Operational Reactor Safety

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Professor of the Practice

Safety Systems and Functions
Lecture 9

Topics to be Covered

- Fundamentals of Safety
  - Introduction to Safety Analysis
  - Defense in Depth
  - Design Basis Accidents
  - Beyond Design Basis Accidents
  - Safety Systems
  - Emergency Safeguards Systems
  - Containment

Key Safety Measures

- Prevention
  - Proper Design and Training
- Protection
  - Monitoring and Control Systems
  - Active shutdown and cooling systems
- Mitigation – limit consequences
  - Engineered Safety Systems

Called Defense in Depth Approach

Energy Sources

- Stored Energy in Fuel, Steam and Structures
- Energy from nuclear transients
- Decay Heat
- Chemical Reactions
- External events – seismic, tornadoes, hurricanes, etc.

Mission - Remove Heat

- Prevent fuel cladding failure or core melting
  - Install systems to do this under many transient and accident conditions
- If unsuccessful, keep radioactive materials in the containment
  - Assure containment function is maintained and not breached by overpressure or missiles
- If unsuccessful, limit releases
- If unsuccessful, implement emergency plan

Design Basis Accidents

- Overcooling
- Undercooling
- Overfilling
- Loss of Flow
- Loss of Coolant
- Reactivity
- Anticipated Transients without Scram
- Spent fuel or handling events
- External Events

Energetic Reactions in Reactors

TABLE 13-1
Properties of Potentially Energetic Chemical Reactions of Interest in Nuclear Reactor Safety†

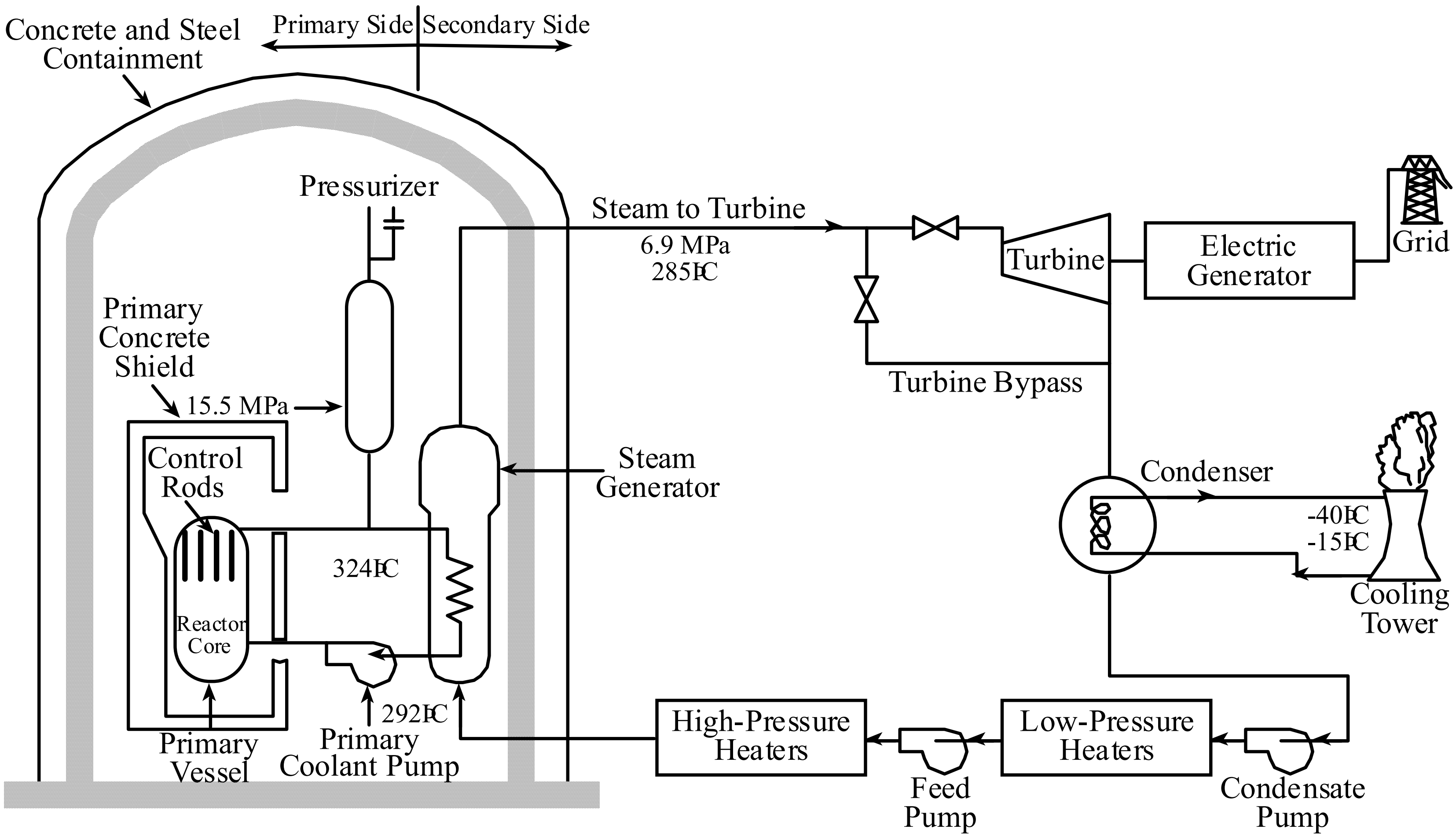
Reactant R	Temperature (°C)	Oxide(s) formed	Heat of reaction‡ with: Oxygen (kcal/kg R)	Heat of reaction‡ with: Water (kcal/kg R)	Hydrogen produced with water (l/kg R)
Zr (liq.)	1852§	ZrO_2	−2883	−1560	490
SS (liq.)	1370§	FeO, Cr_2O_3, NiO	−1330 to −1430	−144 to −253	440
Na (solid)	25	Na_2O	−2162	—	—
Na (solid)	25	NaOH	—	−1466	490
C (solid)	1000	CO	−2267	+2700	1870
C (solid)	1000	CO_2	−7867	+2067	3740
H_2 (gas)	1000	H_2O	−29,560	—	—

