Nuclear Reactors

Nuclear Reactor Components

Fuel and Core

- Fuel
  - Amount and composition to support a chain reaction for a sustained time (years)
  - Will treat fuel as a ‘black box’ for now; detailed discussion of fuels will follow reactor discussion
- Core
  - The tightly packed array of fuel
  - Heterogeneous: rods separated by coolant and/or moderator
  - Homogeneous: Fuel dissolved in coolant and/or moderator

Coolant

- Coolant: none is ideal
  - Low melting point, high boiling point (usually)
  - Non-corrosive
  - Low neutron absorption cross section
  - Stable to elevated temperatures and radiation
  - Low induced radioactivity
  - No reaction with turbine working fluid
  - High heat capacity and heat transfer coefficient
  - Low pumping power
  - Low cost and readily available

Coolant Comparison

Criteria	Light Water	Heavy Water	He	Carbon Dioxide	Na, K	Pb, Bi	Molten Salts	Organics
Low mp	A	A	A	A	D	D	D	A
High bp	D	D	NA	D	A	A	A	D
Corrosion	D	D	A	D	A	A(Pb); D(Bi)	A	A
Stability-T	A	A	A	D	A	A	A	D
Stability-γ	D	D	A	?	A	A	A	D
Induced activity	A	D	A	A	D(Na); A(K)	A(Pb); D(Bi)	D (Li)	A
Working fluid	A	A	A	A	D	M	M	M
Heat transfer	M	M	D	D	A	A	A	M
Pumping power	M	M	D	D	A	A	A	M
Cost	A	D	D	A	A	A	A	A
Availability	A	A	D	A	A	A	A	A
% of world reactors	85	10	0	4	1 (Na)	0	0	0

Moderator

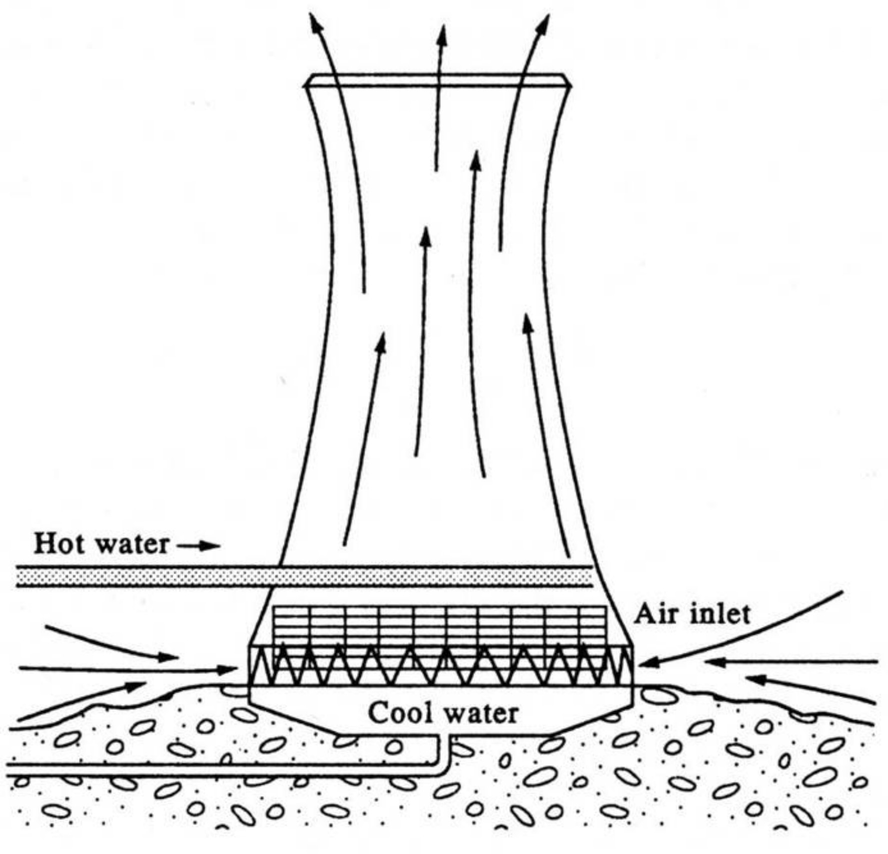
- Thermal reactors only
  - Moderating ratio discussed earlier
- For water-cooled reactors the coolant is the moderator
- Only other moderator in use or expected to be in use is graphite
  - Now: He
  - Future: Perhaps molten salt coolant
  - Density: Theoretical 2.26 g/cm^3, actual 1.6-1.7 g/cm^3
  - Annealing may be needed periodically at low temps

Major Components

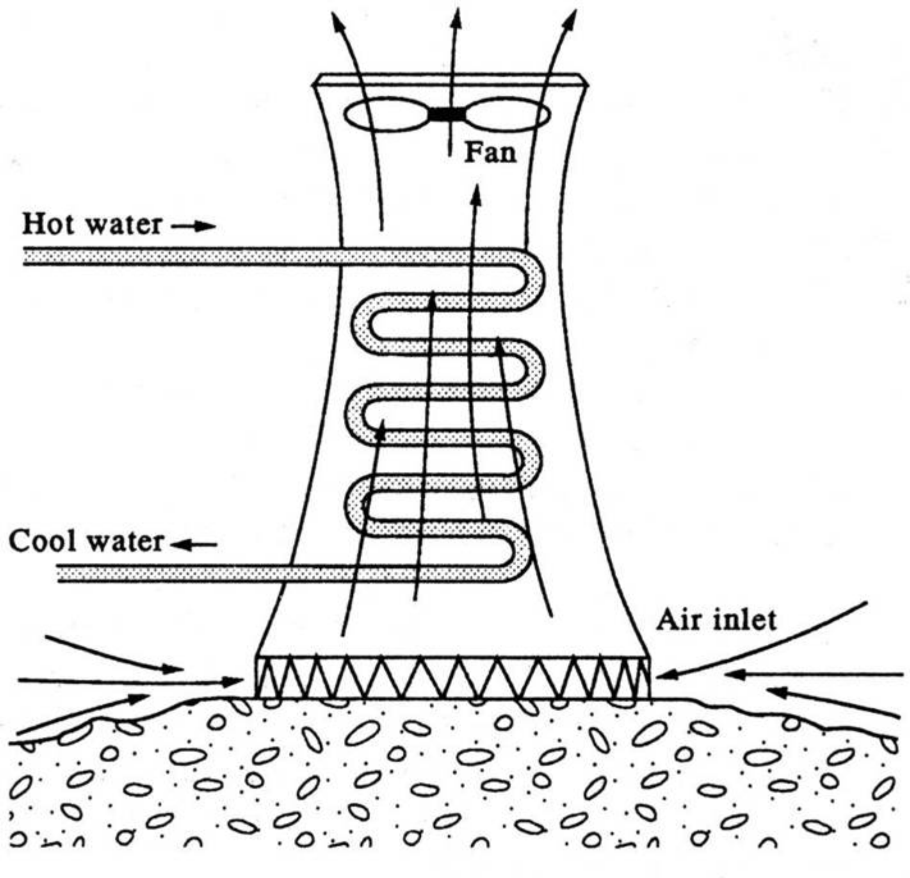
- Pressure vessel for water and gas-cooled reactors
- Coolant pumps or compressors
- Heat exchangers (some)
- Turbine-Generator
- Condenser/cooler/cooling towers
- Interconnecting piping
- Waste processing
- Water pool to store spent fuel
- Labs and shops to handle mildly radioactive items

Cooling Tower Types

- Can be natural circulation or mechanical (fan) driven, wet or dry

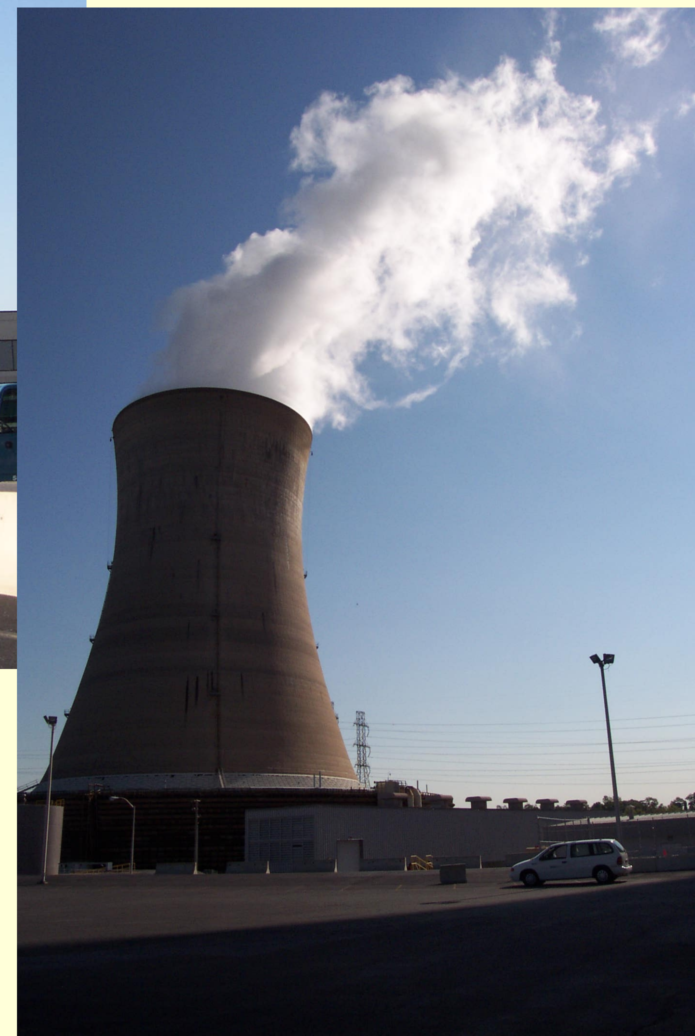


(a) "wet" (evaporative)



(b) "dry" (air flow)

Cooling Towers



Waste Processing: Liquid

- Coolant water makeup and cleanup
  - Corrosion control is a major issue; water chemistry is carefully controlled
  - Removal of radioactive species and species that produce penetrating radiation when activated
    - Use ion exchange, reverse osmosis
    - Evaporation to concentrate dissolved species, recycle water
    - Concentrate is solidified (grout) or stabilized (absorption) to become a solid waste

Waste Processing: Gaseous

- Gaseous effluent
  - Building maintained under negative pressure
    - The higher the radioactivity, the lower the pressure
  - Final effluent passed through gaseous effluent treatment system
    - Hold up short lived isotopes of Kr, Xe, N, and I on charcoal beds or similar to allow them to decay
    - High-Efficiency Particulate Air (HEPA) filter
    - Beds and filters eventually become solid wastes

Waste Processing: Solid

- Solid wastes
  - Solid product from gas and liquid treatment
  - Other radioactive wastes: lab equipment, protective gear, failed equipment, ...
- Put in drums and sent to near-surface low-level waste disposal site for burial

Radiation Protection

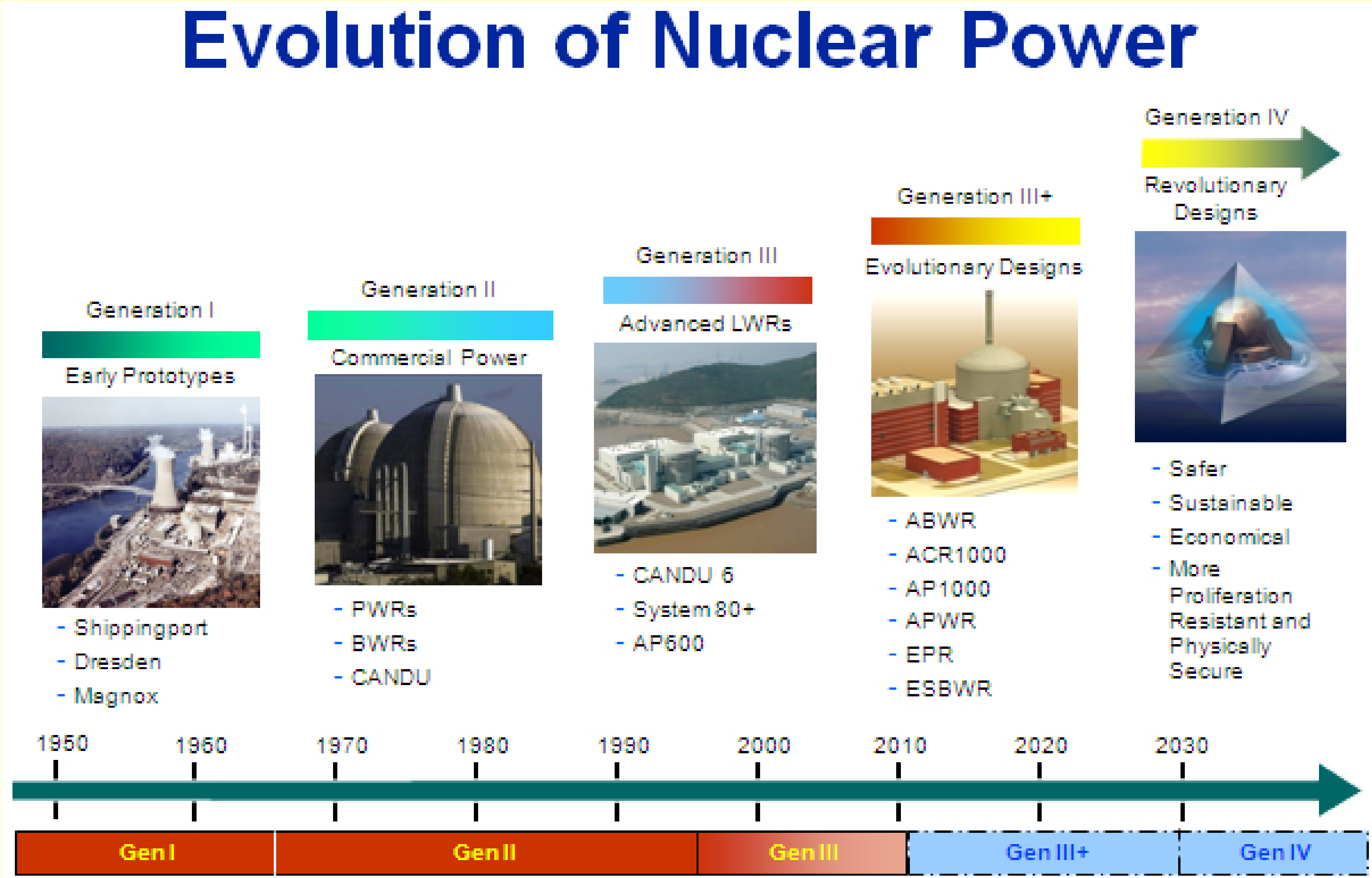
- Routine radiation protection is primarily an issue for workers; public is too far away
- Radiation sources
  - Reactor (limited access during operation)
  - Trace contamination in cooling water
  - Places where nuclides accumulate (e.g., cleanup systems, waste storage areas)
- Most shielding is concrete or water
  - Some steel or other metals in tight areas
- Limit time and increase distance: ALARA
  - Worker dose monitored carefully by resident staff

