
  - Why missed in analysis ?
- Was reactor vessel in danger of exploding ?
  - What was missing in the approach ?
  - NRC - Industry

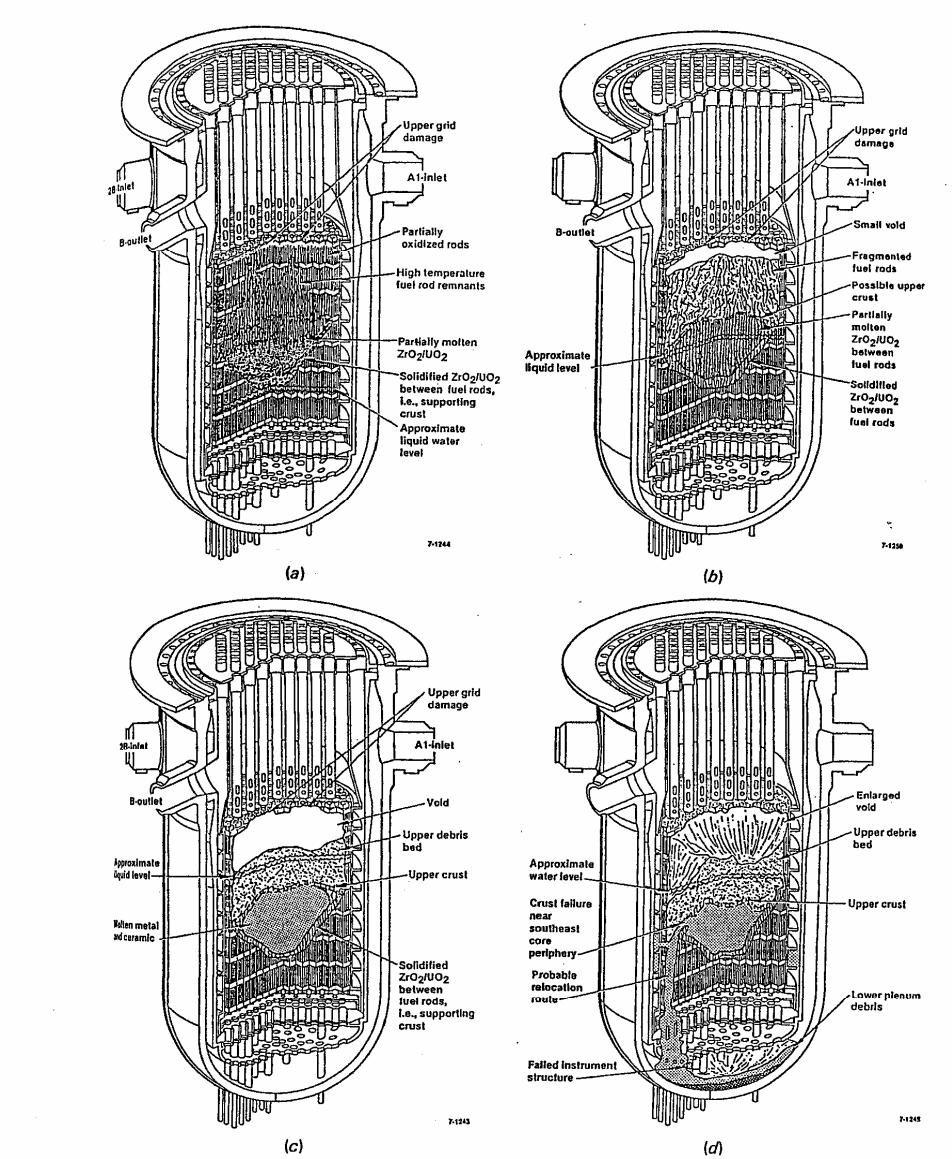
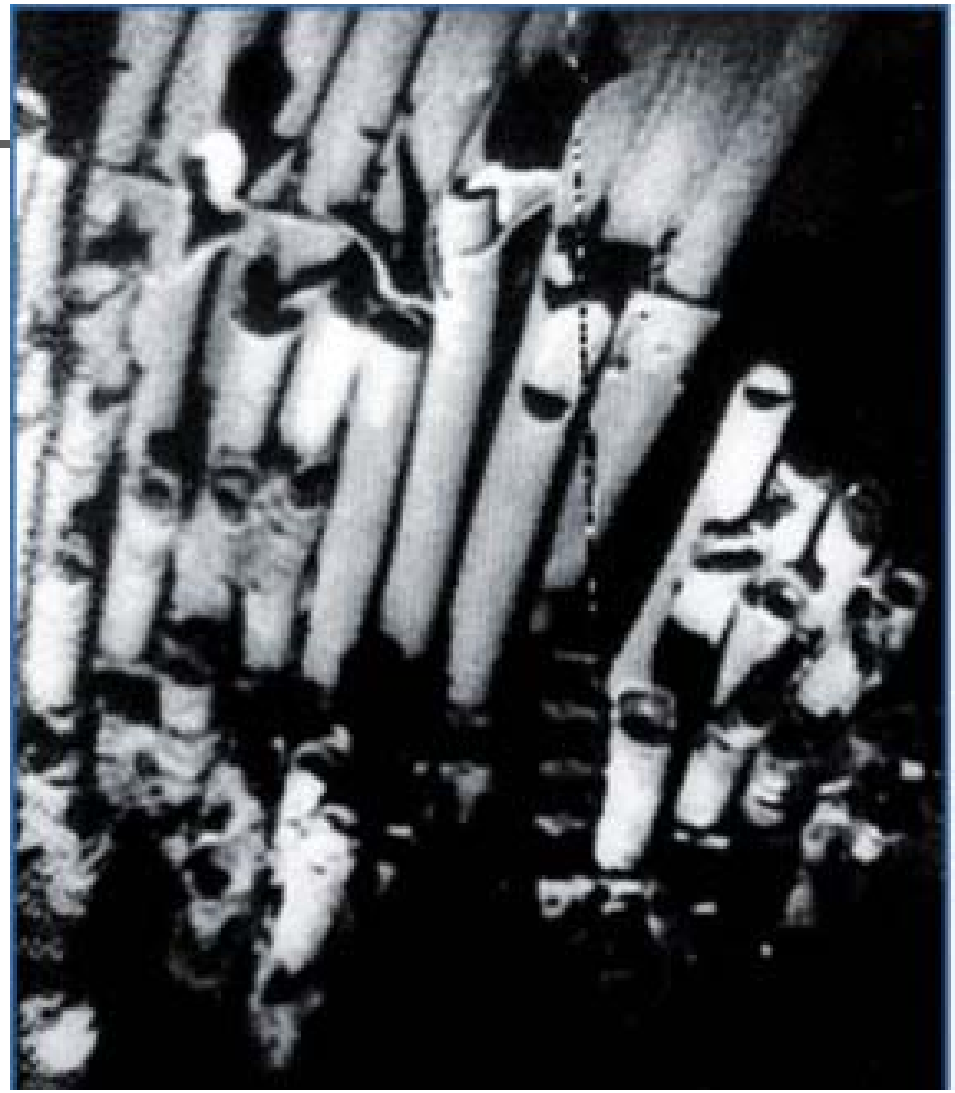
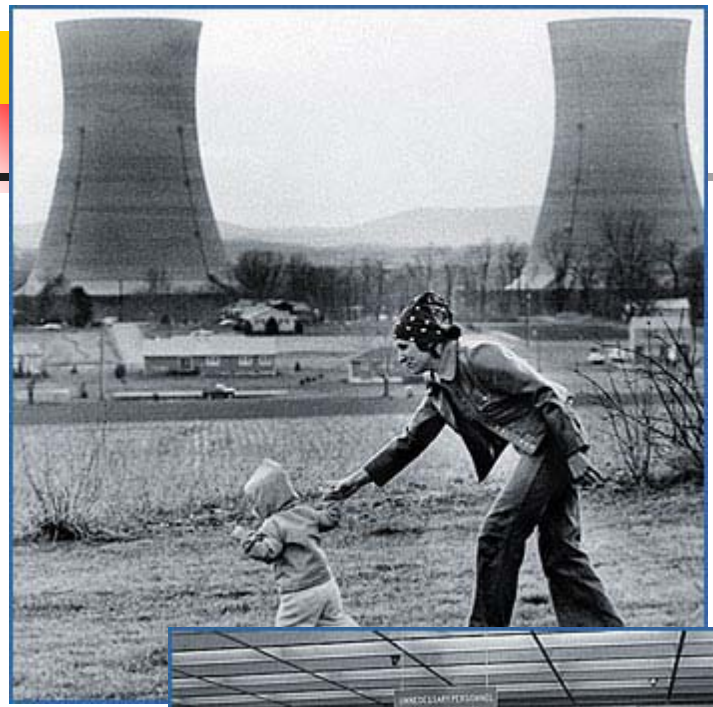