†Adapted from T. J. Thompson and J. G. Beckerley, eds., *The Technology of Nuclear Reactor Safety*, Vol. 1, by permission of The MIT Press, Cambridge, Mass. Copyright © 1964 by the Massachusetts Institute of Technology.

‡Positive values indicate energy that must be added to initiate an endoergic reaction; negative values indicate energy released by exoergic reactions.

§Melting point.

Pressurized Water Reactor Schematic



Specific Design Basis Accidents

- Steam line break
- Loss of Flow
- Loss of heat sink
- Steam generator tube(s) rupture
- Control rod ejection or rapid withdrawal
- Anticipated Transients without Scram
- Pressurized thermal shock
- Loss of coolant
  - Double ended guillotine break
  - Small Break

Typical PWR

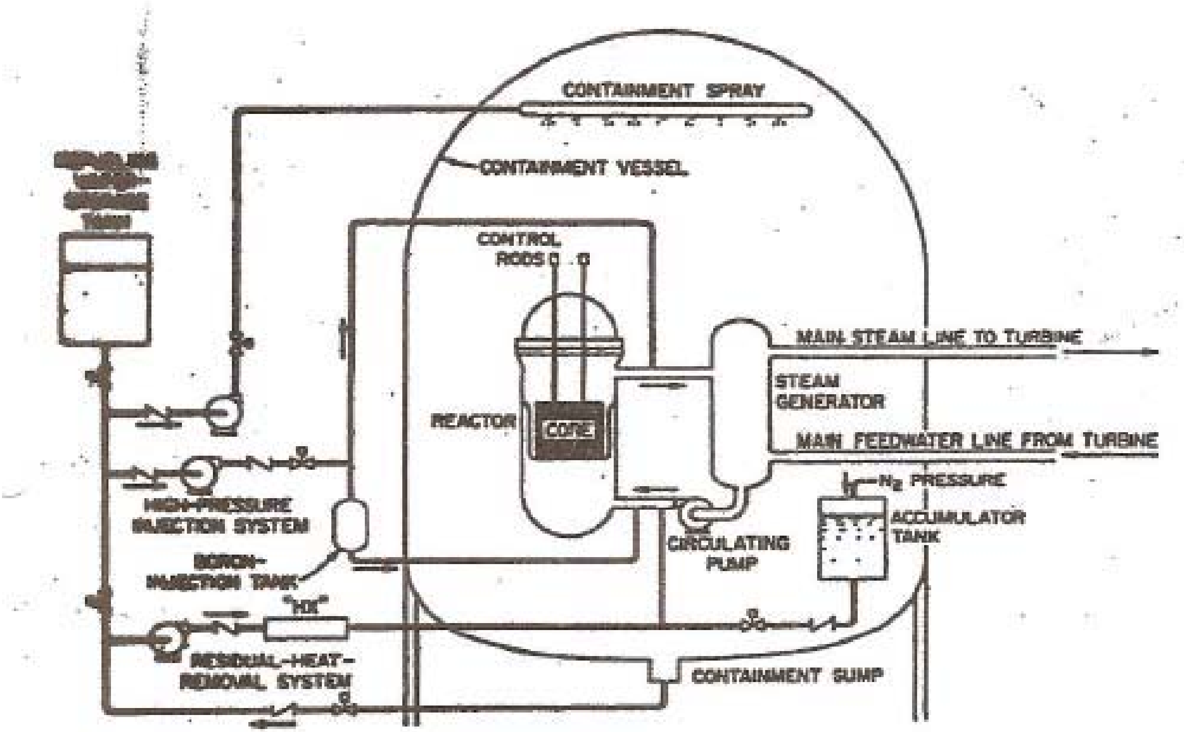


FIGURE 14-2
Engineered safety systems for a PWR. (From W. B. Cottrell, "The ECCS Rule-Making Hearing," *Nuclear Safety*, vol. 15, no. 1, Jan.–Feb. 1974.)

Severe Accidents

- Beyond Design Basis
  - Successive failures of the engineering safety systems
  - Looking for cliff edge effects that may need to be addressed if consequences are severe and scenario is plausible.
  - Core Melt scenarios - vaporization
    - Steam explosion
    - Hydrogen explosion
    - Fission product inventory for release

Fission Products for Release

TABLE 13-2
Estimate of Fission Products Available for Release from an LWR Meltdown Accident†

Fission products	Cumulative release percentage			
	Gap	Meltdown	Vaporization‡	Steam Explosion
Noble gases (Kr, Xe)	3.0	90	100	90 (X)(Y)
Halogens (I, Br)	1.7	90	100	90 (X)(Y)
Alkali metals (Cs, Rb)	5	81	100	—
Te, Se, Rb	10^{-2}	15	100	60 (X)(Y)
Alkaline earths (Sr, Ba)	10^{-4}	10	11	—
Noble metals (Ru, Mo)	—	3	8	90 (X)(Y)
Rare earths (La, Sm, Pu) & refractories (Zr, Nb)	—	0.3	1.3	—

†Adapted from WASH-1400 (1975).
‡Exponential loss over 2 h with a half-time of 30 min. If a steam explosion [illegible] first, only the core fraction not involved in the explosion can experience vaporization.
§X = fraction of core involved; Y = fraction of inventory remaining for release.

