Nuclear Safety

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22.06: Engineering of Nuclear Systems

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Hazard

A very large inventory of radioactive fission products ($>GCi/t_U$), some with long half-life (>years)

Radionuclide content of representative LWR spent fuel at discharge and 180 days of representative LMFBR fuel at discharge and 30 days‡

			Activity, Ci/t metal			
			LWR fuel		LMFBR fuel	
Nuclide	Half-life $T_{1/2}$	Radiations‡	Discharge	180 d	Discharge	30 d
^{3}H	12.3 y	β	5.744×10^{2}	5.587×10^{2}	1.648×10^{3}	1.640×10^{3}
^{85}Kr	10.73 y	β, γ	1.108×10^{4}	1.074×10^{4}	1.473×10^{4}	1.466×10^{4}
^{89}Sr	50.5 d	β, γ	1.058×10^{6}	9.603×10^{4}	1.333×10^{6}	8.939×10^{5}
^{90}Sr	20.9 y	β, γ	8.425×10^{4}	8.323×10^{4}	9.591×10^{4}	9.572×10^{4}
^{90}Y	64.0 h	β, γ	8.850×10^{4}	8.325×10^{4}	1.214×10^{5}	9.572×10^{4}
^{91}Y	59.0 d	β, γ	1.263×10^{6}	1.525×10^{5}	1.794×10^{6}	1.269×10^{6}
^{95}Zr	64.0 d	β, γ	1.637×10^{6}	2.437×10^{5}	3.215×10^{6}	2.340×10^{6}
^{95}Nb	3.50 d	β, γ	1.557×10^{6}	4.689×10^{5}	3.149×10^{6}	2.954×10^{6}
^{99}Mo	66.0 h	β, γ	1.875×10^{6}	3.780×10^{-14}	4.040×10^{6}	2.108×10^{3}
^{99m}Tc	6.0 h	γ	1.618×10^{6}	3.589×10^{-14}	3.487×10^{6}	2.002×10^{3}
^{99}Tc	2.1×10^{5} y	β, γ	1.435×10^{1}	1.442×10^{1}	3.278×10^{1}	3.293×10^{1}

Overarching Objective of Nuclear Safety

Protect staff, public and environment

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Prevent uncontrolled release of radioactivity from plant

Implementation

- Heat removal
- Defense-in-depth:
  - Physical barriers
  - Design, construction and operation

Heat Removal

~98% of all fission products are retained in the fuel pellet unless the fuel melts

It is important to keep the fuel “cool” under all modes of normal operation:

1) Power mode (steady-state): fission energy generates steam which releases energy in turbine and condenser

2) Shutdown mode (turbine not available): decay heat generates steam, which is dumped directly into condenser (PWR and BWR) or atmosphere (only PWR)

3) Refueling mode: fuel is kept under water and decay heat is removed by residual heat removal system (RHRS)

Defense-in-Depth (physical barriers)

There exist multiple physical barriers between the source of radioactivity (the fission products) and the environment/public. The most important barriers are:

1) Fuel pellet: it retains most solid fission products.
2) Cladding: it retains all fission products (gaseous included).
3) Reactor coolant system: robust high-pressure system of pipes + vessel. Most fission products are soluble in coolant and/or deposit on cold surfaces of pipes.
4) Containment: seal tight system is the ultimate barrier to radioactivity release, even if all previous barriers have failed.

Defense-in-Depth (design, construction and operation)

The concept of defense-of-depth extends to nuclear plant design, construction and operation.

Emphasis is on prevention, protection and mitigation.

1) Prevention. Minimize causes of failures/accidents before they occur:

- Design reactor with inherent safety features (e.g. negative moderator, coolant and fuel reactivity coefficients) and margins to failure (e.g. MDNBR>1.3)
- Use of chemically compatible materials (e.g. no graphite and water in core)
- Quality assurance in component manufacturing and construction ("N-stamp")
- Thorough training of operators + conservative operation

Defense-in-Depth (design, construction and operation) (2)

2) Protection. Reactor protection system:

- Monitors plant conditions (e.g. measures temperature, pressure, flow, power, radiation levels)
- Recognizes precursors to transients/accidents
- Actuates scram and safety systems

3) Mitigation. When accidents do occur, mitigate consequences using:

- Engineered safety systems
- Emergency plan/evacuation

Design-Basis Accident Classification

- Undercooling: decrease in secondary-side heat removal (e.g. loss of condenser cooling water)
- Overcooling: increase in secondary-side heat removal (e.g. loss of feedwater heating)
- Overfilling: increase in reactor coolant inventory (e.g. mismatch between feedwater and steam flow in BWR)
- Loss of flow: decrease in core flow rate (e.g. trip of reactor pumps)
- Loss of coolant: decrease of reactor coolant inventory (e.g. break of primary system pipe)

Design-Basis Accident Classification (2)

- Reactivity insertion: uncontrolled insertion of positive reactivity (e.g. rod drop in BWR)
- Anticipated Transients Without Scram (ATWS): a relatively frequent abnormal event (transient) with simultaneous failure to scram (e.g. loss of feedwater without scram)
- Spent fuel accidents: occurring while handling and storing spent fuel assemblies (e.g. drop a fuel assembly, or critical configuration in fuel storage pool)
- External events: an event initiating outside the plant (e.g. earthquake, hurricane, airplane crash)

Engineered Safety Systems

Functions

- Shut-down reactor (i.e. stop the chain reaction) and keep reactor subcritical
- Remove decay heat
- Relieve pressure
- Maintain (or replenish) reactor coolant inventory

Requirements

- Redundancy
- Diversity
- Physical separation

Engineered Safety Systems (2)

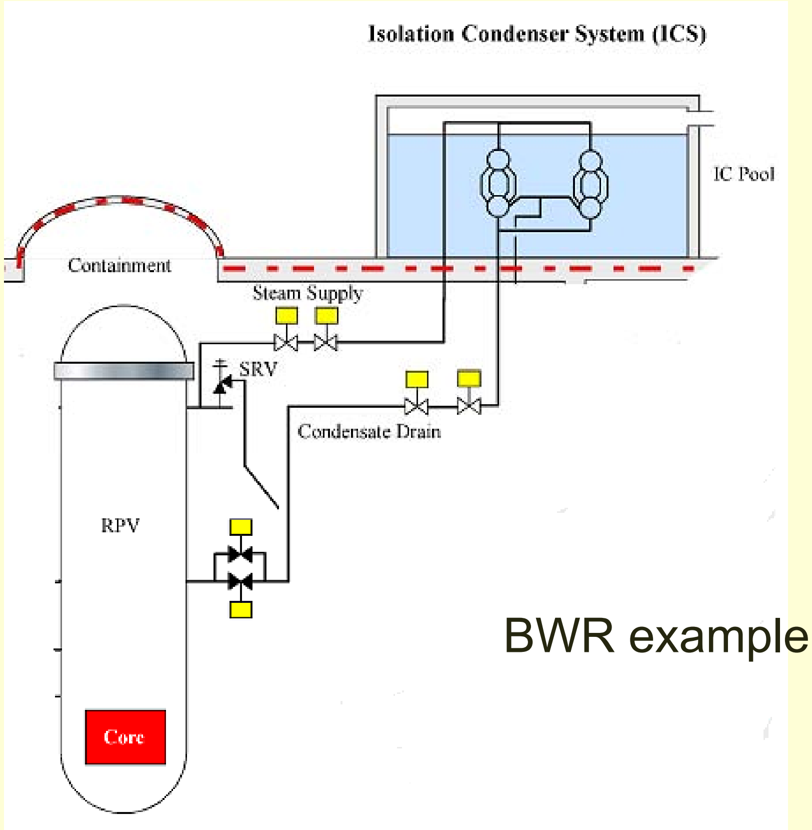
Shut-down reactor:

1) Scram control rods (fast acting: <2 sec)

2) Stand-by boron injection (slower acting, never used)

Remove decay heat:

1) Residual Heat Removal System (RHRS) in PWRs and BWRs, or Isolation Condenser (IC) only in BWRs



BWR example

Engineered Safety Systems (3)

Remove decay heat (cont.):

2) Emergency Feedwater System (EFWS) in PWRs and BWRs

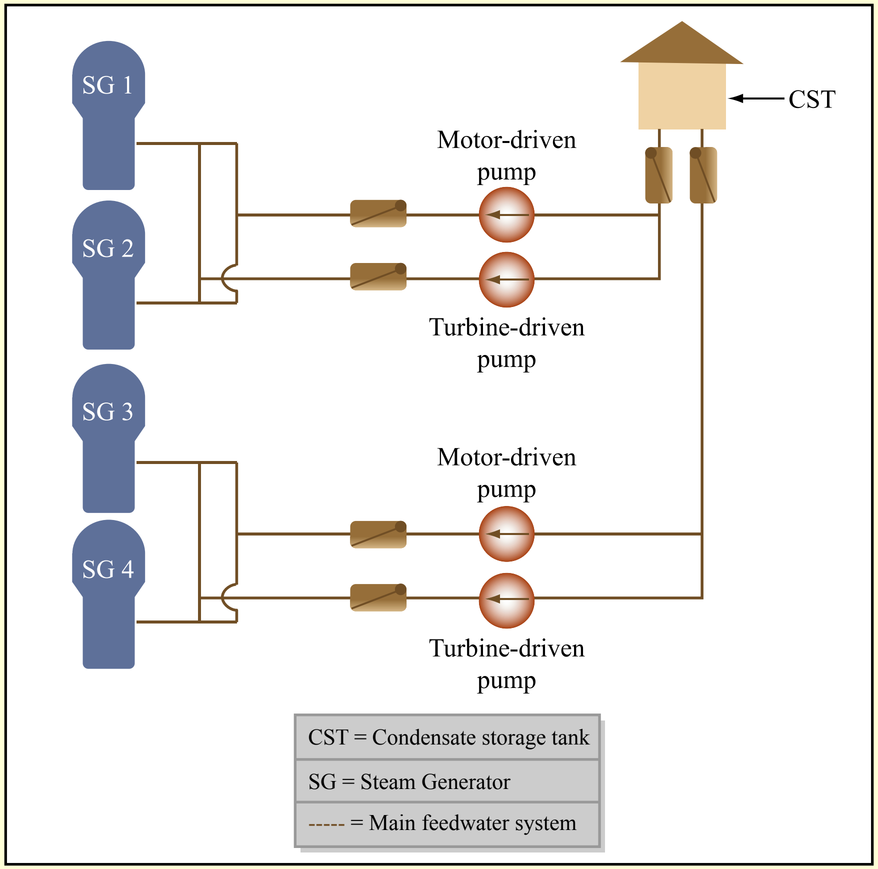


Image by MIT OpenCourseWare.

Note redundancy, diversity and physical separation

M. Gavrilas et al., Safety features of Operating LWRs of Western Design, CRC Press, 1995

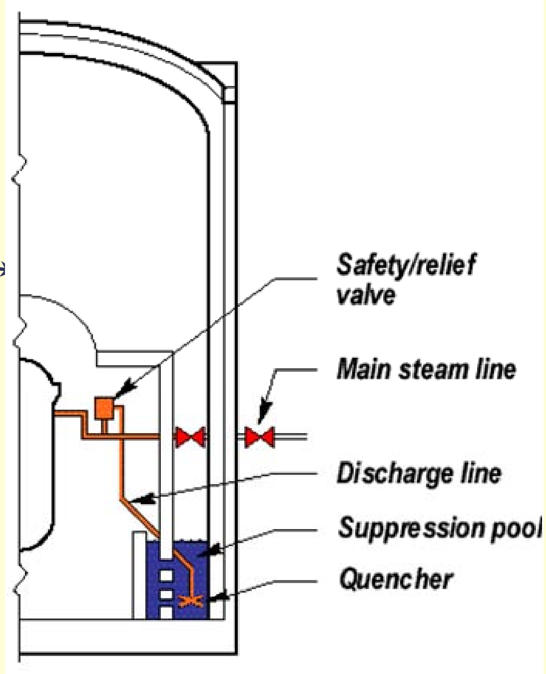
Engineered Safety Systems (4)

Relieve pressure

1) BWR: Safety/Relief Valves (SRVs) located on main steam lines

2) PWR: Safety Valves and Power Operated Relief Valve (PORV)l ocated on top of pressurizer

SRVs and PORV discharge steam into water pools located inside the containment



Maintain (or replenish) reactor coolant inventory

The Emergency Core Cooling System (ECCS) comprises:

- High Pressure Coolant Injection (HPCI) kicks in at high P (e.g. <12.5 MPa in PWR)
- Accumulators kick in at intermediate P (e.g. <4-5 MPa in PWR)
- Low Pressure Coolant Injection (LPCI) kicks in at low P (i.e. ~0.1 MPa)

Engineered Safety Systems (5)

Note:

- All ECCS water is highly borated
- HPCI and LPCI are typically active (based on pumps powered by emergency diesel generators) in some advanced LWRs they can be passive (no pumps or diesels needed)

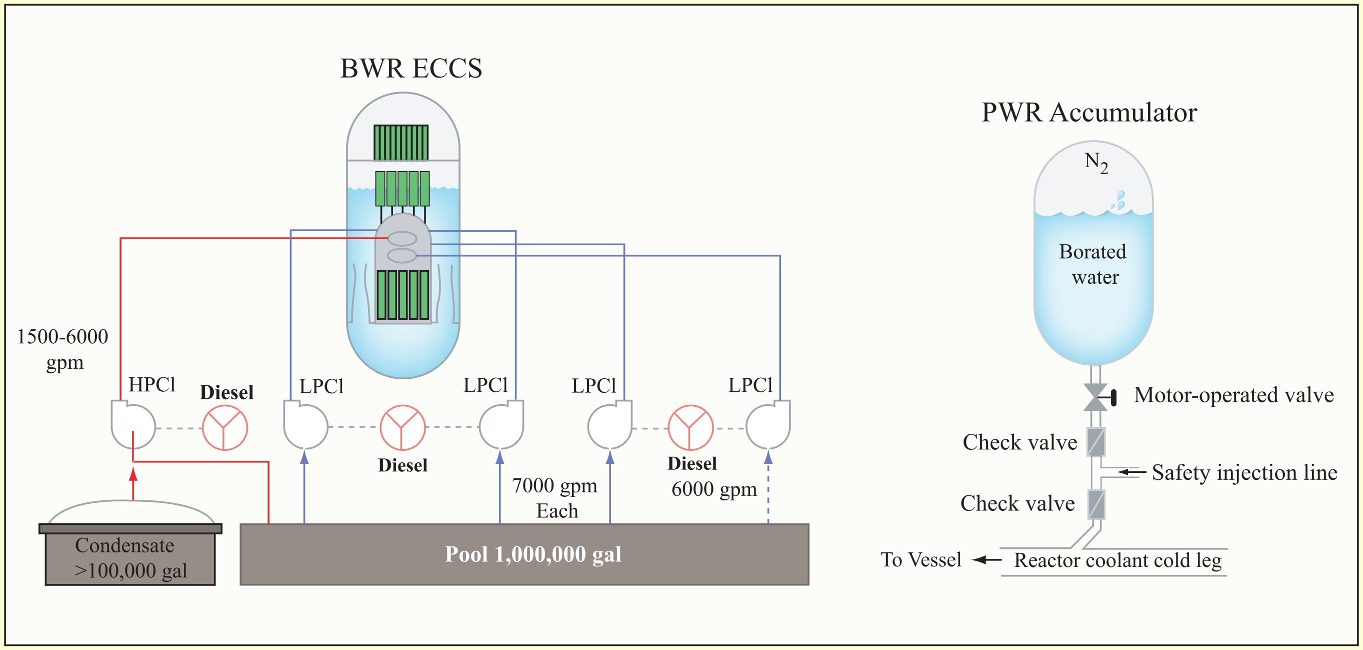


Image by MIT OpenCourseWare.