Public Safety

- Effluent processing: already discussed
- Nuclear accidents: later

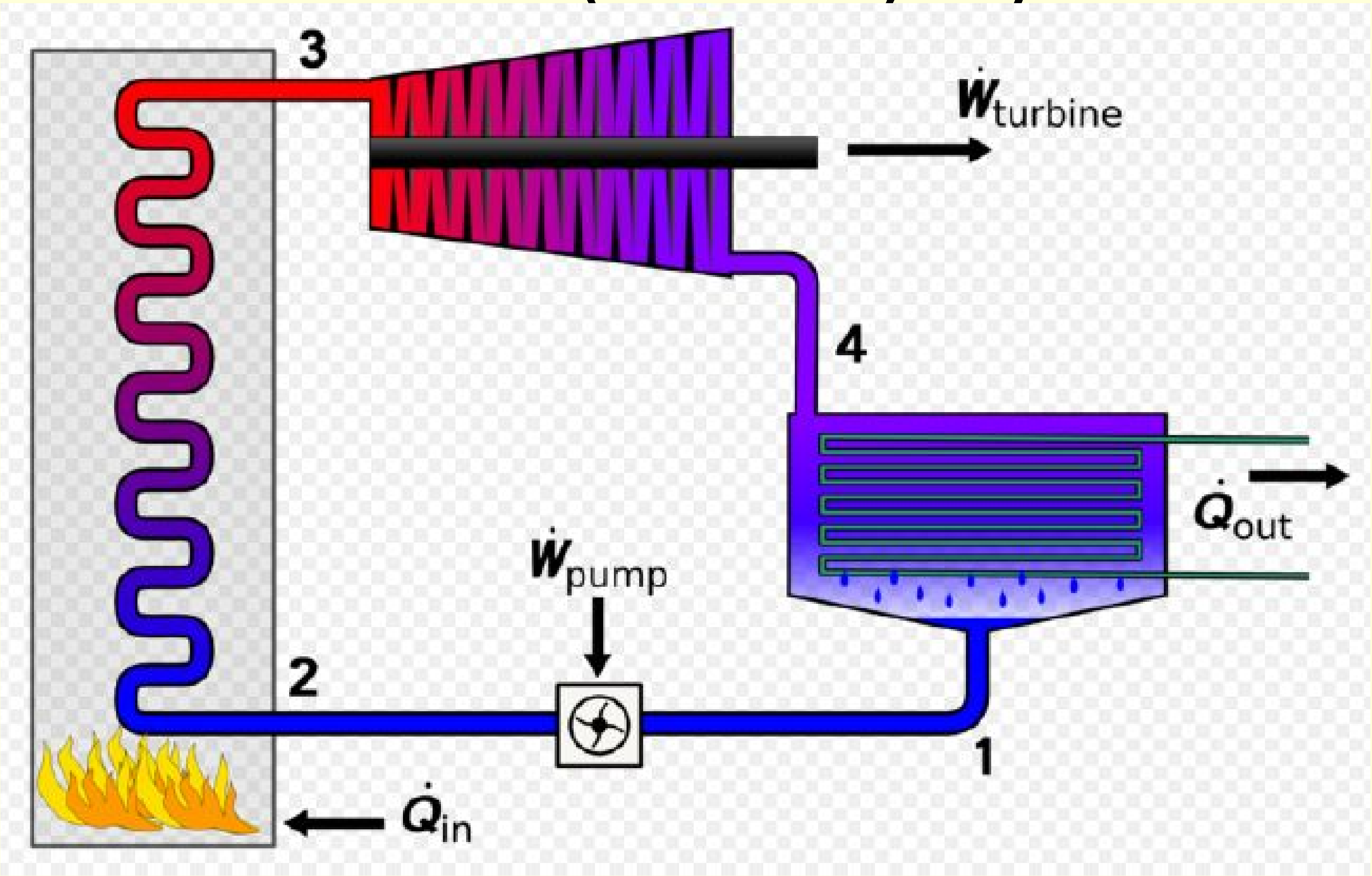
Nuclear Reactor Evolution

Nuclear Reactor Generations

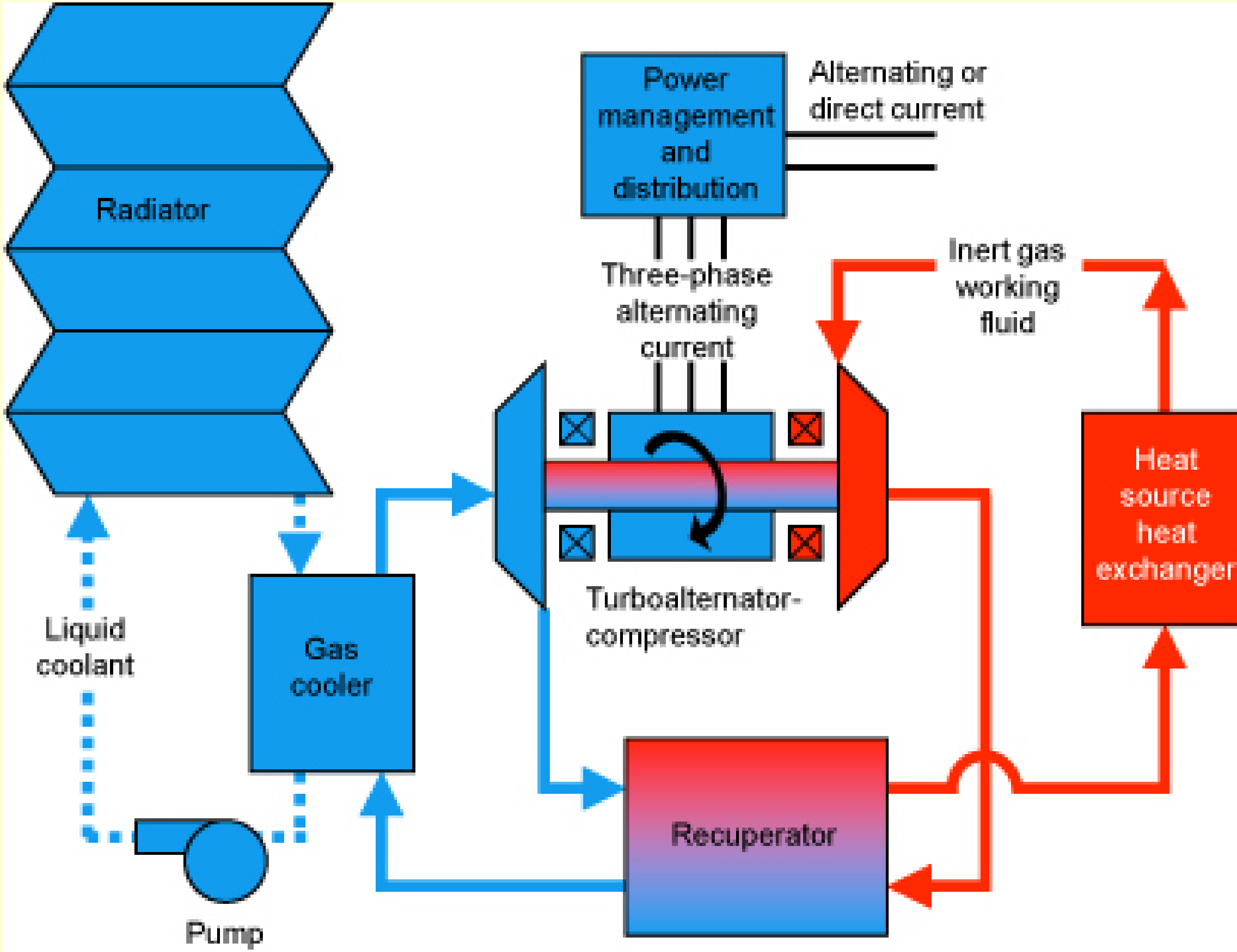


Nuclear Power Plant Thermal Cycles

Rankine (Steam) Cycle



Brayton Cycle: Gas-Cooled



Process Heat Cycle

- The heat from a nuclear reactor is used directly, e.g., petroleum refinery, chemical manufacturing

Reactor Designs

Framework

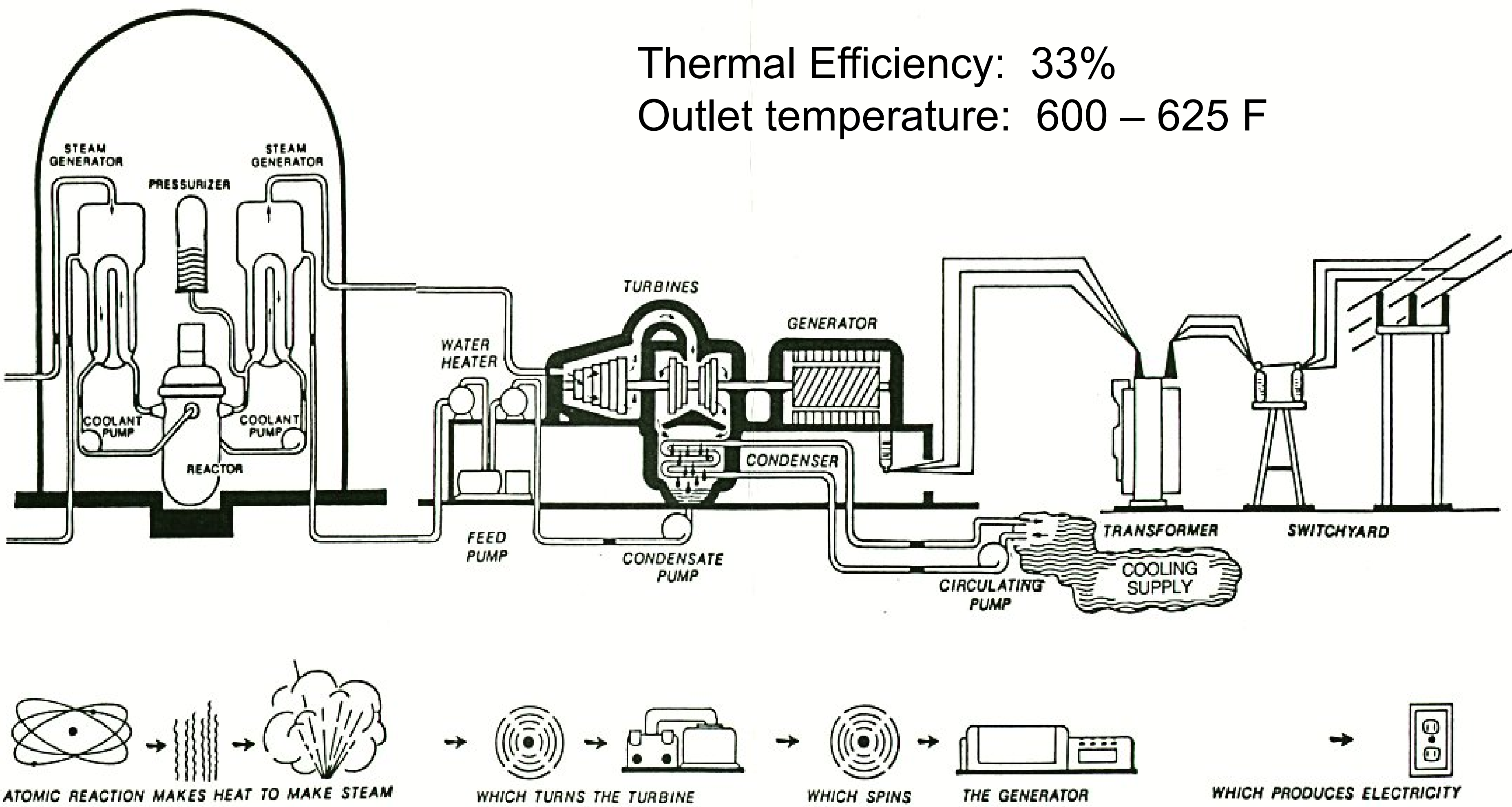
- Will use the type of moderator (or not) and then the coolant as a framework
  - Water moderated
    - Light
    - Heavy
  - Graphite moderated
    - Gas cooled
    - Molten salt cooled
  - Unmoderated
    - Sodium cooled
    - Metal cooled except sodium
  - Legacy reactors
  - Small modular reactors

Reactors

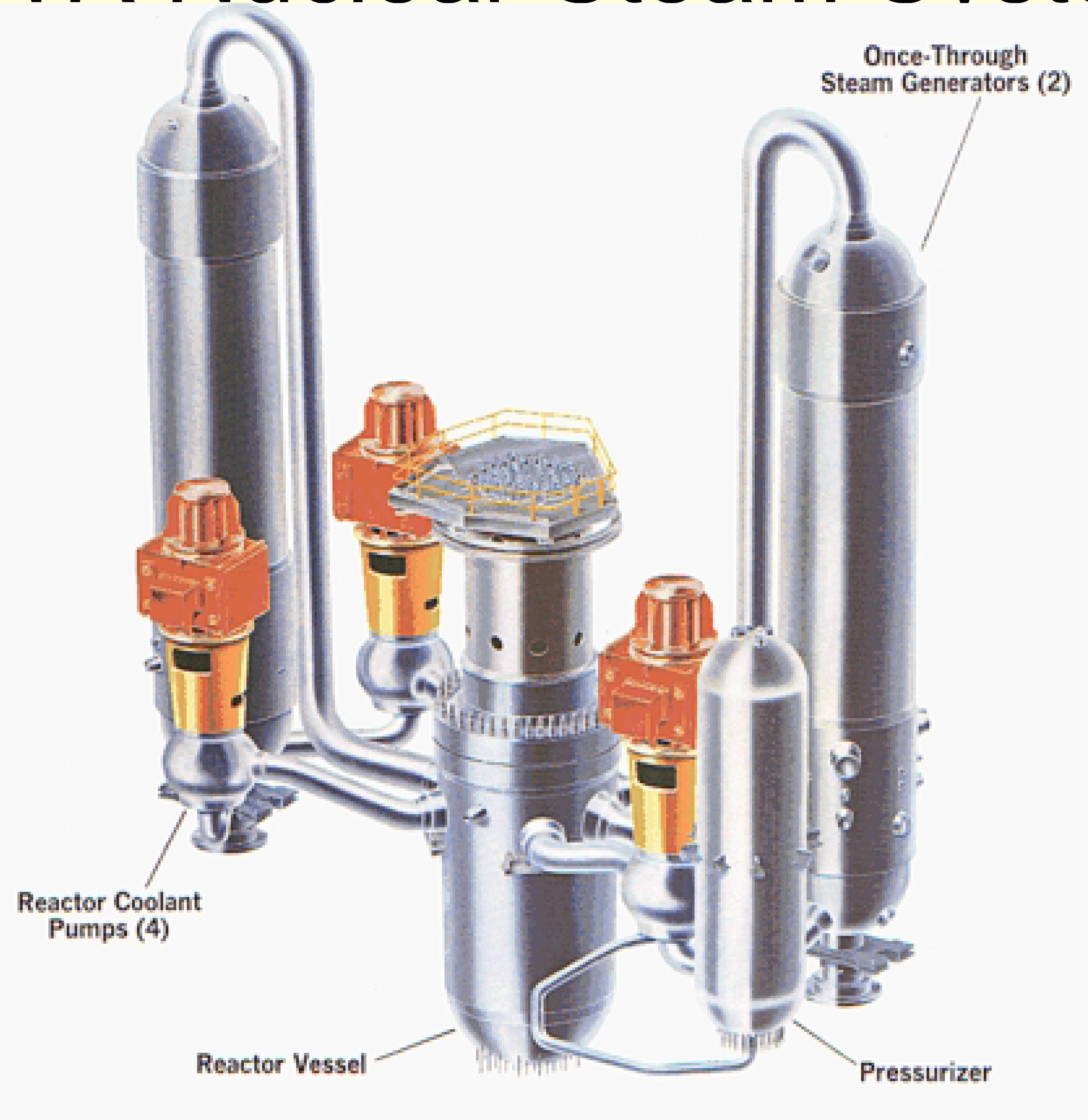
Water Moderated

Pressurized Water Reactor (PWR)