Loss of Coolant Accident Sequence

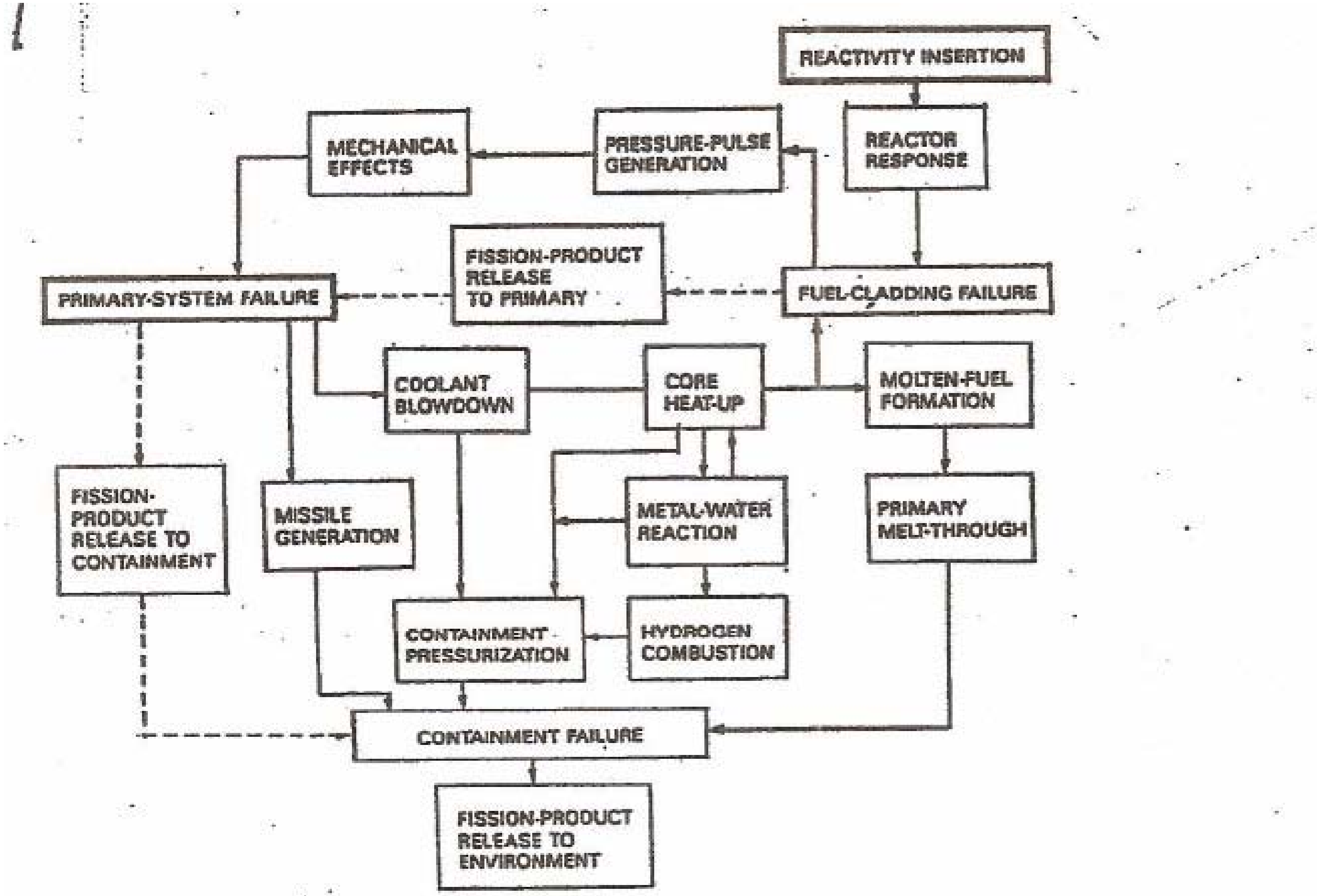


FIGURE 13-1

Loss-of-coolant acc... [LOCA] sequences for light-water reactors. (Adapted from A. Sesonske, Nuclear Power