FIGURE 15-3
Hypothesized condition of the Three Mile Island Unit 2 reactor core at (a) 173, (b) 175–180, (c) 224, and (d) 226 minutes into the accident. (Courtesy of EG&G, Idaho, Inc.)



Inside TMI Reactor Vessel Post Accident



1979

Today

Courtesy of Three Mile Island Nuclear Power Station. Used with permission.

Public Health and Environmental Consequences

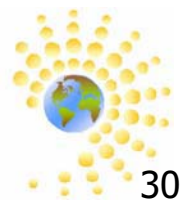
- Studies by EPA, Health and Human Services, DOE, NRC and the State of Pennsylvania
- Thousands of environmental samples
- Conclusions
  - Average dose to 2 million people in area < 1 mrem
  - Max dose at site boundary full time - 100 mrem
  - Natural background in area - 100-125 mrem/yr
  - 1 Chest x-ray - 6 millirem
- No adverse Health Effects

Lessons Learned (Good)

- Water helps even if core is severely damaged
- Vessel did not fail even with molten core in the bottom
- No energetic steam explosion
- Most fission products contained inside
- Containments work

Lessons Learned (not so good)

- Inadequate operator training - formed INPO
- Instrumentation needs upgrading - did it
- Added Safety Parameter Display System
- Added new instrumentation
  - Reactor Water Level
  - Post Accident Sampling System
- Added Shift Technical Advisor to all shifts
- Emergency planning needed upgrading - done
- Focused attention on severe accident research
- Need new operator emergency response procedures - critical safety functions - done
- Risk focus should not be on Large Break LOCA but more likely events
- Use of Probabilistic Risk Analysis to understand safety of plants not just depend on regulations



Powerful Record

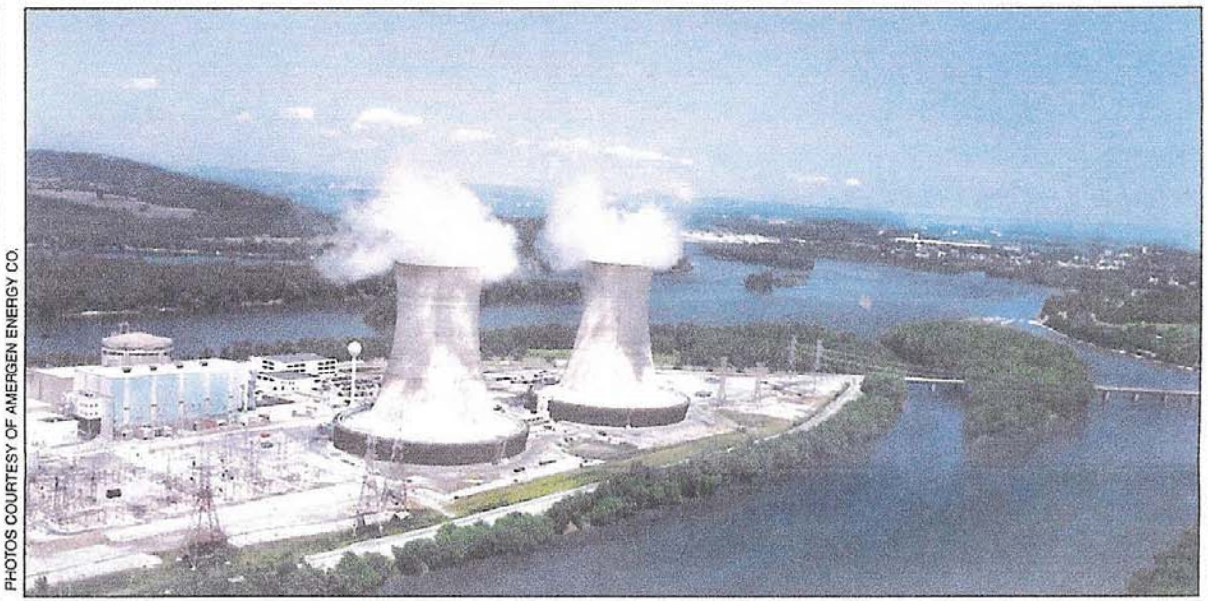
Three Mile Island Reactor Sets World Operating Standard for Third Time

The Three Mile Island (TMI-1) nuclear power plant recently set a world record for continuous days of operation by a pressurized water reactor.

More than 200 pressurized water reactors now generate electricity worldwide. TMI-1, located near Harrisburg, Pa., operated continuously for 680 days until a scheduled refueling in October.

"This achievement is a tribute to the commitment and teamwork of the men and women at TMI-1 and those from around Exelon who support the plant," said Bruce Williams, TMI-1 site vice president. "The ability of our employees to focus on the safe operation of the plant while learning new processes and procedures to improve the way we operate is commendable.

PHOTOS COURTESY OF AMERGEN ENERGY CO.



Three Mile Island generates enough electricity to power a city the size of Philadelphia.

Courtesy of Three Mile Island Nuclear Power Station. Used with permission.

Bottom Lines

- Precursors are important indicators of problems - need to be addressed not ignored
- Industry Complacency is a risk.
- Attention to detail and understanding how plants work is vital
- On-line risk monitors very helpful in gauging plant status
- Knowledgeable and well trained staff and engineers very important
- Management and Safety Culture hugely important to safe operations.

Homework

- Read Rogovin Report Executive Summary
  - Analyze event from the perspective of why the accident happened and why it became a such serious problem. (Beyond the obvious of failing to recognize the open PORV). Given your experience in the simulators (recall that the simulator you were in did not represent control rooms of the 1970's).
    - Consider operator training
    - Regulations
    - Technical response
    - Knowledge
    - Control room Design and instrumentation
    - Fundamental design of reactor
    - Management culture
- Read Steam Generator Report for background on designs

3 pages of analysis (11 font - 1.5 line spacing).

22.091 Nuclear Reactor Safety
Spring 2008