Thermal Efficiency: 33%
Outlet temperature: 600 – 625 F

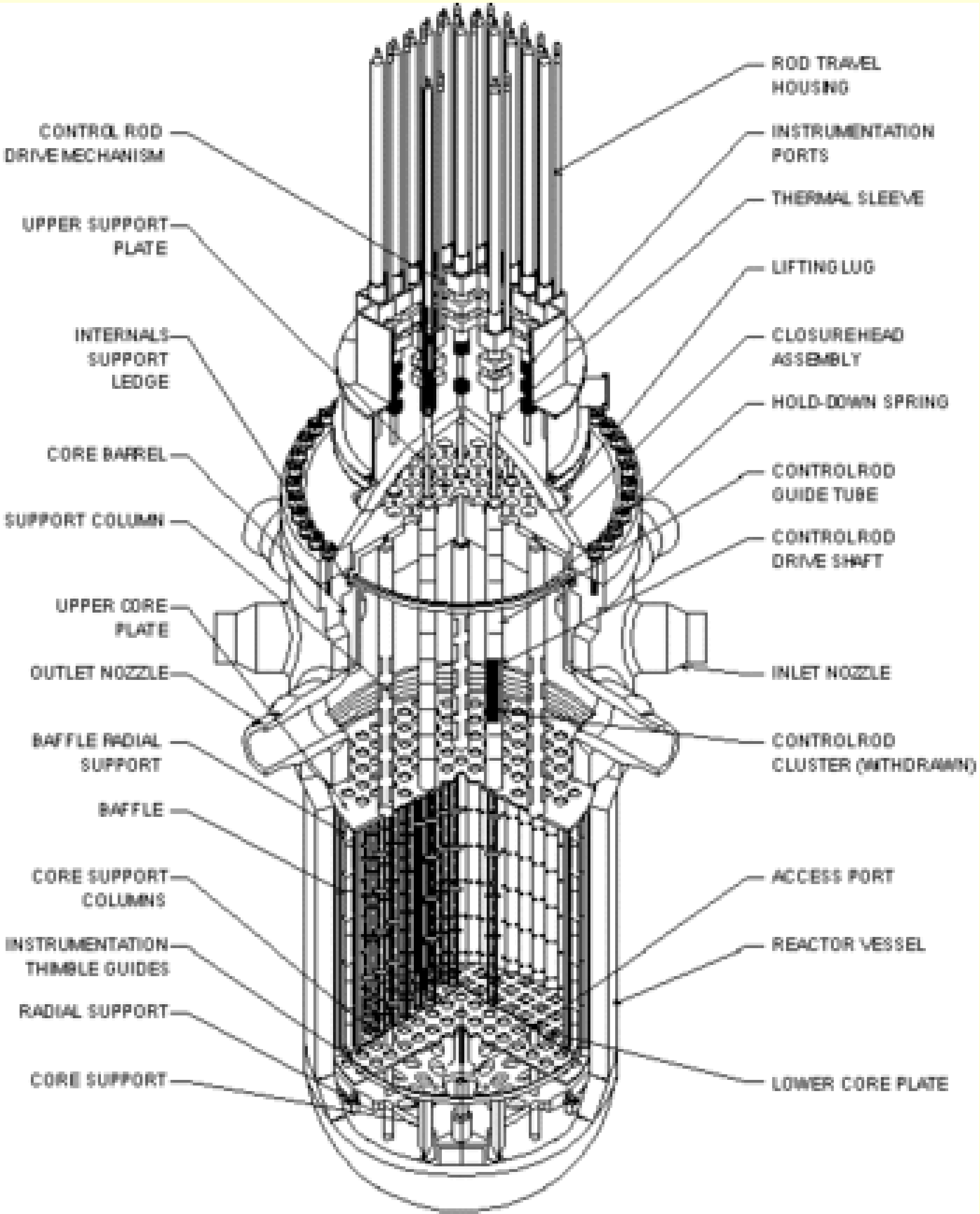


PWR Nuclear Steam System

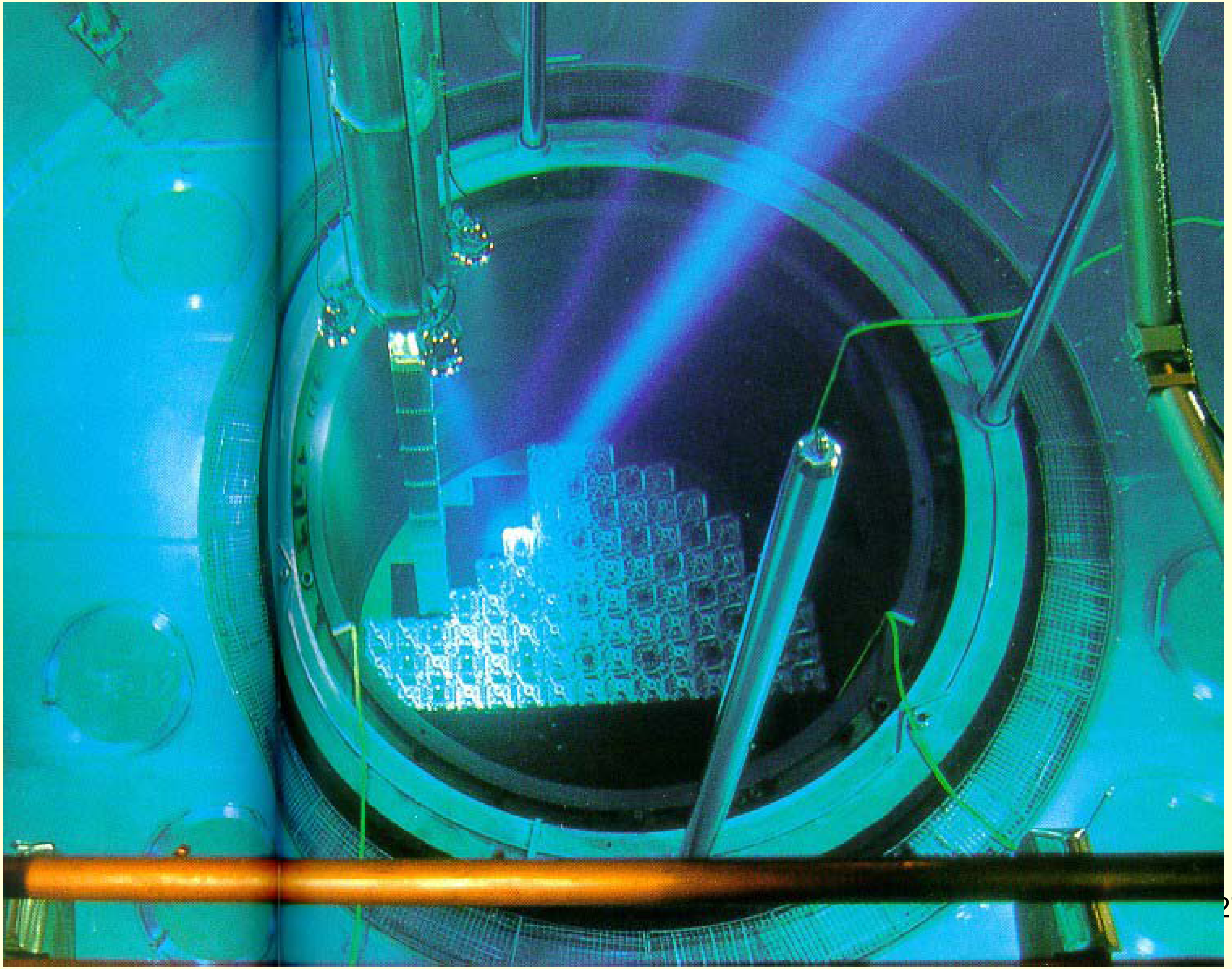


PWR Pressure Vessel

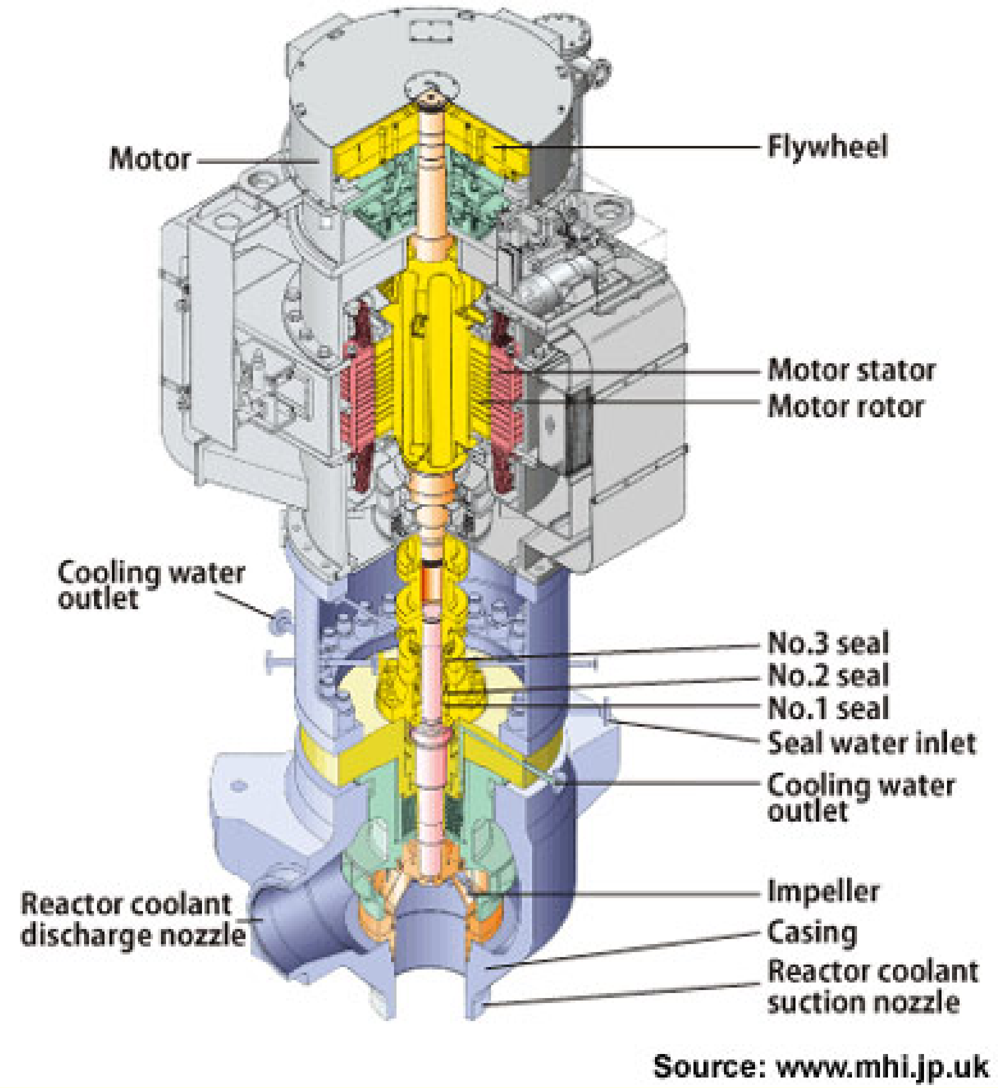
- 15 to 20 ft diameter
- 40 to 60 ft tall
- 10” thick
- Carbon steel lined with stainless steel