Plant Design Analysis, TID-26241, 1973.)

Engineered Safety Systems

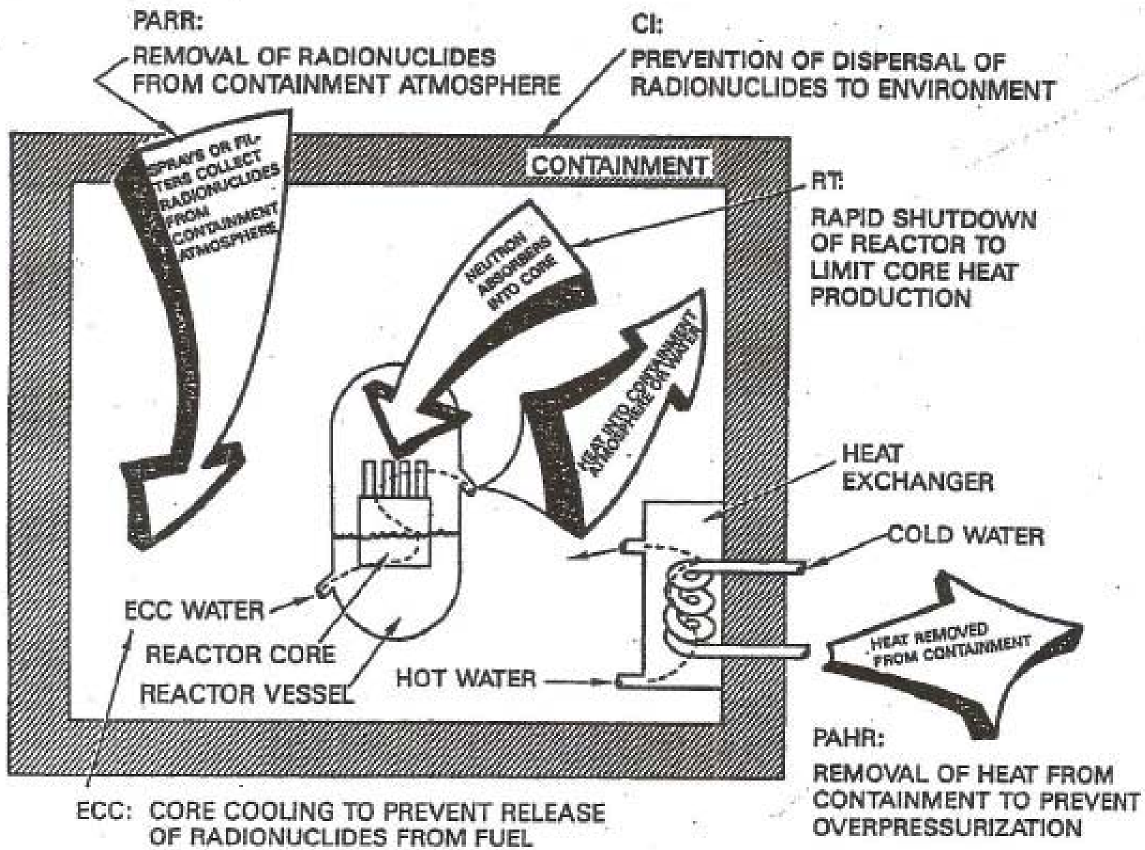


FIGURE 14-1
Conceptual engineered safety systems for LWRs. (Adapted from WASH-1400, 1975.)