M. Gavrilas et al., Safety features of Operating LWRs of Western Design, CRC Press, 1995

Large-Break LOCA

Double-guillotine rupture of the largest pipe in primary system, i.e., cold leg between pump and vessel.

Never happened. It is the worst design-basis accident for LWRs. Historically, treated as a “bounding” event.

Sequence:

1) System depressurizes (**blowdown**) and empties very quickly (<20 sec). Can do nothing about this because it’s so rapid. Note that the reactor becomes subcritical even if CRs are not inserted, why?

At this point the core is uncovered. If nothing is done, it would melt, why?

Large-Break LOCA (2)

2) ECCS (LPCI) kicks in to **refill** the vessel and **reflood** the core. Refill and reflood take a few minutes.

If ECCS fails during refill and reflood, one has a severe accident (partial or complete melting of the core). However, ECCS is designed to be redundant and diverse.

Some advanced LWRs have passive ECCS. All existing LWRs in U.S. have active ECCS, i.e., refill and reflood is done with pumps.

Note that ECCS water is heavily borated. Why?

Large-Break LOCA (3)

Legal limits for LB-LOCAs

Plant must satisfy the following requirements during a LB-LOCA:

- No fuel melting
- Peak Cladding Temperature (PCT) below 1204°C (2200°F), to prevent runaway Zr-steam reaction

  $$Zr + 2\ H_2O \rightarrow 2\ ZrO_2 + 2\ H_2 + 6500\ kJ/kg_{Zr}$$

- Max oxidation of cladding <17% of original thickness, to prevent cladding failure
- Less than 1% cladding oxidation average, to prevent excessive hydrogen production
- No fuel “ballooning”, to maintain coolable geometry in core

Large-Break LOCA (4)

Analysis of LOCAs:

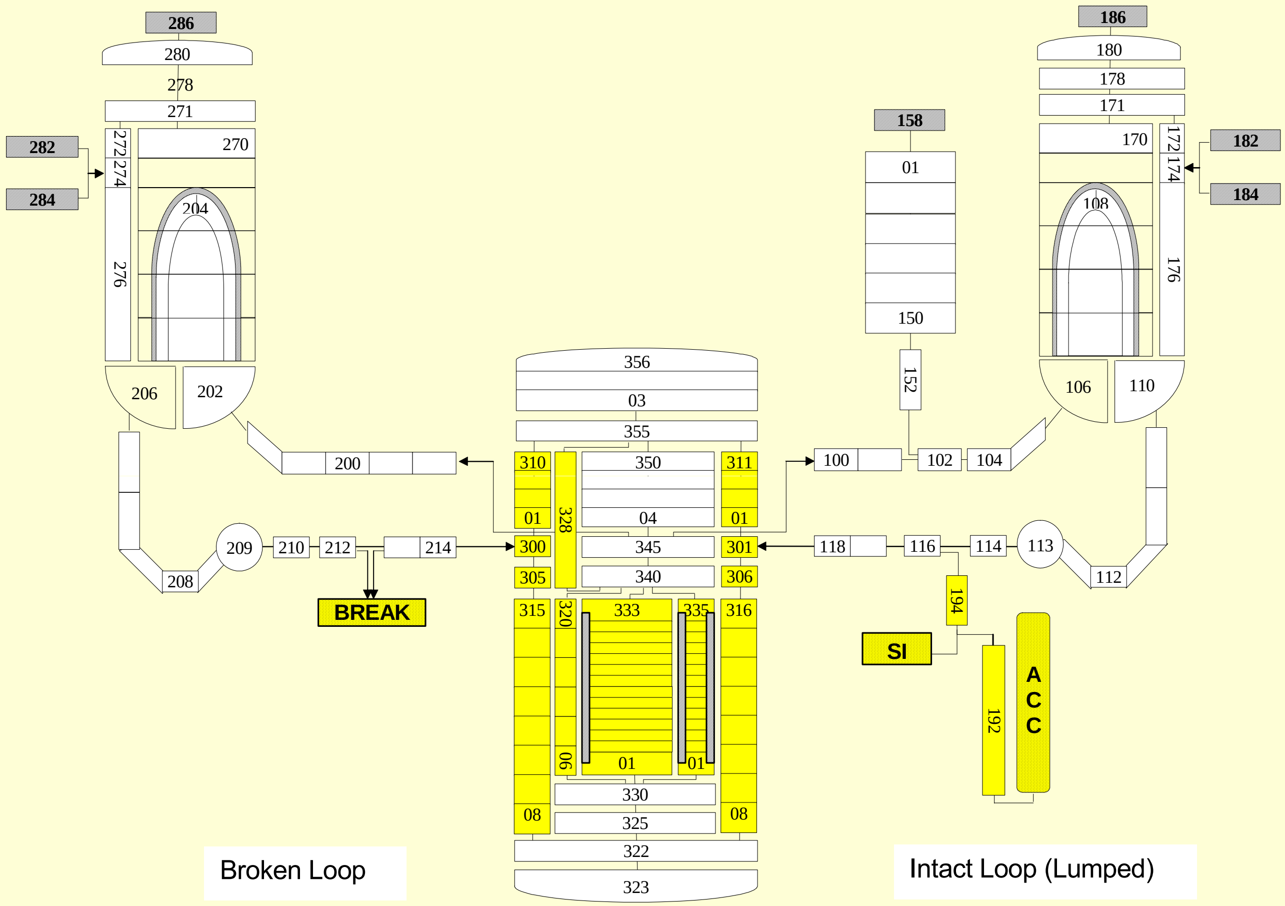
- Entire divisions at vendors to do LB-LOCA analysis, given its importance.

- Sophisticated codes such as RELAP (US), TRAC (US), CATHARE (Europe), MARS (Korea) used for analysis. They all have the same architecture.

- System is sectionalized and time-dependent conservation equations (mass, momentum, energy) are applied to each section. Solving equations numerically the P, T, flow and other useful parameters can be calculated as a function of time in each section. Neutronic behavior (not very important in LB-LOCAs) is simulated with simple kinetic model.