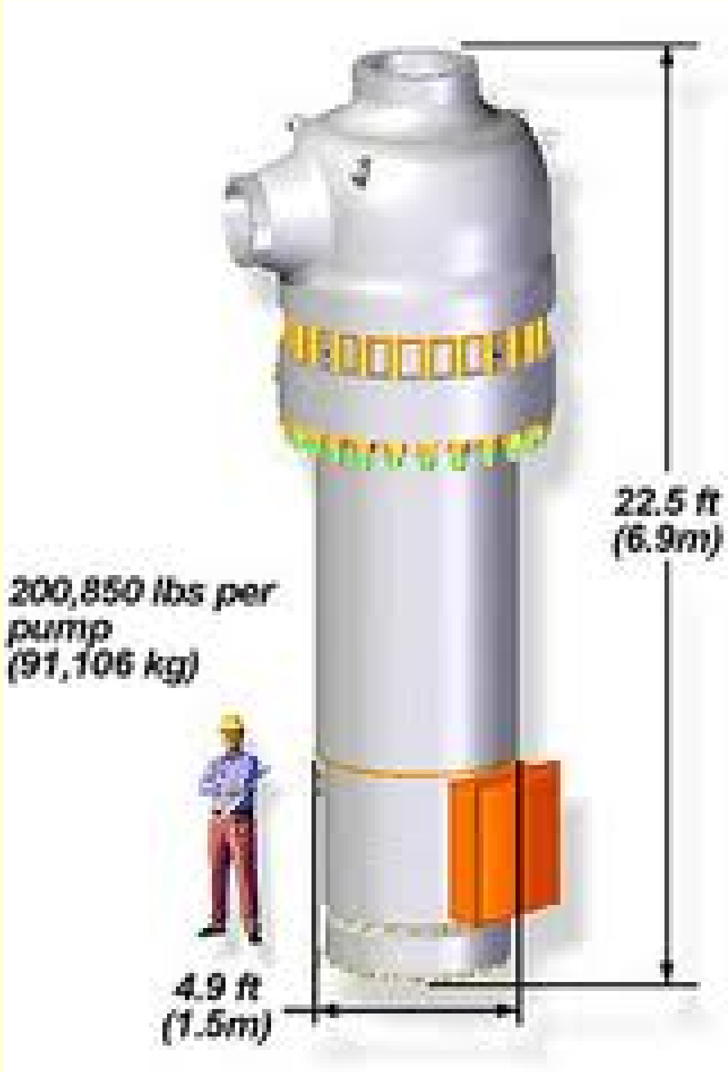


PWR Core

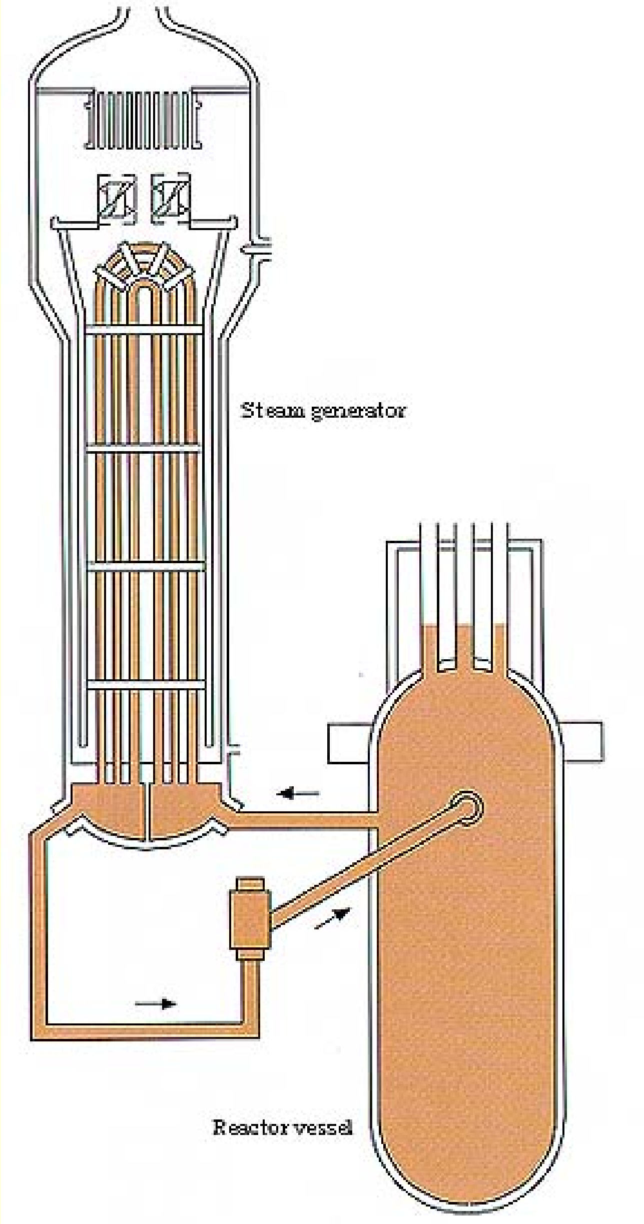


Coolant Pumps





Steam Generator



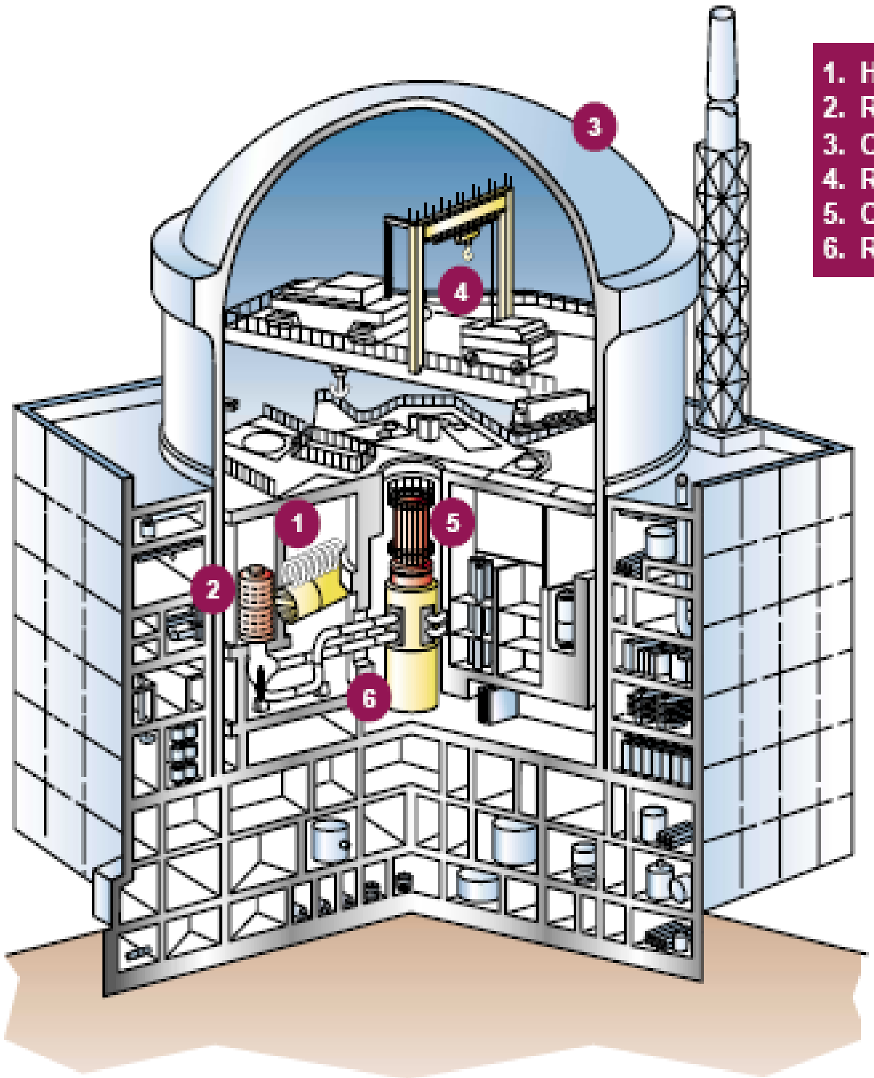
PWR Control

- Rods inserted from top
  - Shut-down: used only to assure complete shutdown after criticality has ceased
  - Full-length: Usually withdrawn but may be used to control transients
  - Part-length: shorter than a fuel assembly, used to shape power in axial direction
  - Typically made of clad Ag-In-Cd
- Routine control: vary the concentration of dissolved boric acid in the coolant
- SCRAM: Emergency shutdown of reactor

Power Uprating

- Over the years the power rating of most nuclear reactors has been increased
  - <2%: Improved reactor physics and heat transfer predictions
  - 2-7%: Improved instrumentation allows reduced margins
  - 7-20%: Better major equipment (pumps, steam generators, etc.)
- Equivalent to building 5200 MWe of capacity

Russian PWR: VVER



1. Horizontal steam generator
2. Reactor coolant pump
3. Containment building
4. Refueling crane
5. Control rod drive assemblies
6. Reactor vessel

The VVER reactor is a pressurized, light-water-cooled and -moderated reactor similar to Western pressurized water reactors (PWRs). There are three predominant models in operation, the VVER-1000 and two versions of the VVER-440.

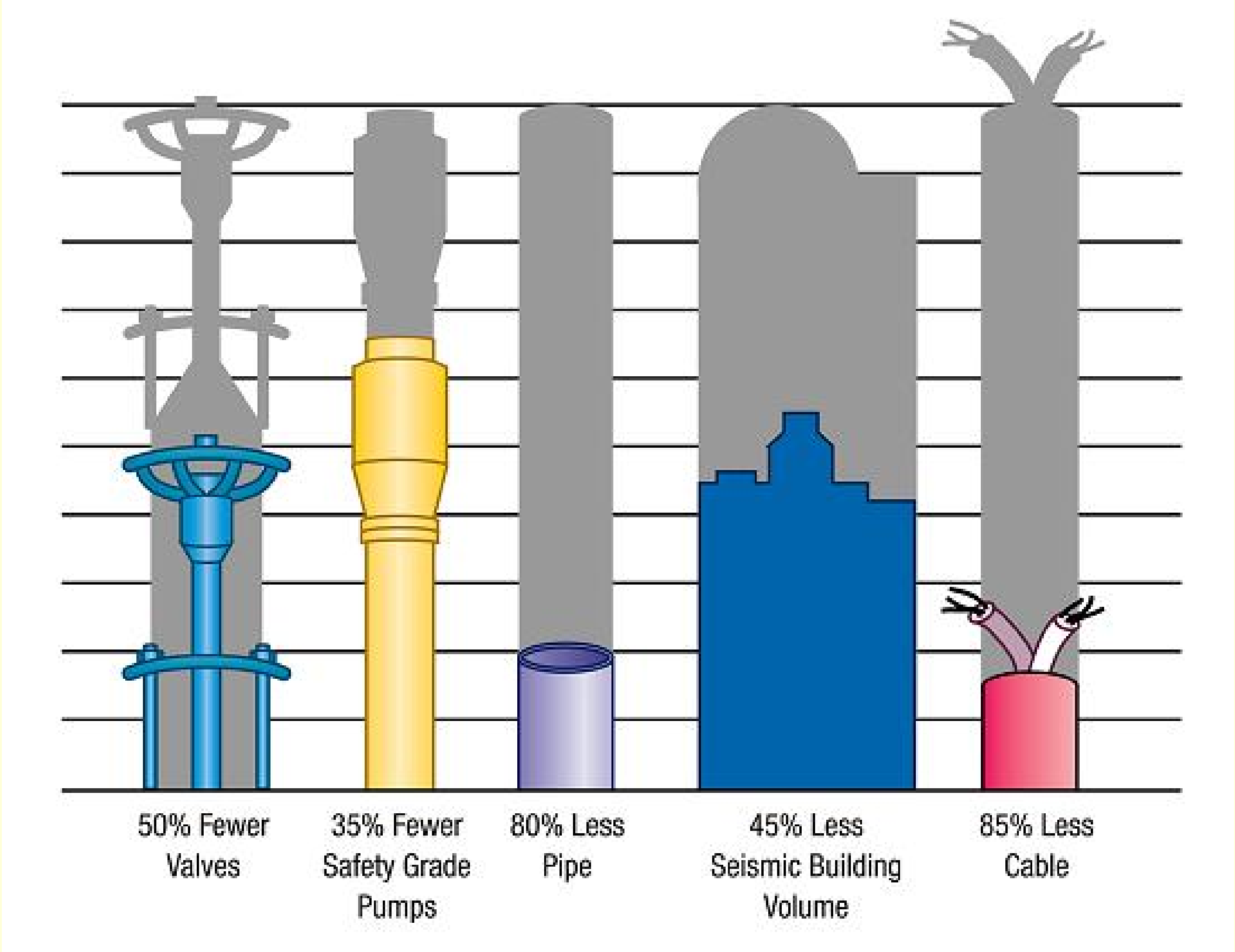
The VVER-1000 is the largest and newest of the VVERs. This third-generation design produces about 1000 megawatts of electricity and meets most international safety standards. The VVER-1000 employs safety systems common in Western plants, including emergency core cooling systems and a containment structure. The VVER-1000 can be found at the Balakovo, Kalinin, Khmelnytskyy, Kozloduy, Novovoronezh, Rivne, South Ukraine, and Zaporizhzhya sites.

GEN III+ PWRs

- Vendors are marketing more advanced PWRs
- Westinghouse: AP600 and AP1000
  - AP = Advanced Passive
- AREVA: US-EPR
  - European Pressurized Reactor
- Mitsubishi: US-APWR

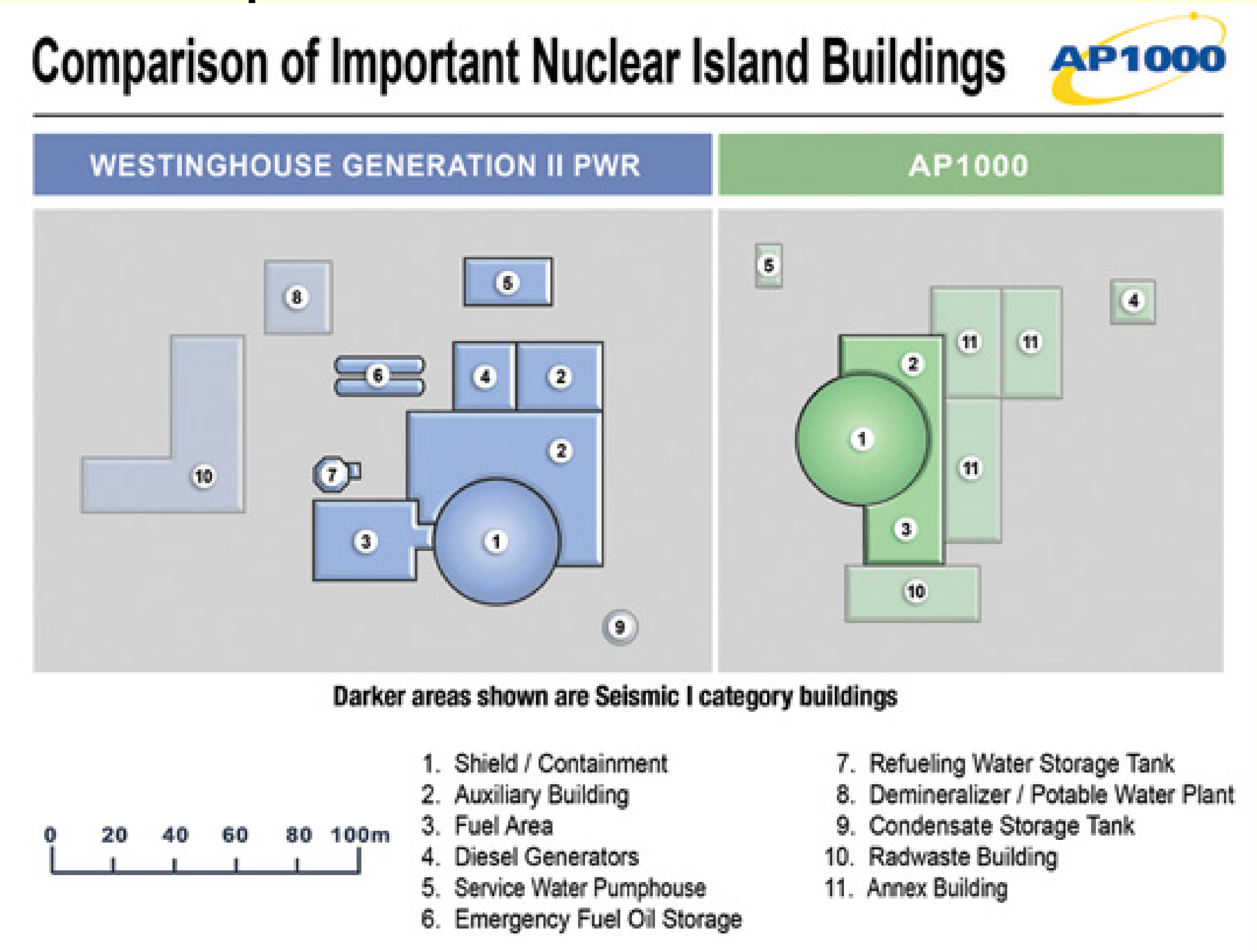
PWR Design Changes

- Less equipment and components



PWR Design Changes

- Smaller footprint: concrete = $$$



Improved Reactor Efficiency

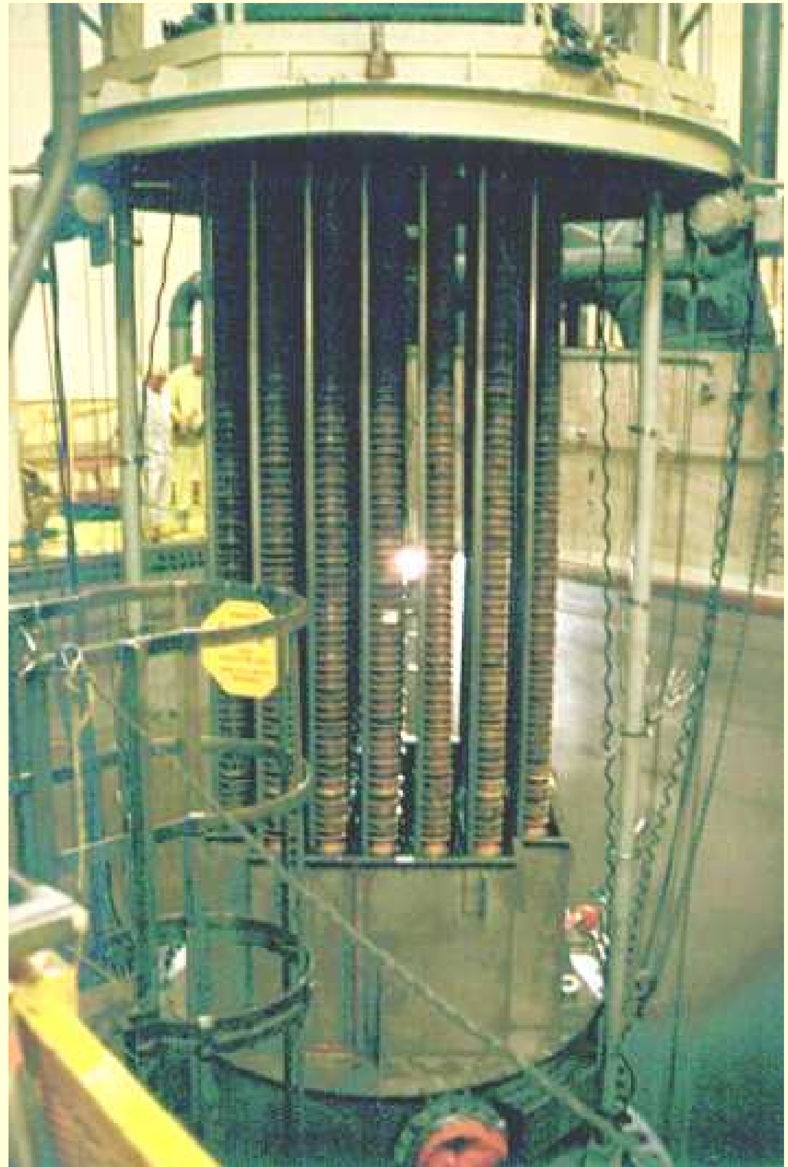
- Thermal efficiency claimed to be increased from 33% to 37%
  - No increase in outlet temperature