PWR Engineered Safety Systems

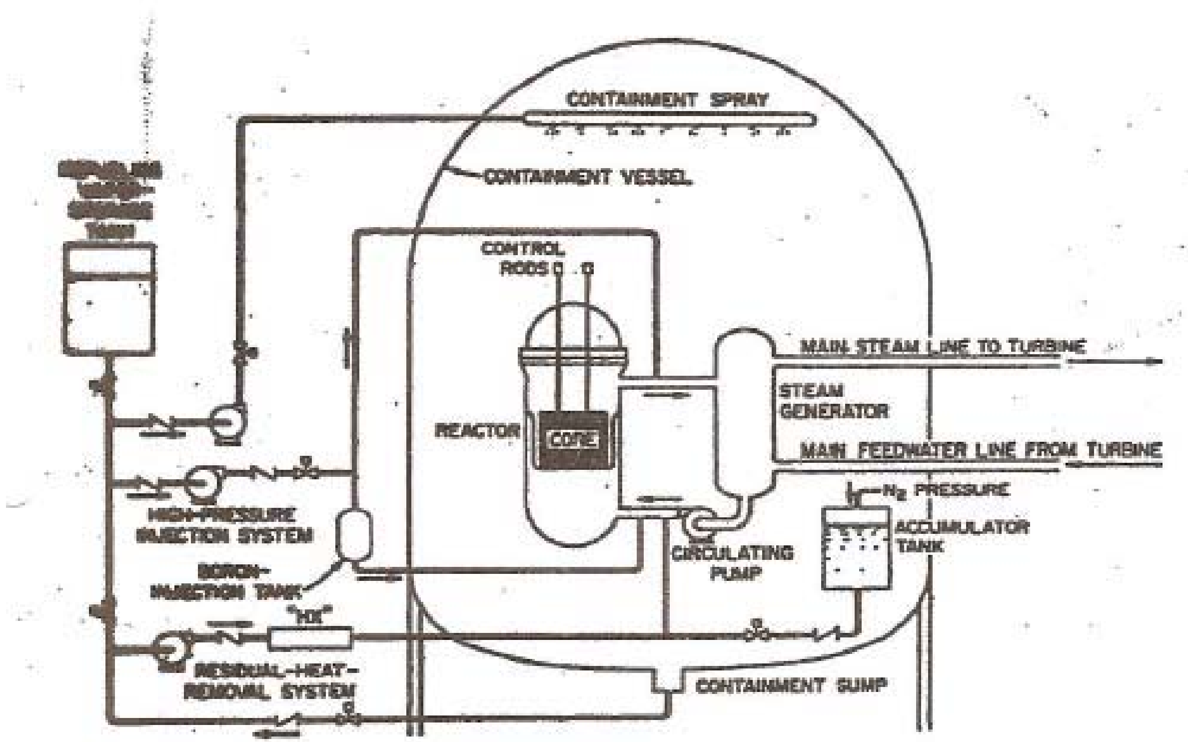


FIGURE 14-2
Engineered safety systems for a PWR. (From W. B. Cottrell, "The ECCS Rule-Making Hearing," *Nuclear Safety*, vol. 15, no. 1, Jan.–Feb. 1974.)