Large-Break LOCA (5)

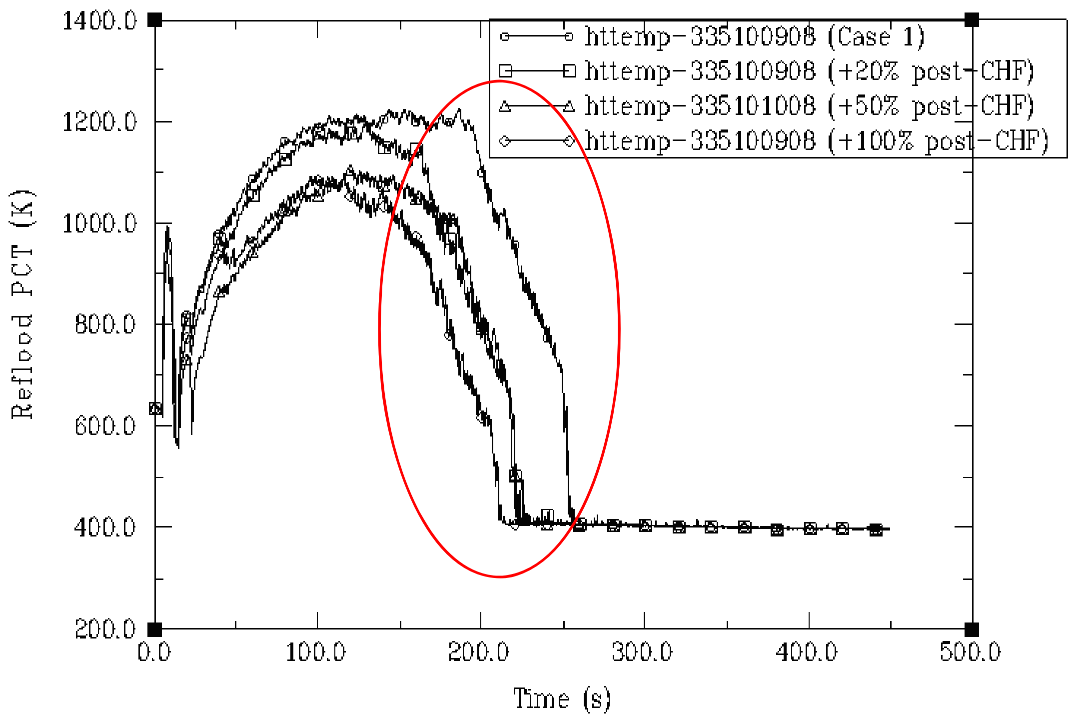
Example of RELAP nodalization for LB-LOCA analysis

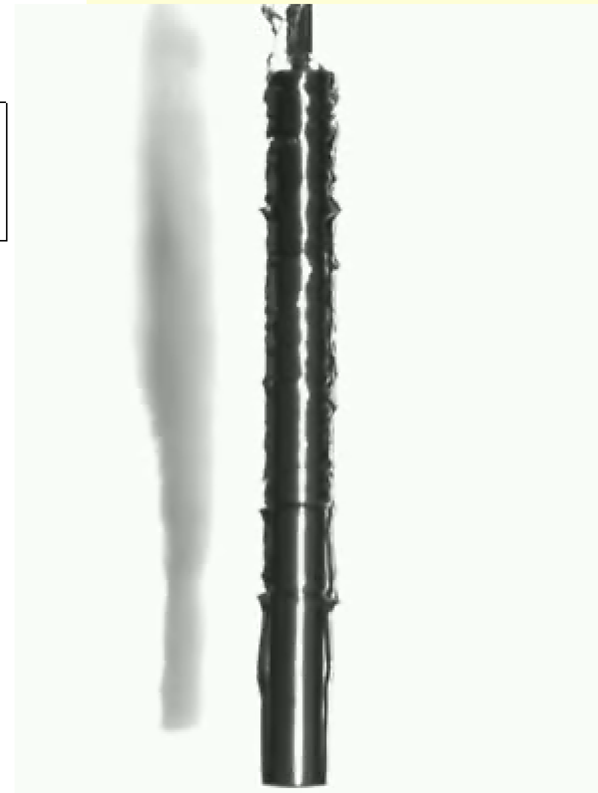


3 intact loops are lumped into one with functioning LPCI train

Large-Break LOCA (6)

Most limiting constraint is PCT<1200°C





PCT has two peaks. Blowdown peak (coolant stagnates after break + energy redistributes) and reflood peak (refill + quenching).

Depending on operating conditions and ECCS design, either blowdown peak or reflood peak is most limiting.

Large-Break LOCA (7)

Conservatism in LB-LOCA analysis (mandatory for licensing analyses)

1) Stored energy (important in blowdown): initial fuel T determined using heat transfer and thermal conductivity correlations yielding highest T
2) Decay heat vs time (important in reflood): use ANS standard +20%
3) Discharge rate through break is calculated using the Moody's model (overestimates discharge rate)
4) No return to nucleate boiling after DNB has been exceeded during blowdown. Return to nucleate boiling is allowed during reflood
5) Conservative film boiling correlations to be used
6) Failure of one ECCS train must be assumed (single failure rule)

PCT predicted with these assumptions is usually much higher than reality, as demonstrated in LOFT experiment at INL in the 80s.

The Containment

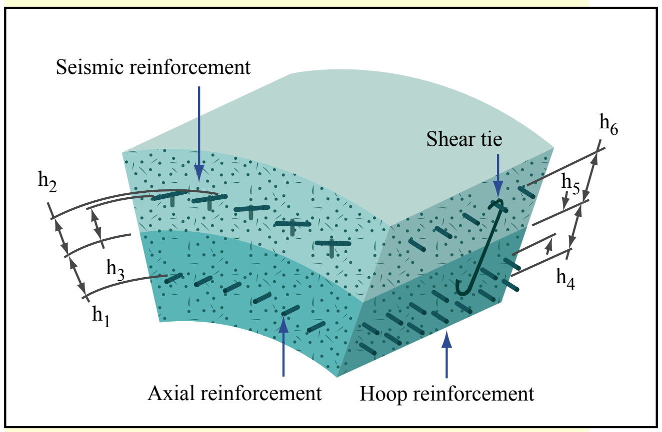
It encapsulates the “nuclear island” + performs three functions

1. Public and Environment Protection
   - Retention of radioactivity
   - Retention of missiles
2. Protection of Plant Systems from
   - Natural elements (flood and storms)
   - Human actions (crashes and explosions, acts of sabotage)
   - Fires
3. Structural Support of Systems
   - Routine service loads
   - Seismic loads
   - Internal loads during accidents

The Containment (2)

- It is a reinforced-concrete building to perform functions 2 (protection from external events) and 3 (structural support)

- It has a steel liner to perform function 1 (retention of radioactivity)