Enabling the Improvements

- Design standardization
- Modular construction of components in factories and assembly in the field
- Efficiency improvements
  – Reactor physics: advanced computing, better data
  – Computer-aided design: advanced computing
  – Lower margins: Better instrumentation
  – Equipment: Advanced computing and knowledge
- More on changes in safety approach and fuels later

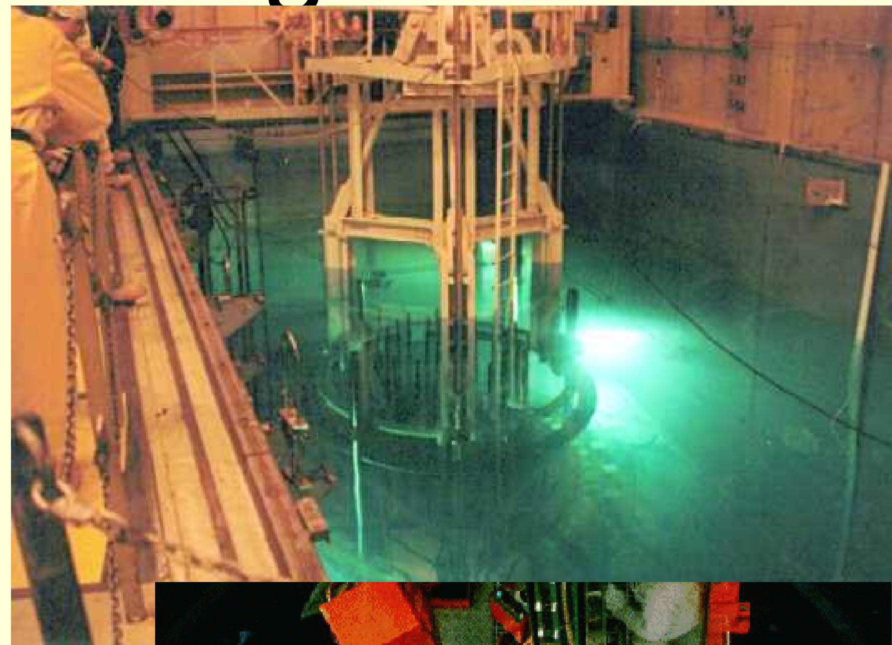
PWR Refueling-1

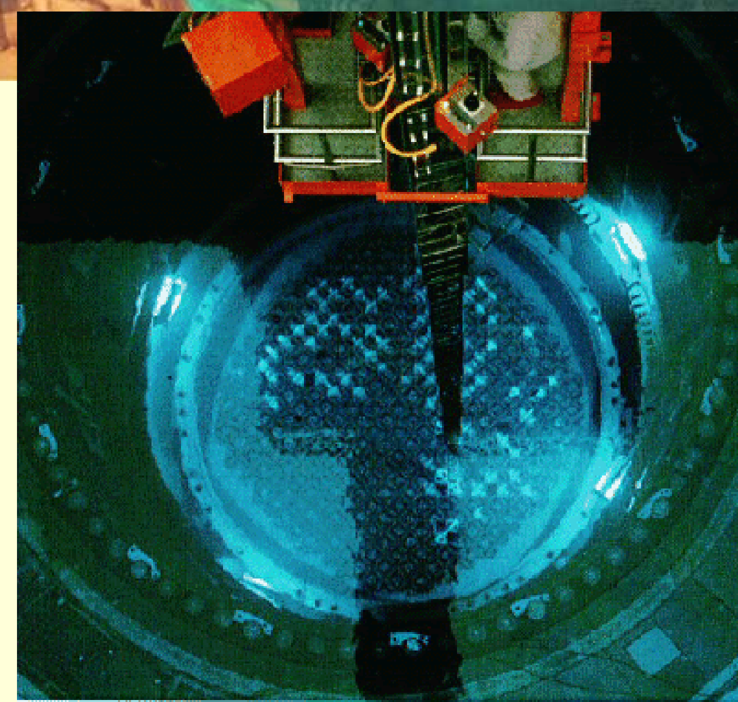
- Shutdown reactor
- Establish high concentrations of boron
- Let it cool and depressurize
- Remove head bolts
- Remove pressure vessel head and control rods



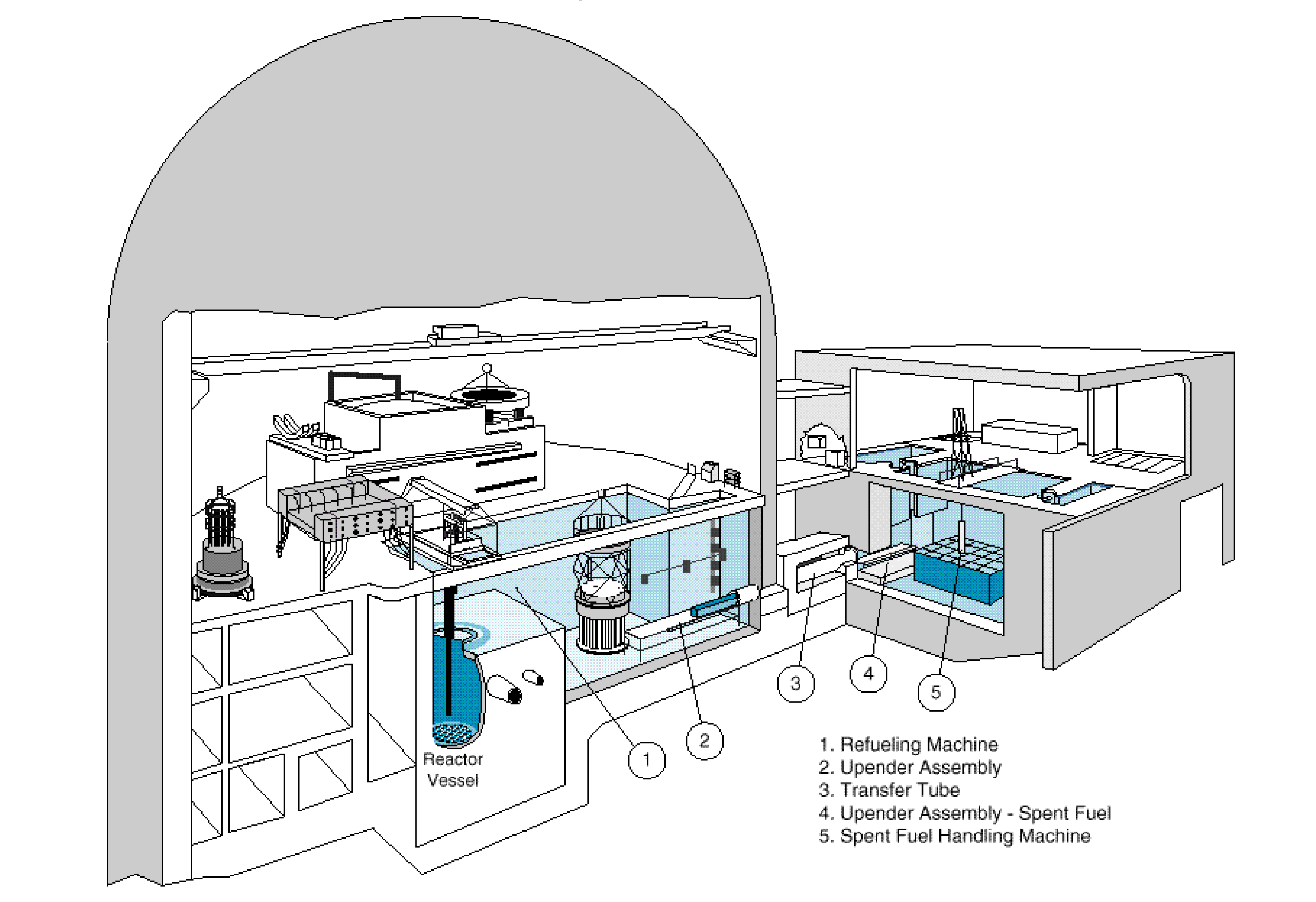
PWR Refueling-2

- Remove the upper internals from the reactor
- Flood the refueling pool
- Begin removing spent fuel and inserting fresh fuel
- A wide spectrum of maintenance on the entire reactor system is done while refueling is ongoing





PWR Refueling-3



PWR Refueling-4

- After refueling the reactor is reassembled by reversing the previous sequence
- Average refueling outage is 38 to 42 days
  - Gen III+ is shooting for half of this
- After initial load 20% to 33% of the core is replaced during each refueling outage

Nuclear Accidents

- A nuclear reactor is a very concentrated source of heat: 50 to 100 kW/liter
- Immediately after shutdown the reactor is generating about 6% of its operating power due to decay heat
  - 200 MW for a large reactor
  - Declines about 10%/day in the short term

Progress of a Reactor Accident

- The primary coolant loop is breached and coolant water escapes
  - Reactor goes subcritical: no coolant
- Fuel surface dries out and begins to heat
- ~2200 F the cladding begins to fail and burn
- Radionuclides are volatilized from the fuel and enter the containment outside the reactor
- An over-pressurized containment can be breached and radionuclides escape to the environment

Objective

- Rule #1: Keep the core wet
  - If not, really bad things happen
    - Cladding breach and release of volatile species
    - Cladding fire
    - Fuel melt
    - Steam explosions
- Rule #2: See Rule #1
  - Defense in depth: multiple barriers
- Rule #3: Deal with it

Preventing an Accident

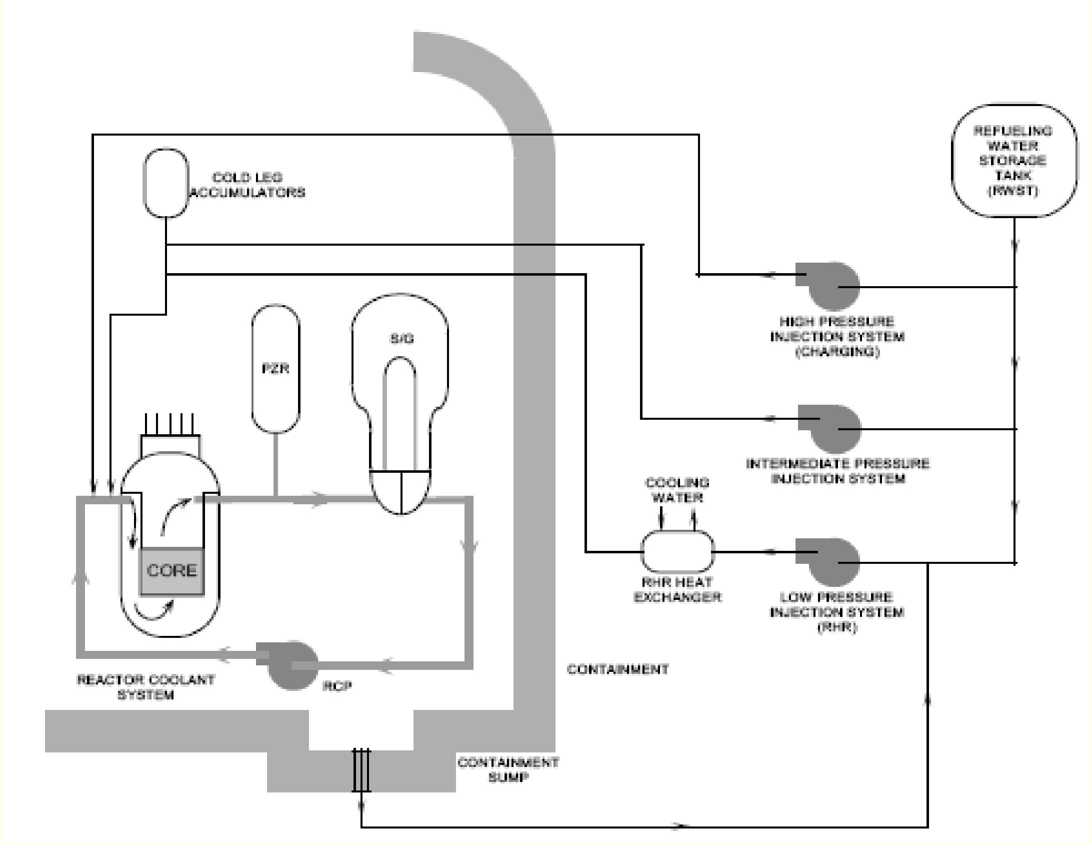
- Design solutions
  - Eliminate features that facilitate coolant release
    - Pressure vessel penetrations below the core
    - Requirement for active cooling in accidents
- Detection solutions
  - Detect potential problems before they can lead to coolant loss, e.g., corrosion
  - Detect coolant loss early and accurately
- Training solutions
  - Understand the reactor: normal and off-normal
  - Understand when to intervene -- or not

Controlling an Accident

- If coolant loss occurs supply more coolant and sustain it
  - Coolant and power are essential
  - Recirculation of water from a sump is necessary

Power
- External
- Emergency

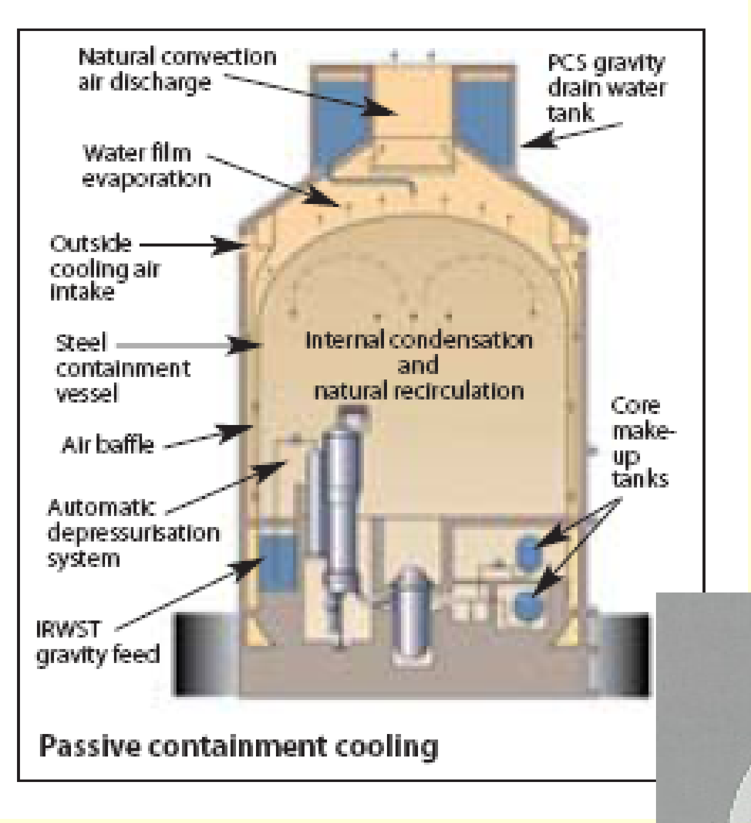
diesel generators (tested regularly) are needed