PWR Containment

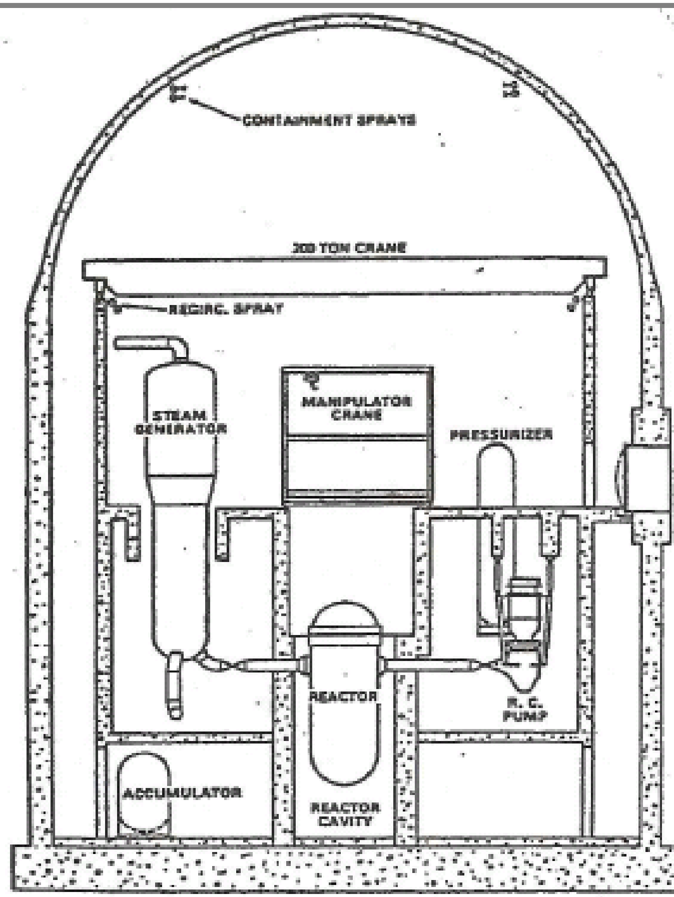


FIGURE 14-4
Representative PWR containment. (From NUREG-1150, 1989.)

Containment Pressure Response

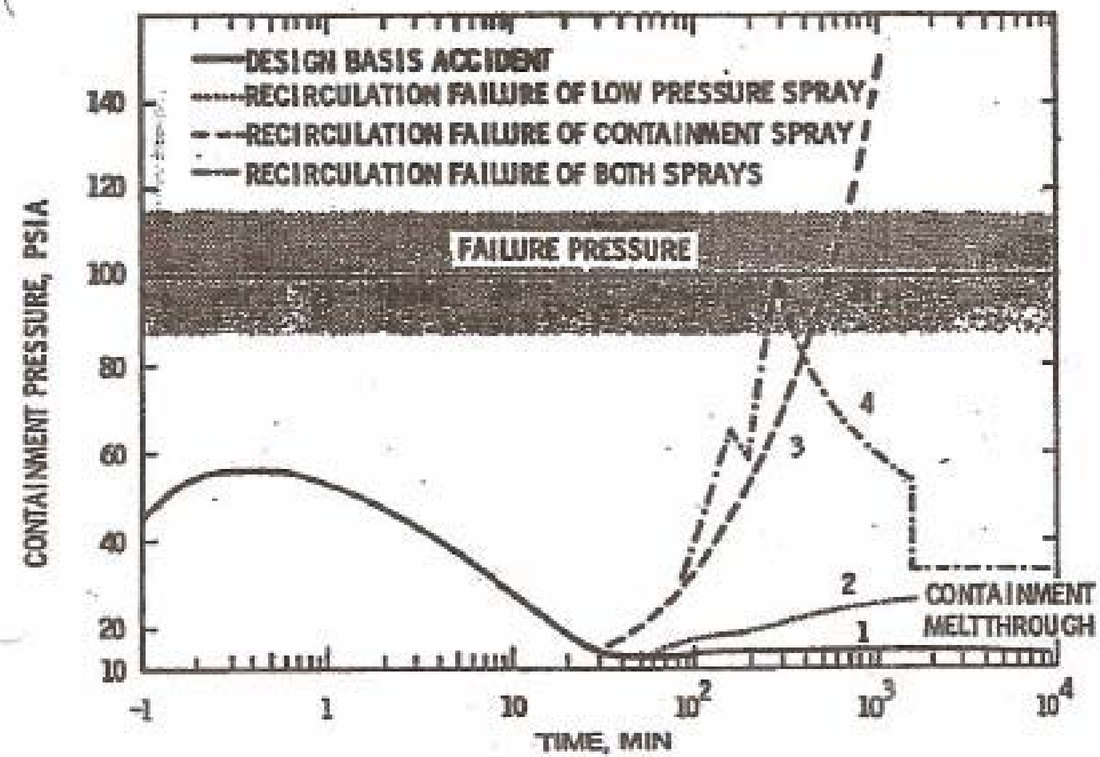


FIGURE 14-5
Containment pressure response for a PWR to a design-bases LOCA with assumed safety system failures. (Adapted from WASH-1400, 1975.)