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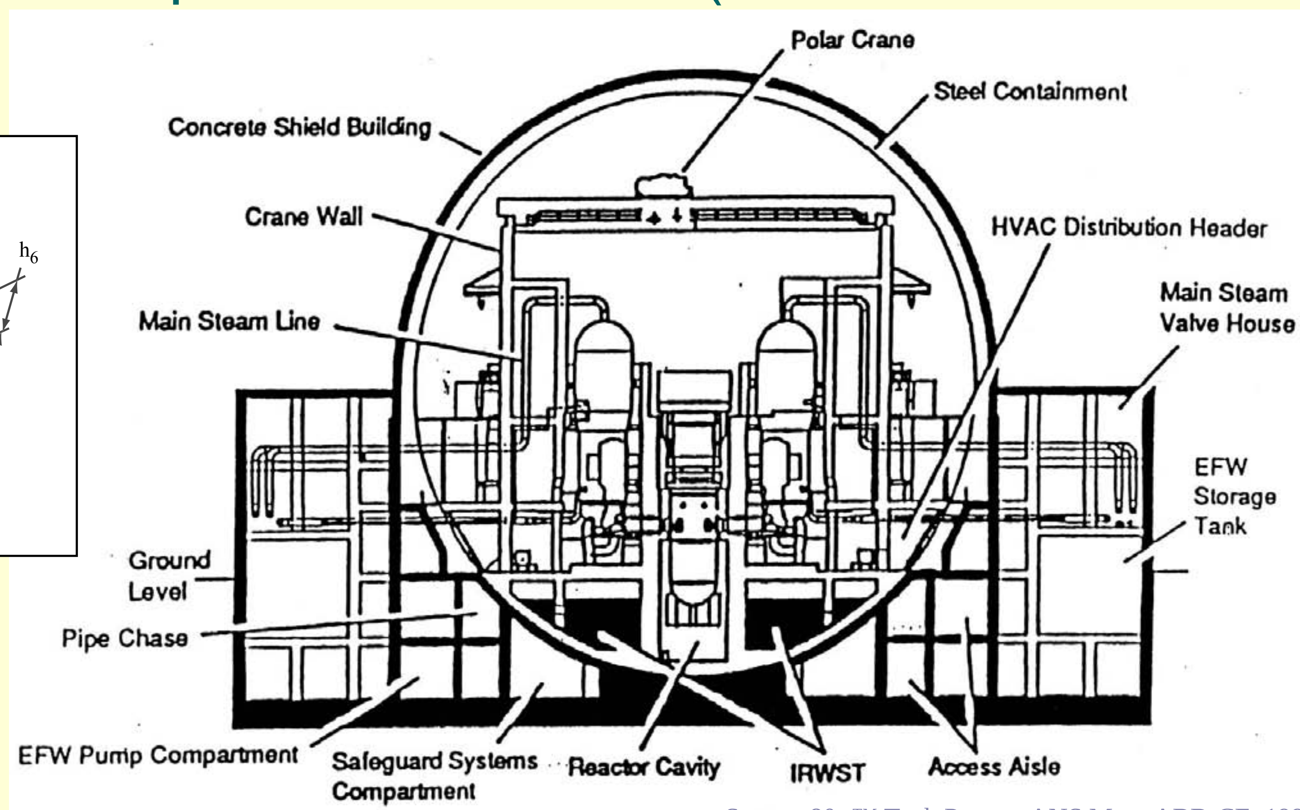


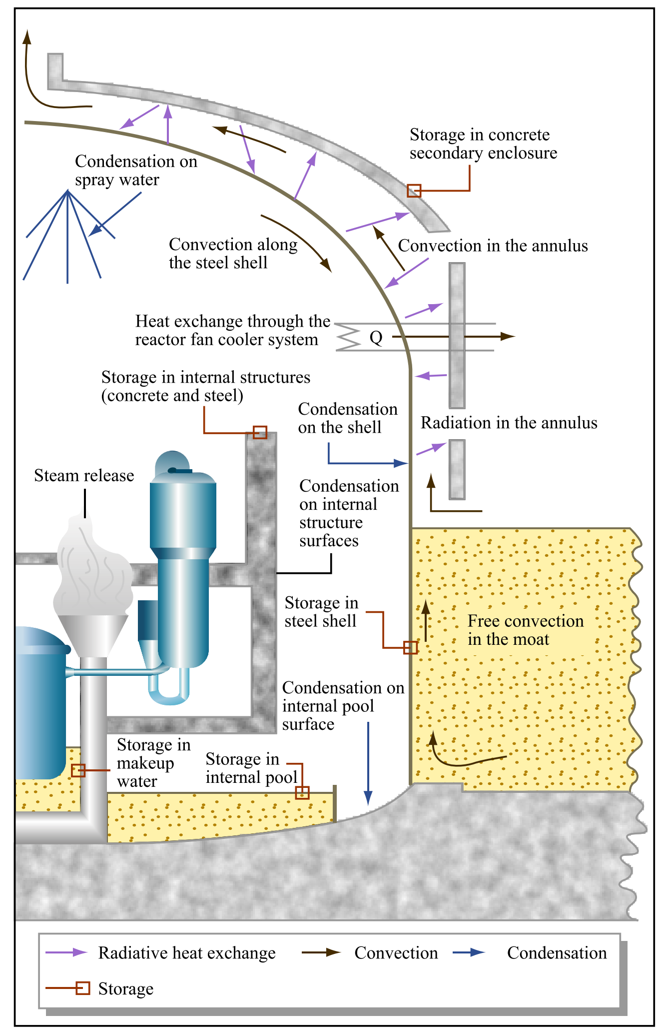
System 80+™ Tech Papers, ANS Mtg., ABB-CE, 1992.

The Containment (3)

The most serious design-basis challenge to the containment is pressurization following a LB-LOCA

Energy "sources":

- Primary system inventory
- Decay heat
- Chemical reactions (Zr-H_2O, H_2 detonation)
- Stored energy in hot structures



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The Containment (4)

Two basic types of containment:

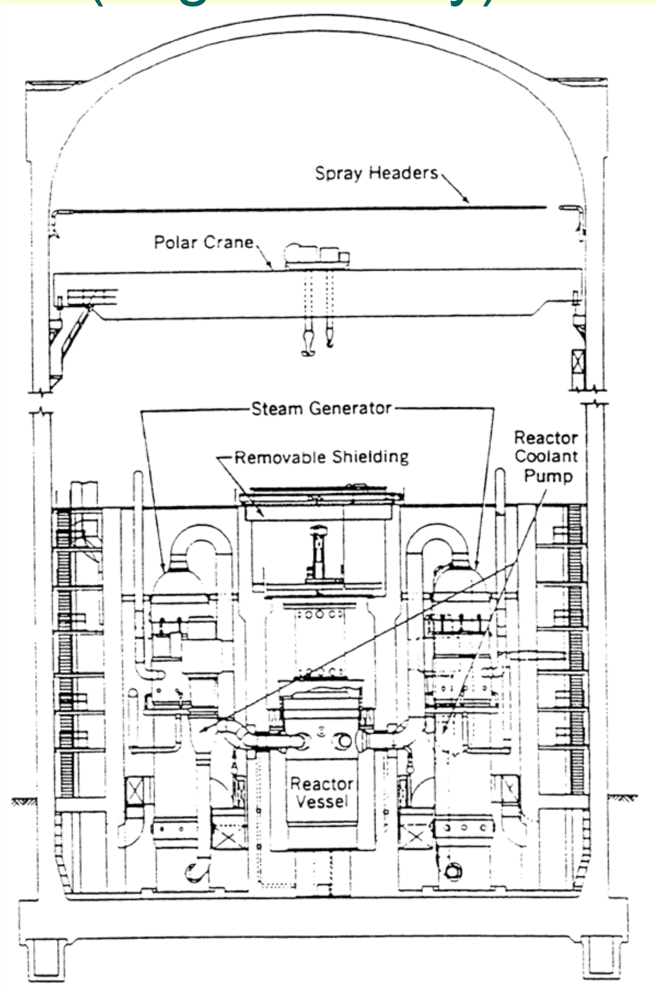
1) Pressure containment. Designed large enough to accommodate all mass/energy without exceeding pressure limit during initial spike
2) Pressure-suppression containment. To mitigate the initial pressure spike, it uses:
   - Suppression pools or
   - Ice condensers

Long-term (beyond initial pressure spike) all containments need:

- Sprays (keep pressure low + scrub containment atmosphere)
- H_2/O_2 recombiners or N_2 inertization (prevent H_2 detonation)
- Dedicated heat exchangers (keep containment cool)
- Venting through filters made of gravel, sand, water, etc. (done in Sweden, France, Germany, not US)