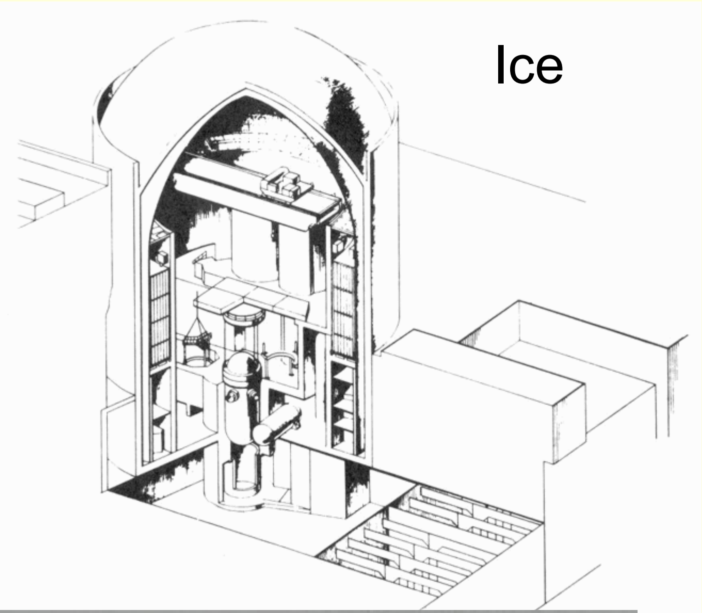


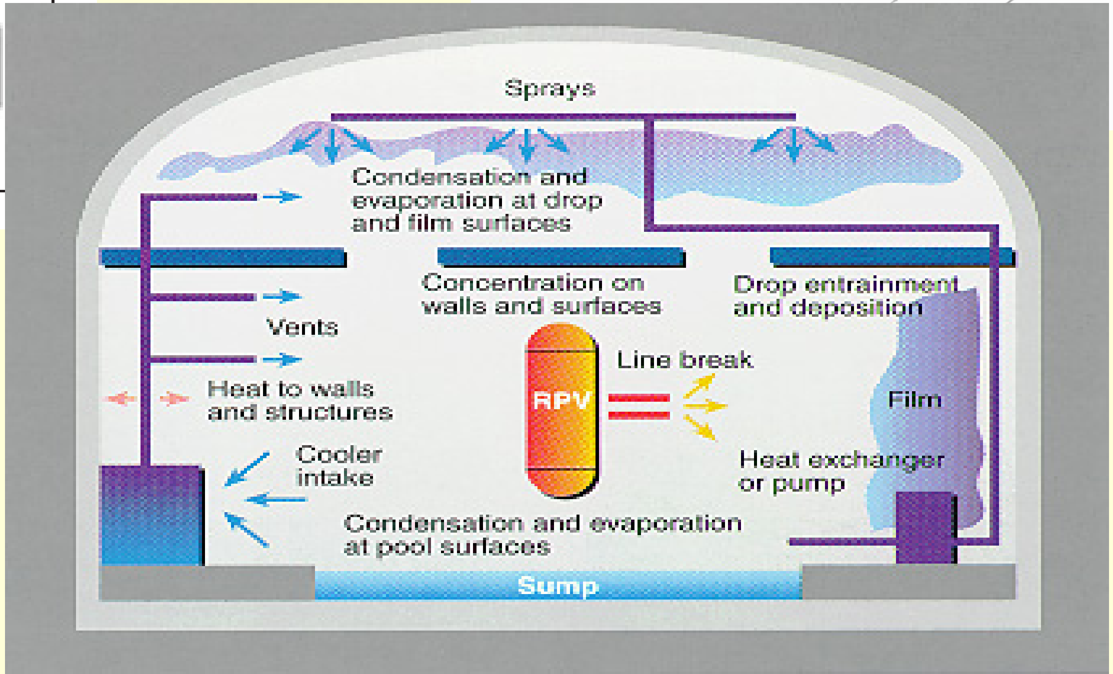
Containing a Release

- Keep releases from pressure vessel within the building
  - Issue: contain increasing pressure from steam
- Solution: Containment Dome
  - Reinforced concrete
  - Enough volume to handle pressure
  - Design features to reduce pressure
    - Water spray
    - Ice bank
    - Heat exchange to the environment
    - Not standardized for PWRs
- Last resort: filtered venting to reduce pressure

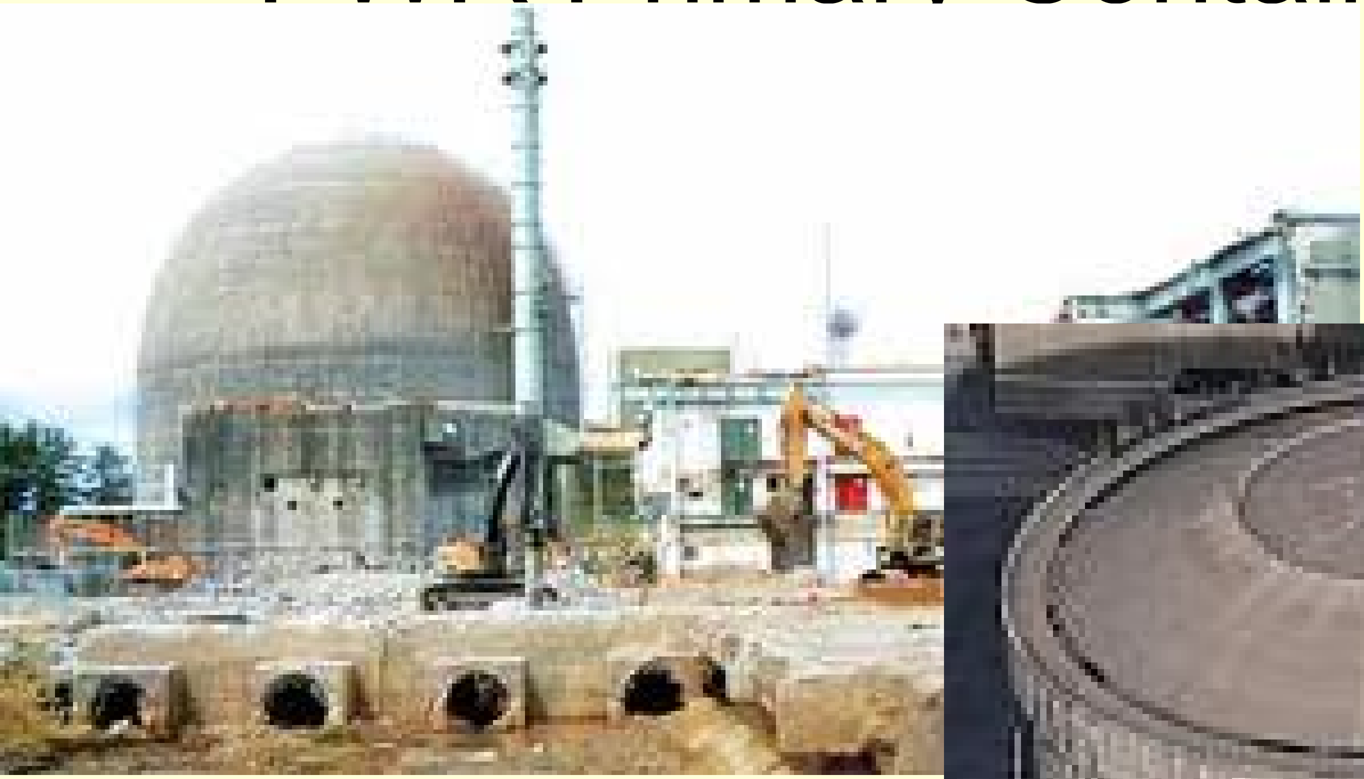
PWR Containment Approaches







PWR Primary Containment

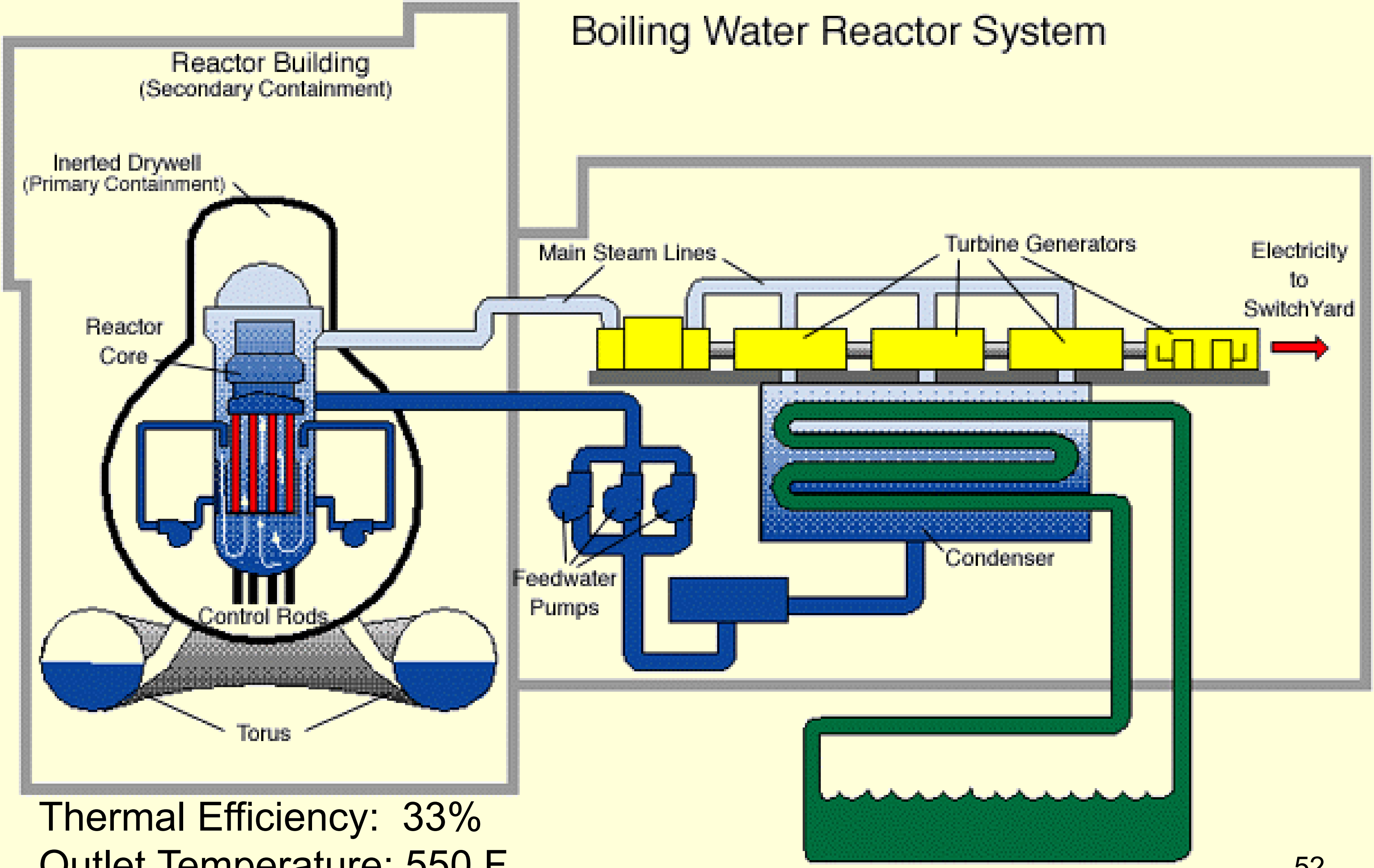


GEN III+ Safety Features

- Westinghouse AP reactors
  - Water reservoir: In an accident the well surrounding the pressure vessel is flooded
  - Passive cooling: water circulates in the core via natural convection
  - Containment building also operates passively: containment within containment
- AREVA
  - Core catcher for melted debris
  - No passive cooling

Boiling Water Reactors

Boiling Water Reactor (BWR)



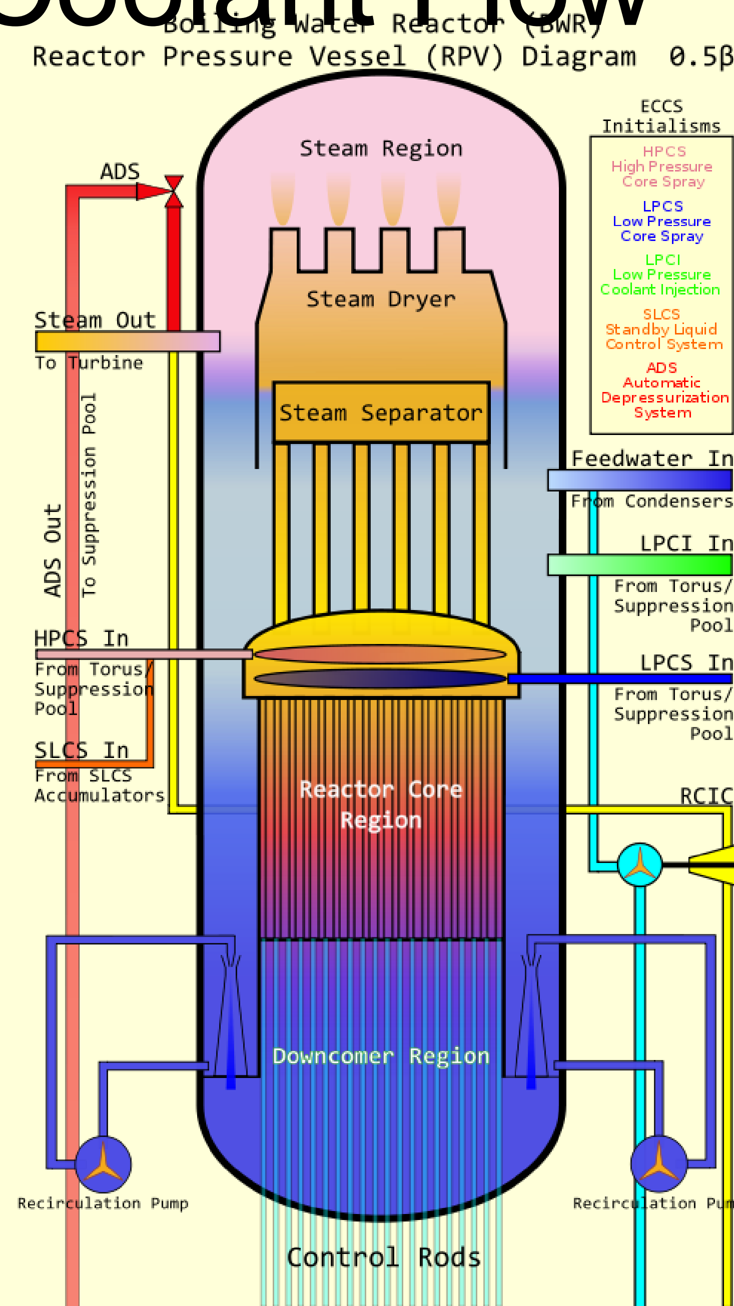
Thermal Efficiency: 33%
Outlet Temperature: 550 F