BWR Early Engineered Safety Systems

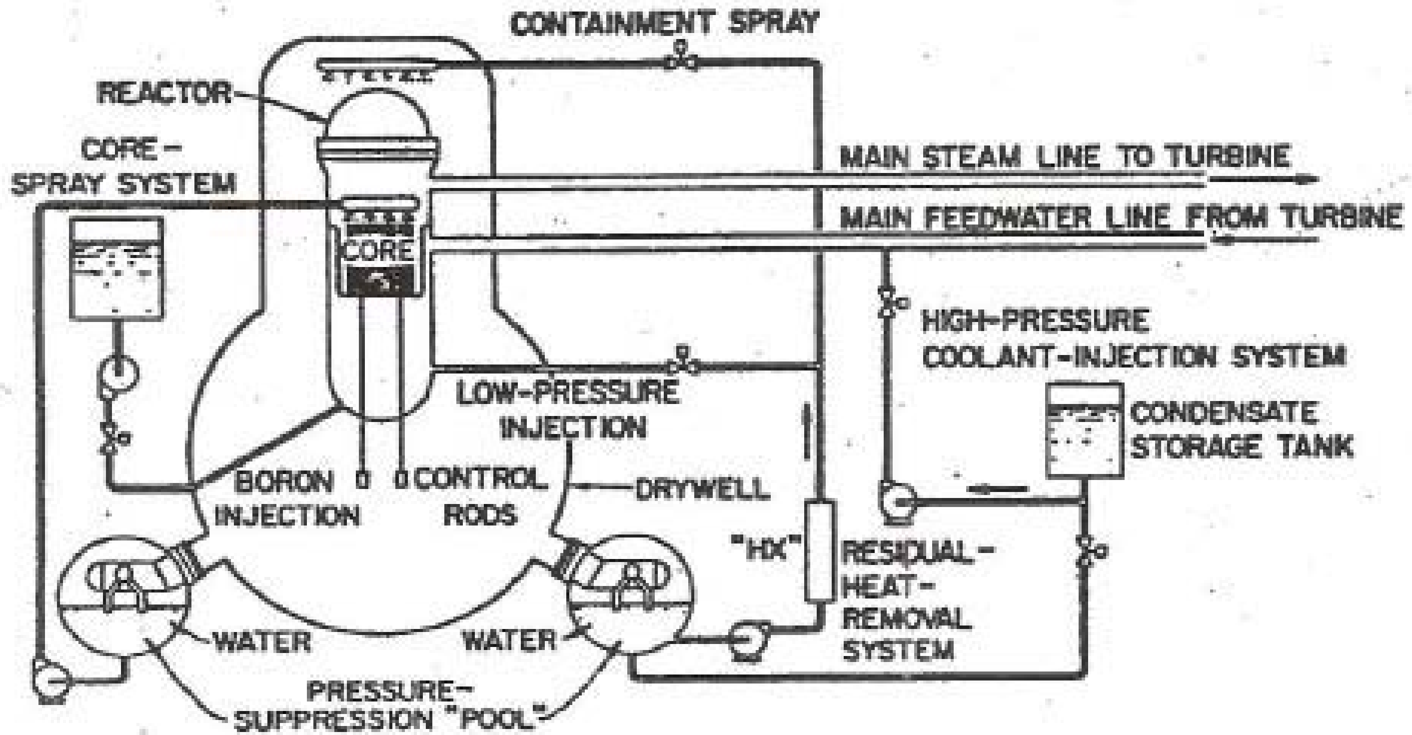
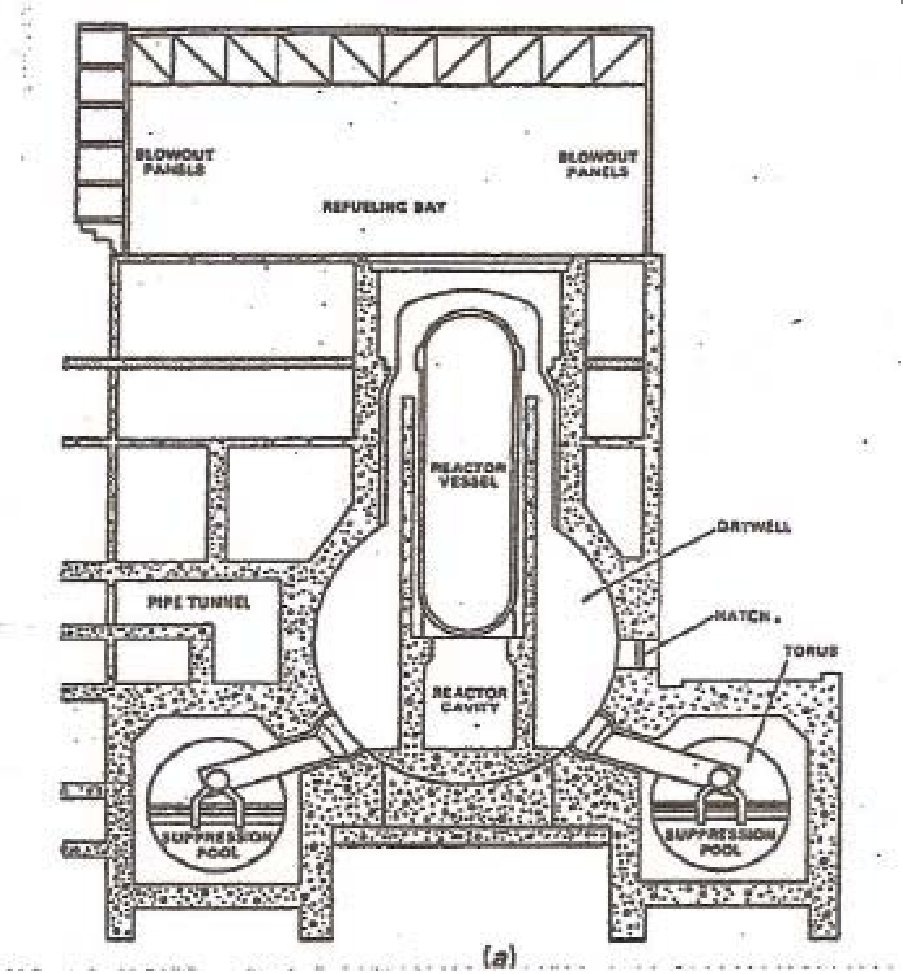
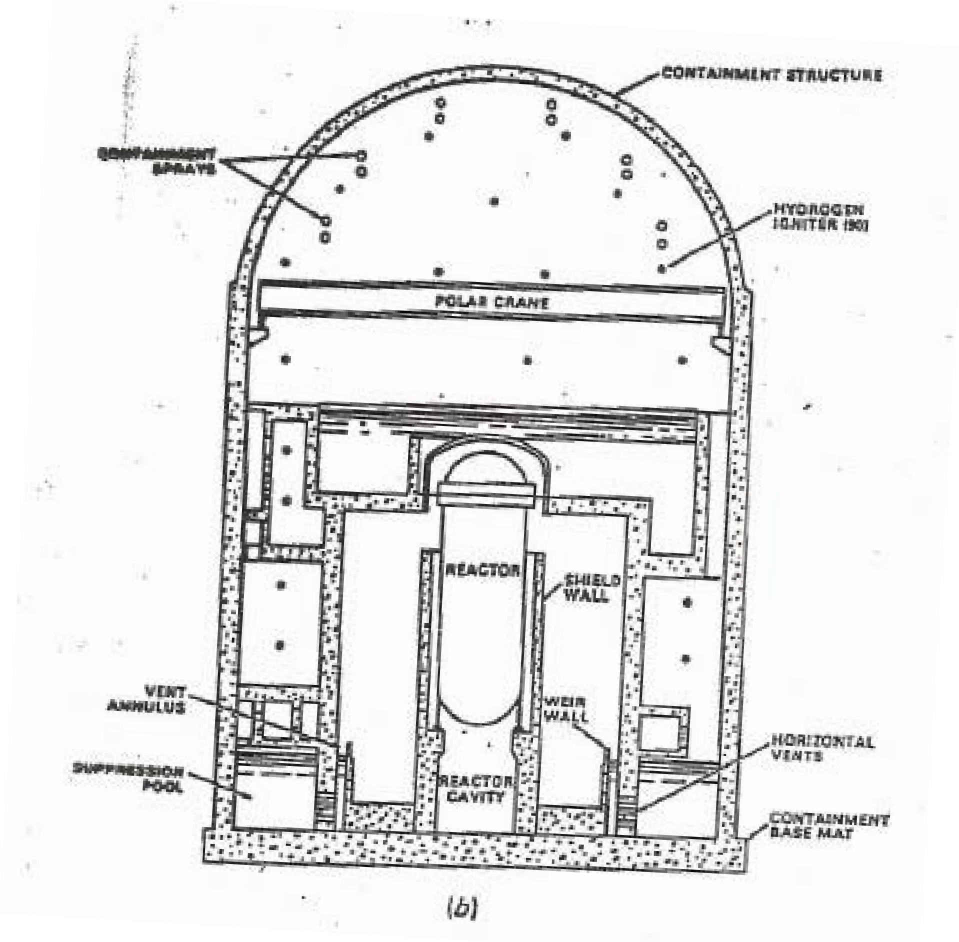


FIGURE 14-6
Engineered safety systems for an early BWR. (From W. B. Cottrell, "The ECCS Rule-Making Hearing," *Nuclear Safety*, vol. 15, no. 1, Jan.–Feb. 1974.)

Early BWR Containment Design



Later Version of BWR Containment



Containment Leakage

- Function of event and chemistry in building
- Driven by containment pressure
- Source terms
  - Noble gases – not captured
  - Elemental iodine – reactive and plated out
  - Organic iodides – not chemically reactive
  - Particulates and aerosols – heavy settle out
- What is not chemically reacted in containment, plated out or settled out is available for release.

Reading and Homework Assignment

1. Read Knief Chapter 13
2. Problems: 13.3, 13.5, 13.8, 13.12 Extra: 13.11