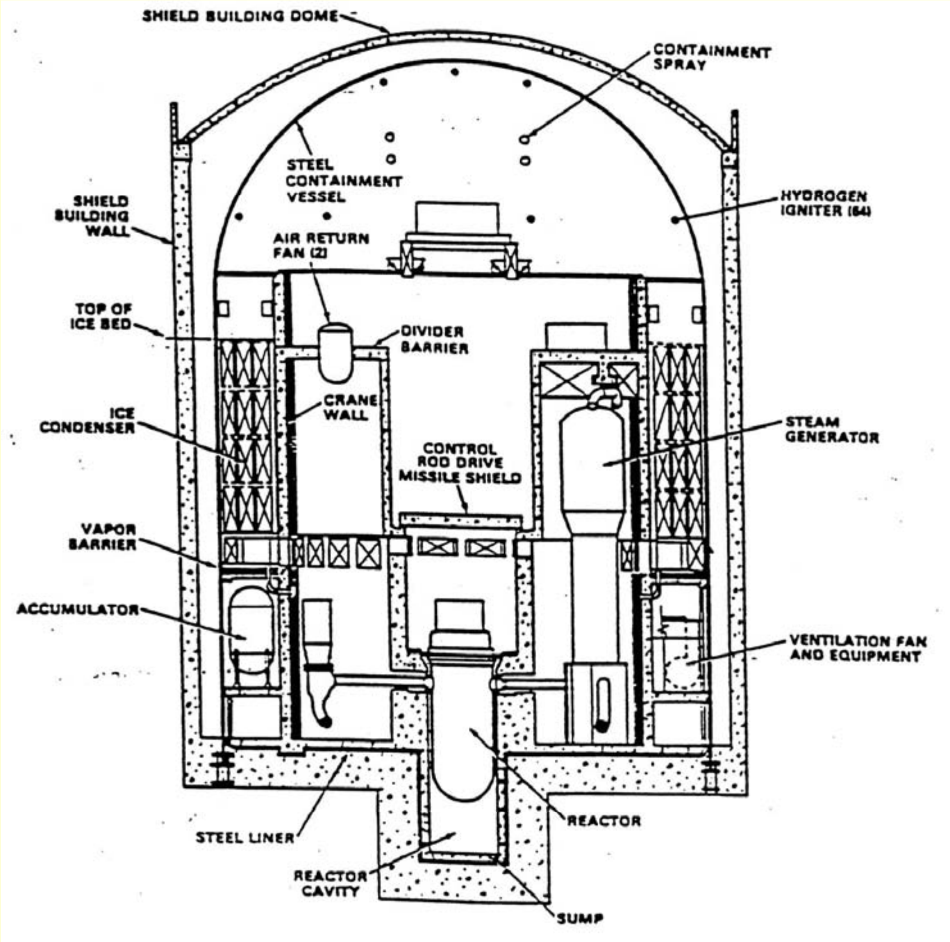
The Containment (5)

Pressure containment (large and dry)



B&W, "Steam, Its Generation & Use," 1972.

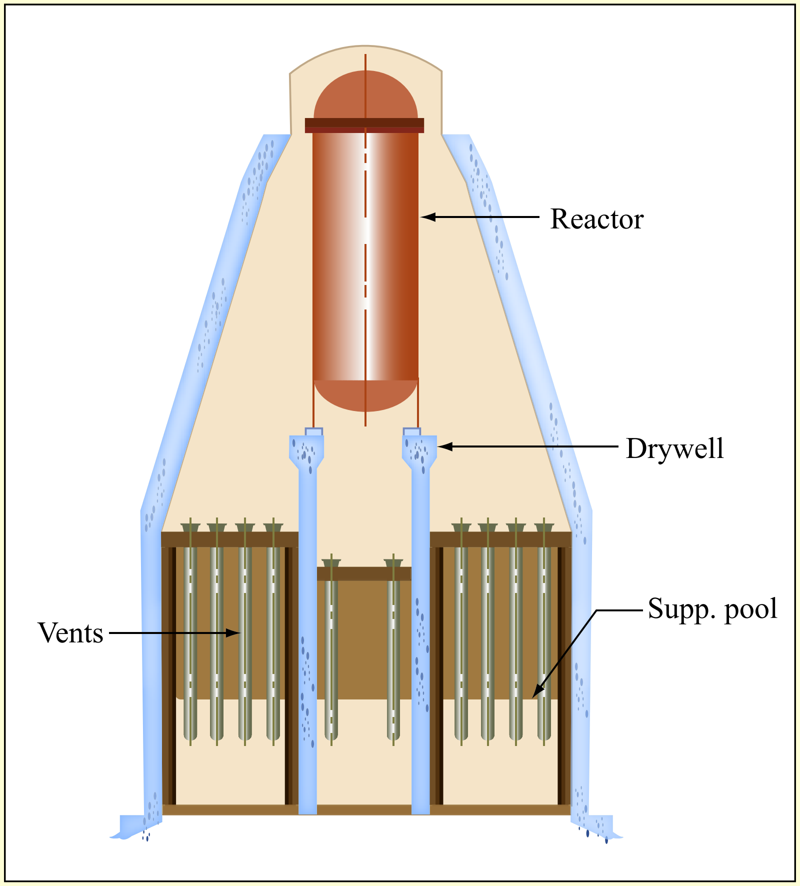
Pressure suppression containment (ice condensers)



Sequoyah nuclear power plant

The Containment (6)

Pressure suppression containment (suppression pool)



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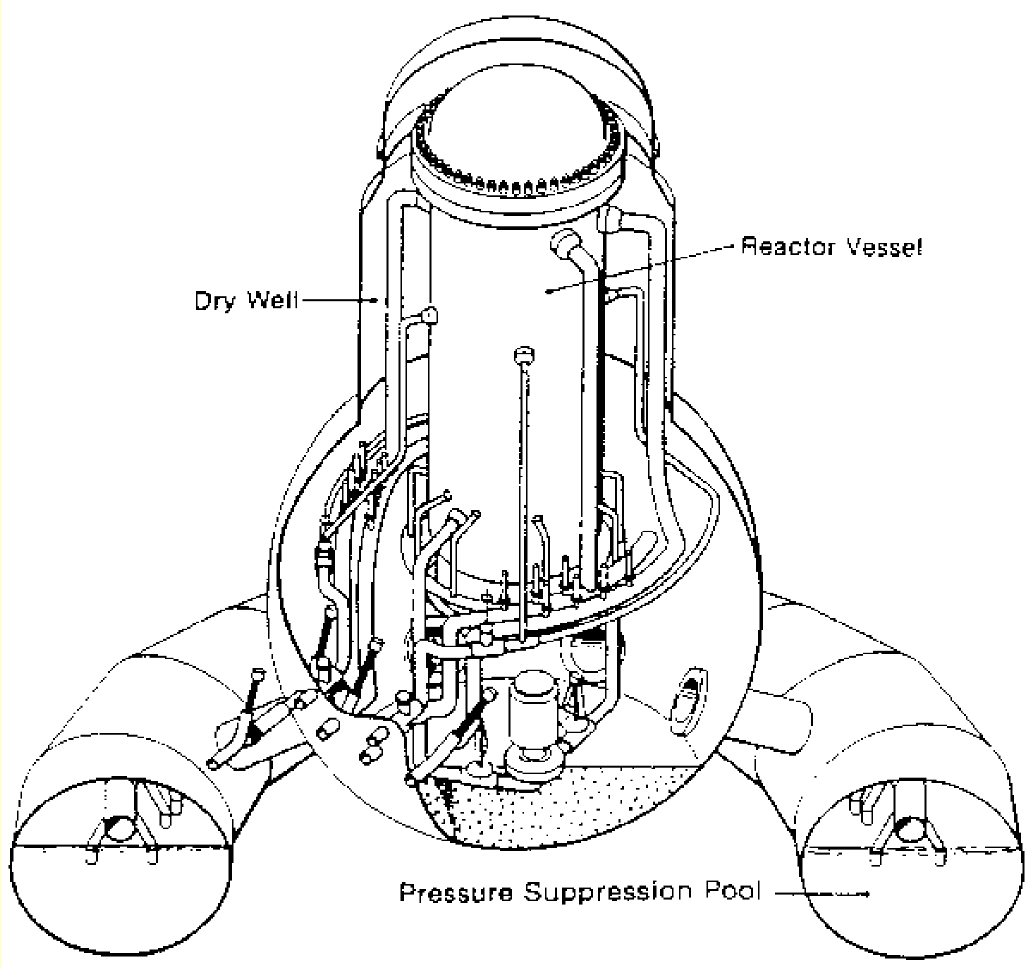
Pressure suppression containment ("doughnut" suppression pool)