Key Features vs. PWR

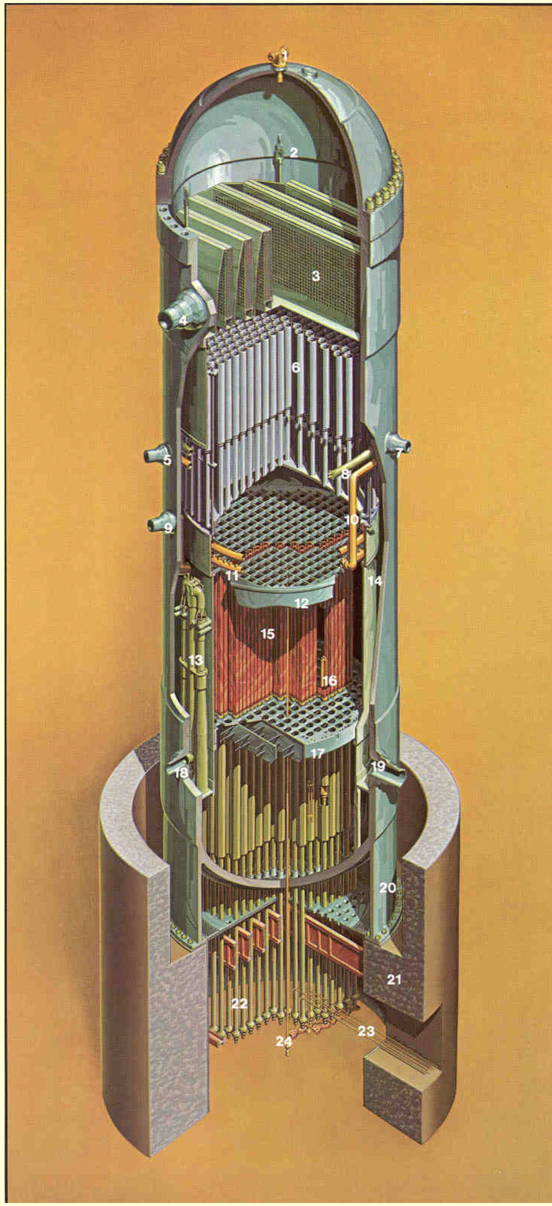
- Only a primary loop: water boils in core and steam goes to turbine
- Boiling does not allow use of boric acid for control
  - Control rod material is typically B_4C
- One vendor for many years so designs are more standardized
- Steady evolution
  - Reactor: BWR/1 → BWR/6
  - Containment: Mark I → Mark III

BWR Reactor Coolant Flow

- Two water loops
  - Primary coolant
  - Internal recirculation
- Steam separator and dryer
  - Vessel is taller (~60 ft) and wider (20-25 ft) than PWR
  - Pressure is lower as is wall thickness
- Control rods enter from bottom



BWR Reactor



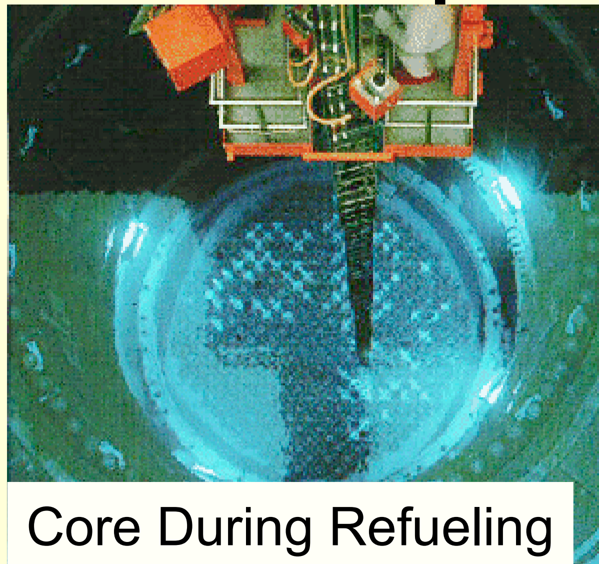
BWR/6
REACTOR ASSEMBLY

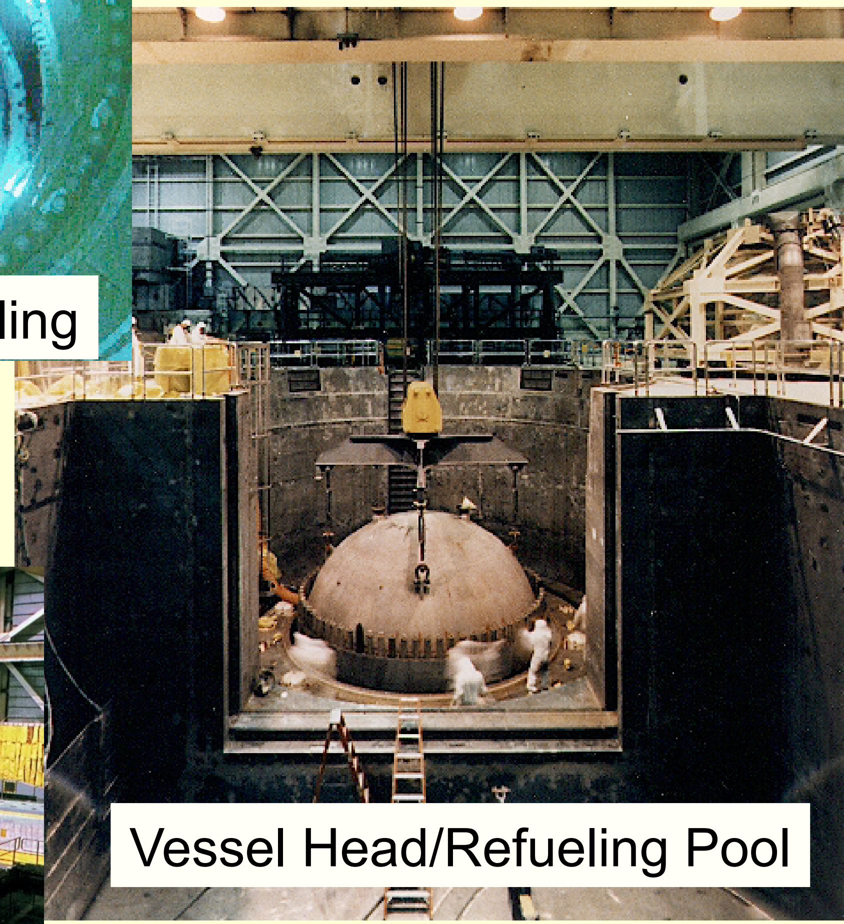
1. VENT AND HEAD SPRAY
2. STEAM DRYER LIFTING LUG
3. STEAM DRYER ASSEMBLY
4. STEAM OUTLET
5. CORE SPRAY INLET
6. STEAM SEPARATOR ASSEMBLY
7. FEEDWATER INLET
8. FEEDWATER SPARGER
9. LOW PRESSURE COOLANT INJECTION INLET
10. CORE SPRAY LINE
11. CORE SPRAY SPARGER
12. TOP GUIDE
13. JET PUMP ASSEMBLY
14. CORE SHROUD
15. FUEL ASSEMBLIES
16. CONTROL BLADE
17. CORE PLATE
18. JET PUMP / RECIRCULATION WATER INLET
19. RECIRCULATION WATER OUTLET
20. VESSEL SUPPORT SKIRT
21. SHIELD WALL
22. CONTROL ROD DRIVES
23. CONTROL ROD DRIVE HYDRAULIC LINES
24. IN-CORE FLUX MONITOR