A.V. Nero, Jr., *A Guidebook to Nuclear Reactors*, 1979.

Source: Nero, Anthony V. *A Guidebook to Nuclear Reactors.* Berkeley, CA: University of CA Pr, 1979. ISBN: 9780520036611.

The Containment (7)

Typical design parameters for US containments

Plant/Type	Design Pressure (kPa)	Total Containment Free Volume (m^3)	Allowable Leak Rate (vol%/day)	Capability Pressure (kPa)
Limerick/BWR Mark-II	480	11,600	0.5	1066
Grand Gulf/BWR Mark-III	204	47,300	0.4	515
Sequoyah/PWR Ice Condenser	184	34,000	0.25	446
Peach Bottom/BWR Mark-I	528	8,000	0.5	908
Zion/PWR Large Dry	425	73,600	0.1	1024
Surry/PWR Subatmospheric	411	51,000	0.1	921

Beyond-Design-Basis ("Severe") Accidents

- Cause of severe accidents is inadequate fuel cooling, resulting in fuel melting
- Can occur only with simultaneous failure of engineered safety systems
- Sequence:

- LB-LOCA with failure of ECCS
- Fuel cladding damage and ballooning
- Coolant flow restriction due to deformed cladding
- Fuel damage and fission product release
    - Noble gases + volatile fission products (I, Br, Cs , Rb, Te , Se, Sr , Ba)
    - Non-volatile fission products remain with the fuel

Beyond-Design-Basis ("Severe") Accidents (2)

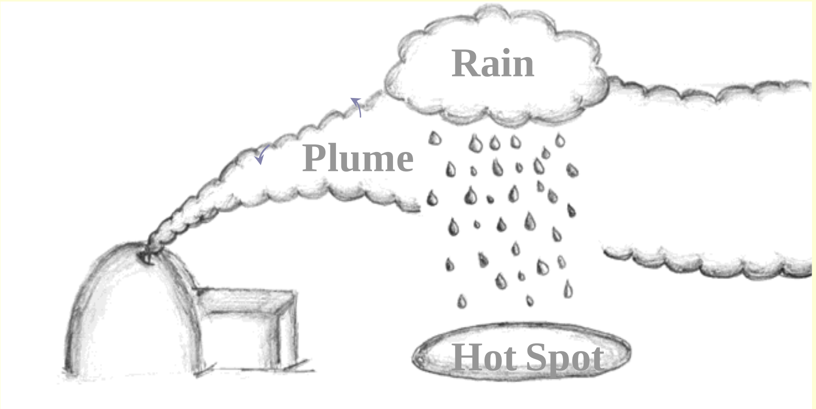
- Sequence (cont.):
  - Fuel melts and relocates to bottom of reactor vessel
  - Molten fuel breaches vessel
  - Molten fuel spreads on containment floor and is cooled (solidified) by water below vessel
  - Concrete floor decomposition results in generation of large amounts of CO_2 which further pressurizes the containment
  - H_2 from cladding/water reaction further pressurizes the containment
  - If pressure is very high, containment can develop cracks and some fission products will escape into atmosphere

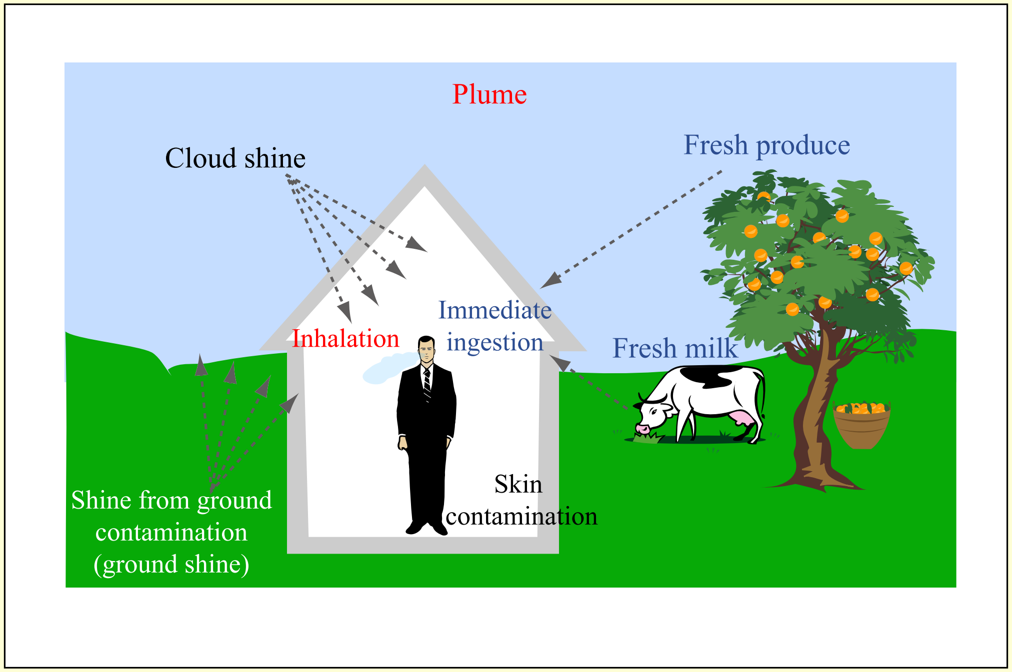
Beyond-Design-Basis ("Severe") Accidents (3)

- Sequence (cont.):

- Fission products form a plume (cloud-shine) and can be transported to ground by settling and rain-out (ground-shine)

- Population is irradiated





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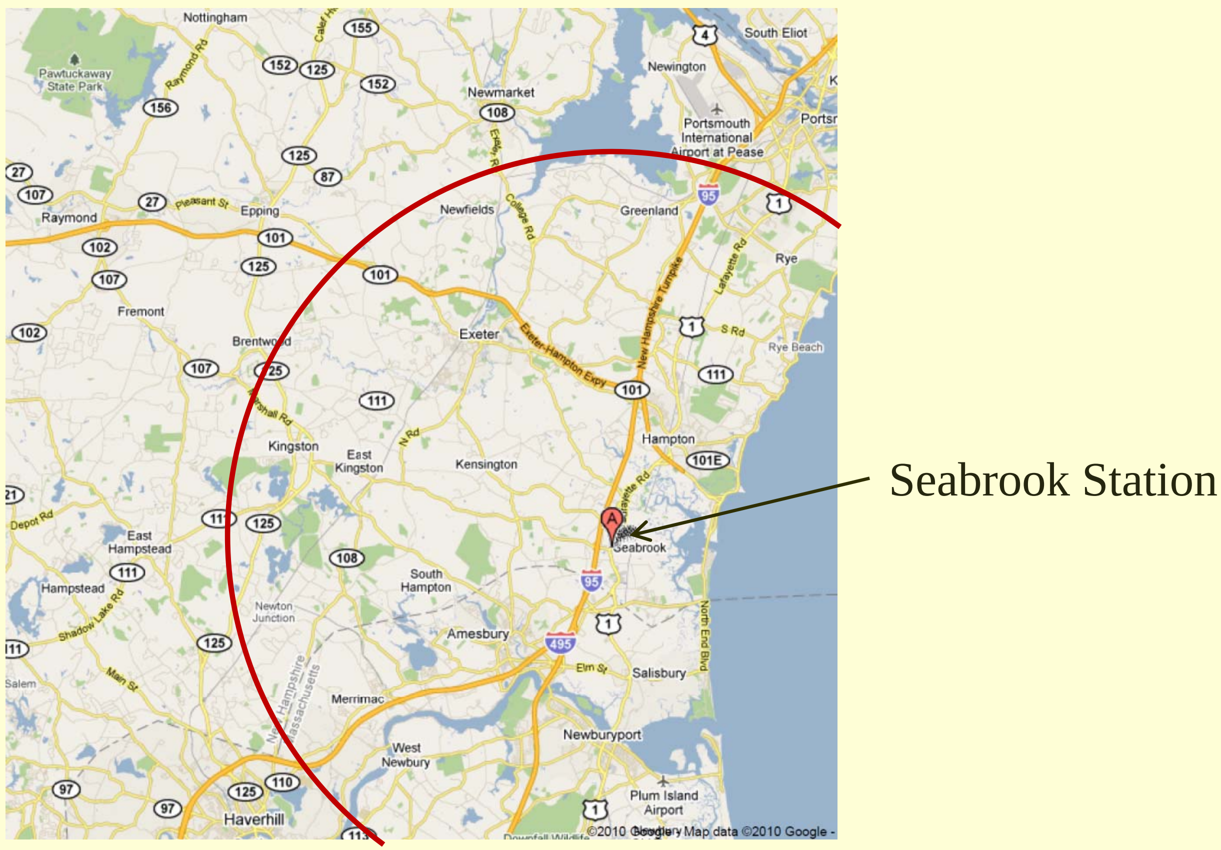
Emergency Plan/Evacuation

Last resort. In case of severe accidents, if significant radioactivity release from the plant is expected, population within 10 miles radius from plant can be evacuated or sheltered to avoid high radiation exposure.



Quantification of Nuclear Risk

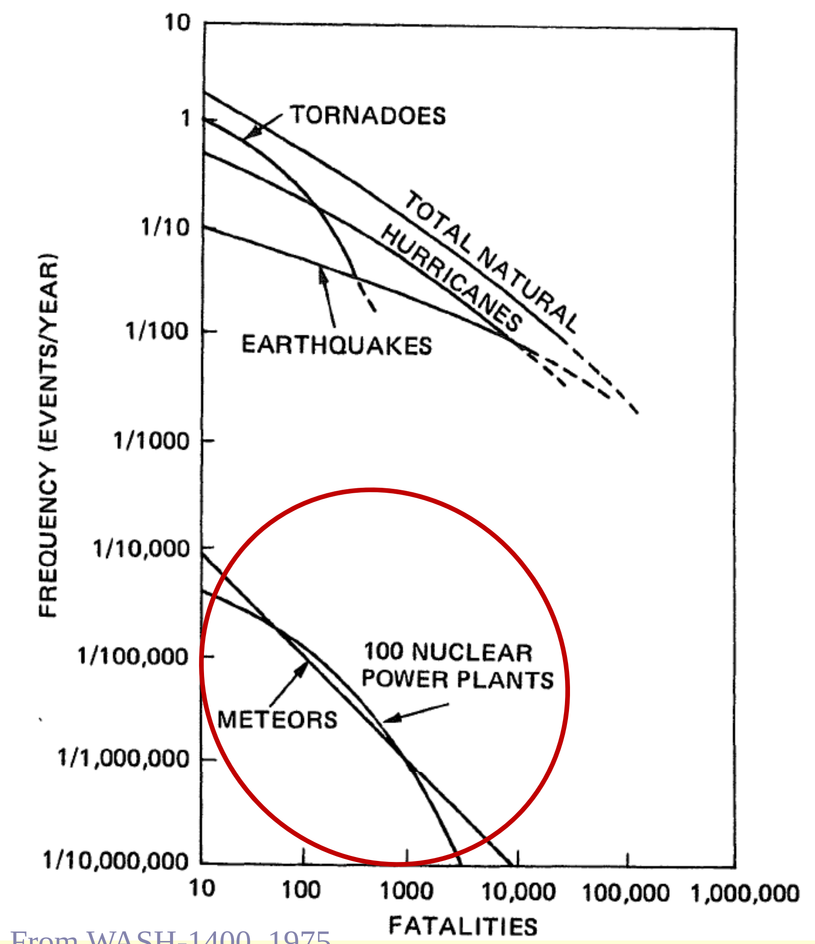
Risk (= frequency of an event × its consequences) can be quantified through the use of Probabilistic Risk Assessment (PRA)

- A complex event (e.g. a nuclear accident) is broken into a sequence of individual events (e.g. failure of a safety pump, failure of a valve, containment bypass, etc), each with a given probability to occur
- The probability of the sequence is calculated using the formal rules of probabilities (essentially AND/OR logic operators)
- The consequences of the event (e.g. human fatalities due to release of a certain amount of radioactivity) are calculated and risk curves (frequency vs consequences) can be constructed to compare the risk from various events, or even various technologies.

PRA was pioneered by the nuclear industry, but its use is now widespread, e.g. aviation and space industry, chemical industry, economics, etc.

All about PRA in 22.38

Quantification of Nuclear Risk (2)



From WASH-1400, 1975

Cause	Time (days)
Being unmarried-male	3500
Cigarette smoking-male	2250
Heart disease	2100
Being unmarried-female	1600
Being 30% overweight	1300
Being a coal miner	1100
Cancer	980
Cigarette smoking-female	800
Less than eighth-grade education	850
Living in unfavorable state	500
Serving in the U.S. army in Vietnam	400
Motor vehicle accidents	207
Using alcohol (U.S. average)	130
Being murdered (homicide)	90
Accidents for average job	74
Job with radiation exposure	40
Accidents for "safest" job	30
Natural background radiation (BEIR, 1972)	8
Drinking coffee	6
Oral contraceptives	5
Drinking diet soft drinks	2
Reactor accidents (Kendall, 1975)	2**
Reactor accidents (Wash-1400, 1975)	0.02**
Radiation from nuclear industry	0.02**
PAP test	-4
Smoke alarm in home	-10
Air bags in car	-50

Average Loss in Life Expectancy Due to Various Causes

**Assumes that all U.S. power is nuclear.

Image by MIT OpenCourseWare.

These numbers include the risk from severe accidents!

Protect Public and Environment

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Nuclear Safety

Heat Removal
- Steady-state
- Shutdown
- Refueling

Defense in Depth

Effective Regulator (NRC)
Peer Oversight (INPO)

Physical Barriers
- Fuel pellet
- Cladding
- Coolant system
- Containment

Design, Construction and Operation
- Prevention (inherently stable design, QA, operator training, conservative operation, etc.)
- Protection (reactor protection system)
- Mitigation:
  - engineered safety systems
  - emergency plan/evacuation