GENERAL ELECTRIC

BWR Components

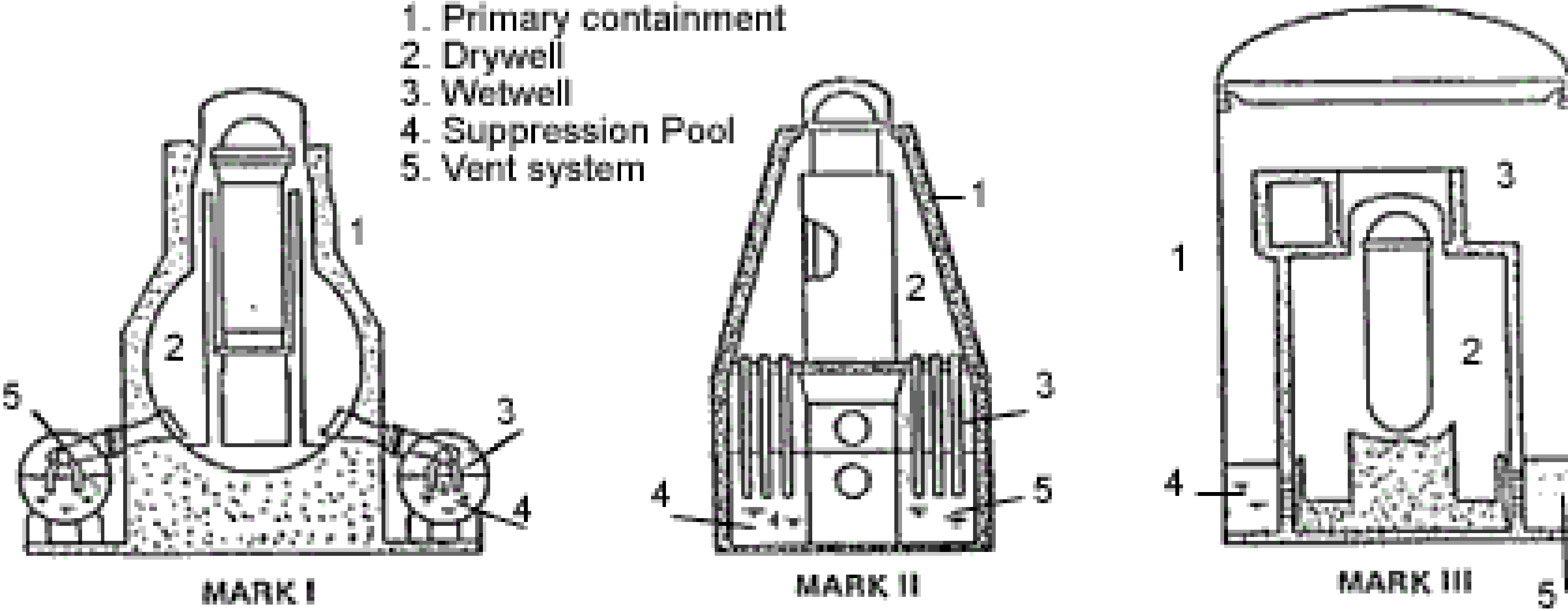
Core Basket


Core During Refueling


Vessel Head/Refueling Pool

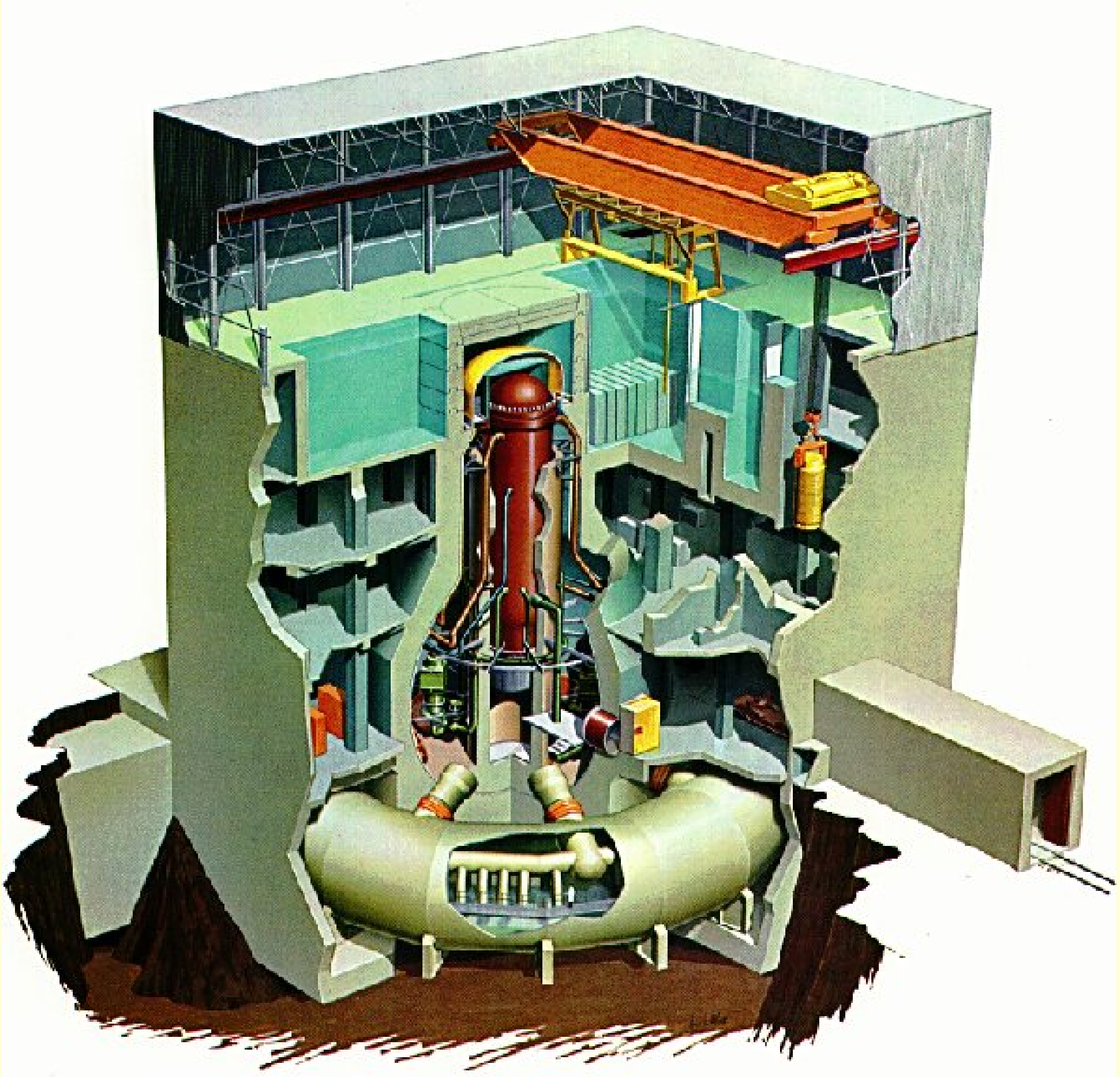

Refueling Floor & Machine

BWR Safety Systems



General Electric pressure suppression system designs

BWR Mark I Building Layout

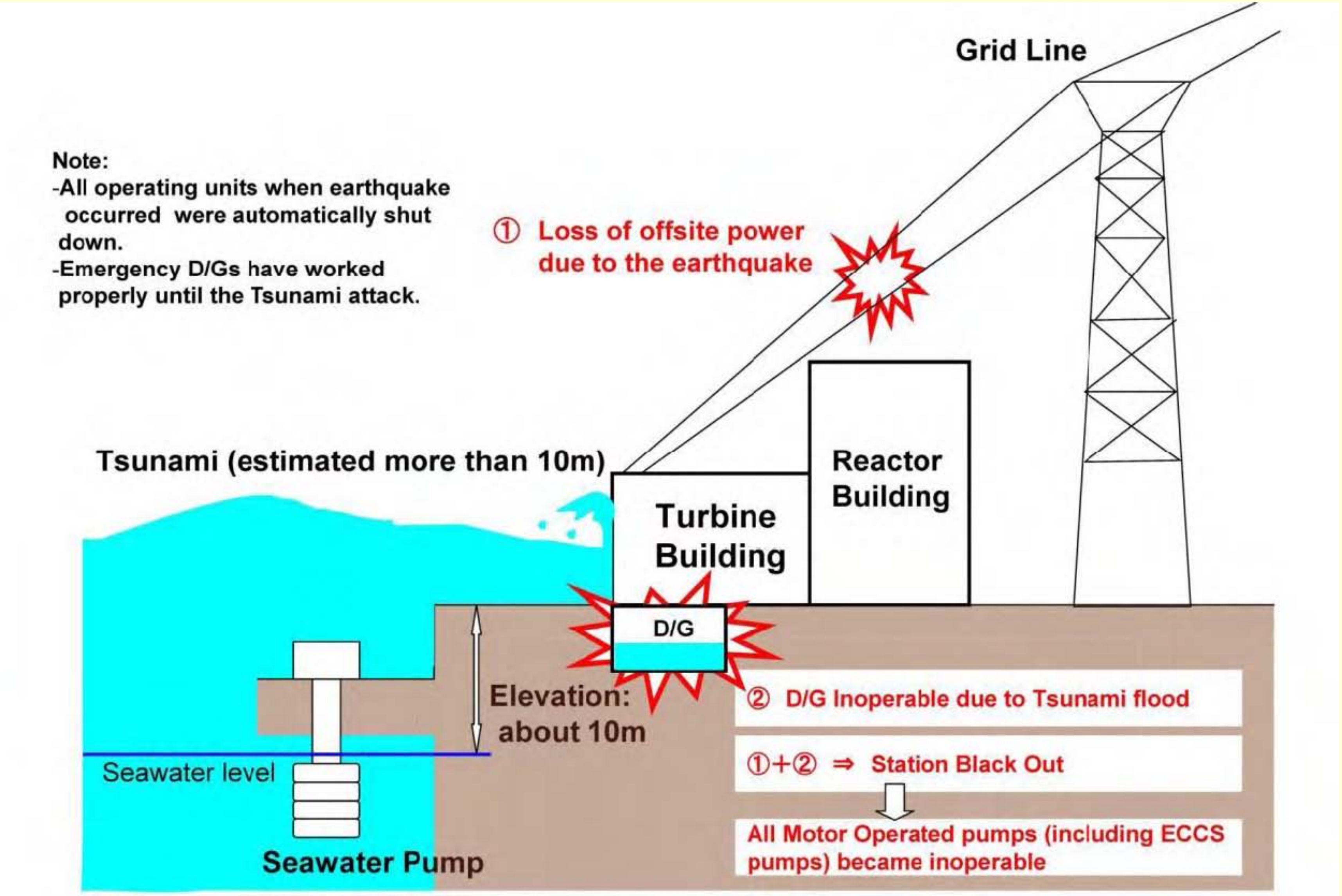


BWR Mark I Torus at Brown's Ferry

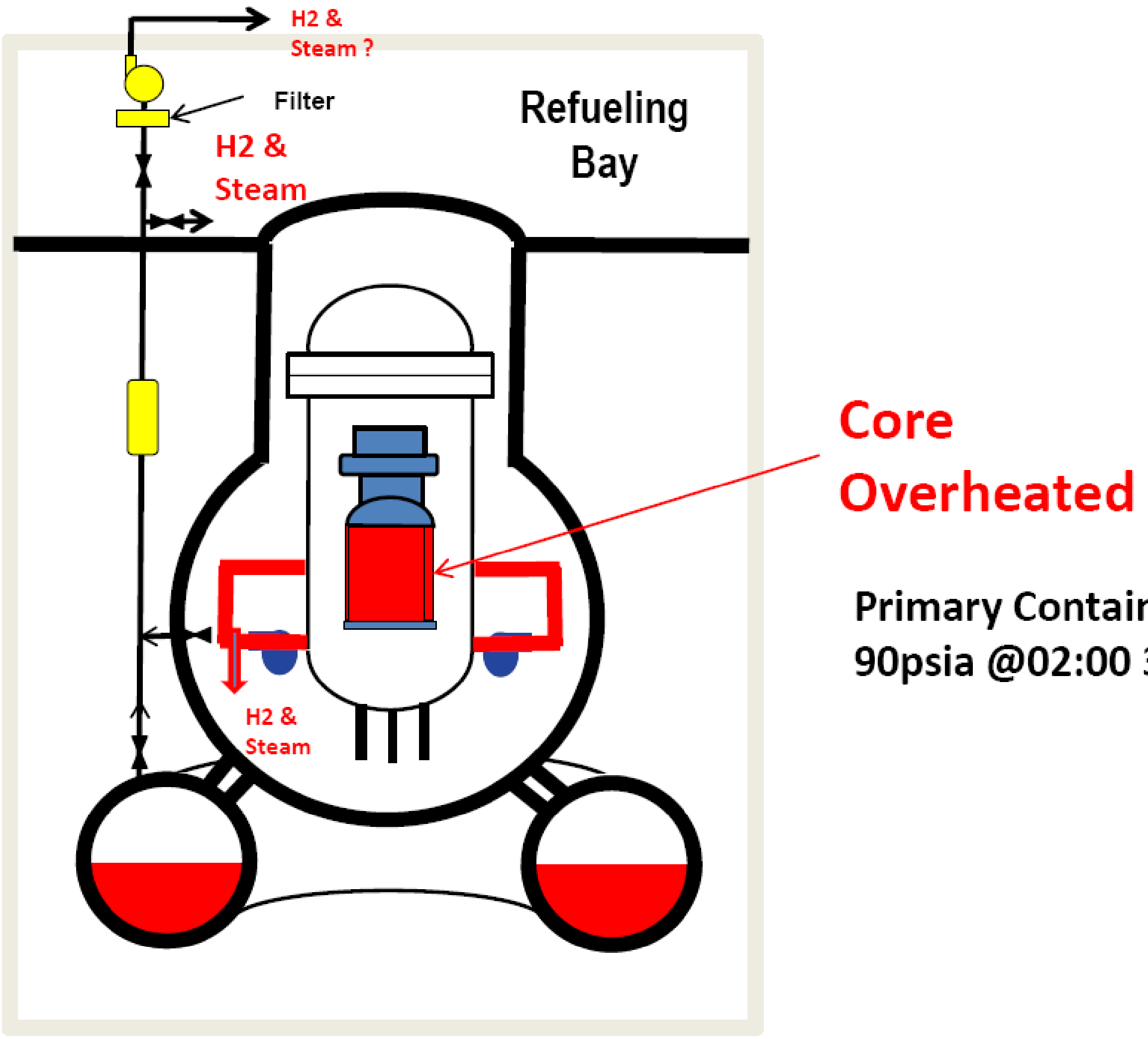
Fukushima Daiichi Event

- Initial status
  - Plants are oceanfront
  - Units 1-3, 5, and 6 operating; U4 shut down for repair
- Event: 3/11/11, 14:46 JST
  - 9.0 offshore quake; design basis was 8.2: 6.3x
  - A 14m tsunami an hour later
    - Design basis 5.7m above sea level
    - Reactors and equipment 10-13m above sea level

Fukushima Daiichi Unit 1-3 Event



Fukushima Daiichi Unit 1-3 Event



**Primary Containment Pressure~
90psia @02:00 3/12**

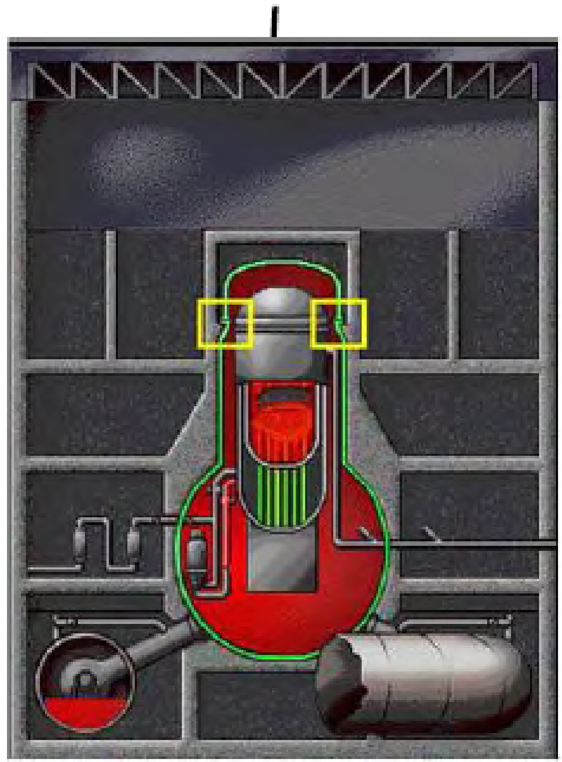
3/12 ~05:30 U1
3/13 ~ 00:00 U2
3/13 ~ 08:40 U3

Fukushima Daiichi Unit 1-3 Event

Primary Coolant System

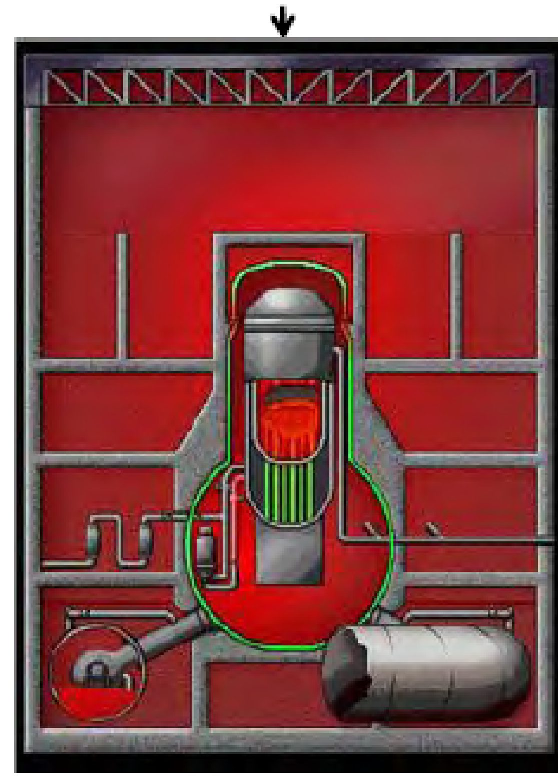
Core Over Heat
-Clad Burst ~900C
-Clad Oxidize ~1200C
-H2 Release
-Partial Melt~1800C-2700C
-Primary Coolant System Overpressure

Primary Containment



Vent from Primary Coolant Sys to Primary Containment- H2, Steam, & Fission Products (Xe, Kr, I, Cs etc)

Secondary Containment



No Primary Containment Cooling therefore Primary Containment Overpressure- Vent to Secondary Containment

Fukushima Daiichi Unit 1-3 Event

Fukushima Daiichi Unit 4 Event

- Repairs: No fuel in reactor
- Refueling cavity presumed to be flooded; gate status unknown
- Explosions occurred and damaged secondary containment

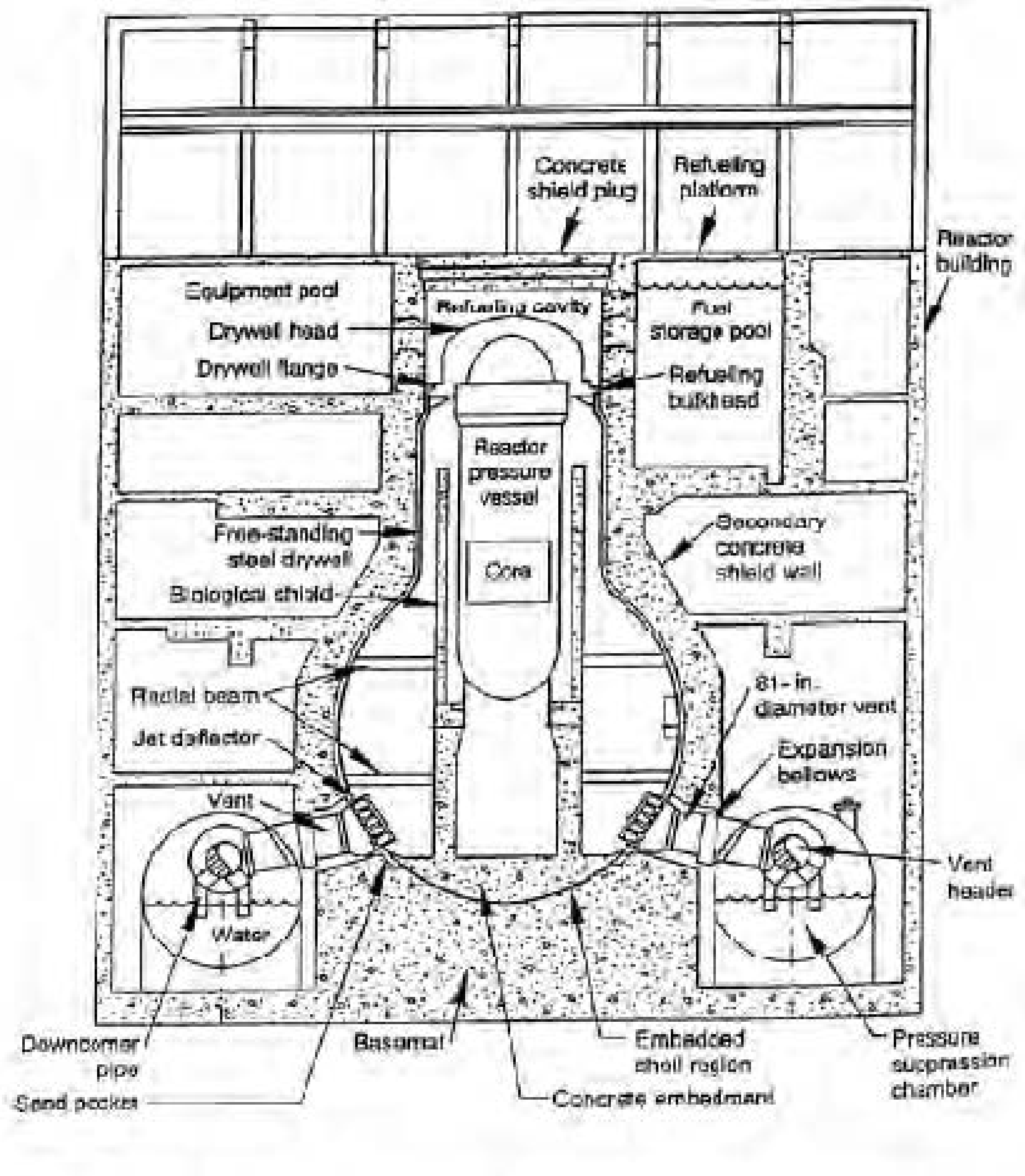


Figure 20. Mark I General Electric GE BWR Containment.

Fukushima Daiichi Unit 4 Event

- Source of explosion not certain
  - First thought to be due to low water levels leading to fuel overheating, oxidation, and hydrogen release
- More recent video from a submersible device in the pool showed little damage
  - Spent fuel in refueling cavity?
  - Acetylene
  - Hydrogen from Unit 3 via common ventilation system

Fukushima Daiichi Event

- Managing the situation
  - Keep pouring water into reactor buildings
    - Created a large contaminated water management problem which led to releases to the ocean
    - Cracks resulted in leaks to the ocean
  - Inert primary containment
  - Restore site power
  - Restore power inside reactors
  - Restore closed-loop cooling
  - Contain gaseous releases
  - Process contained contaminated water
  - D&D: Will take years

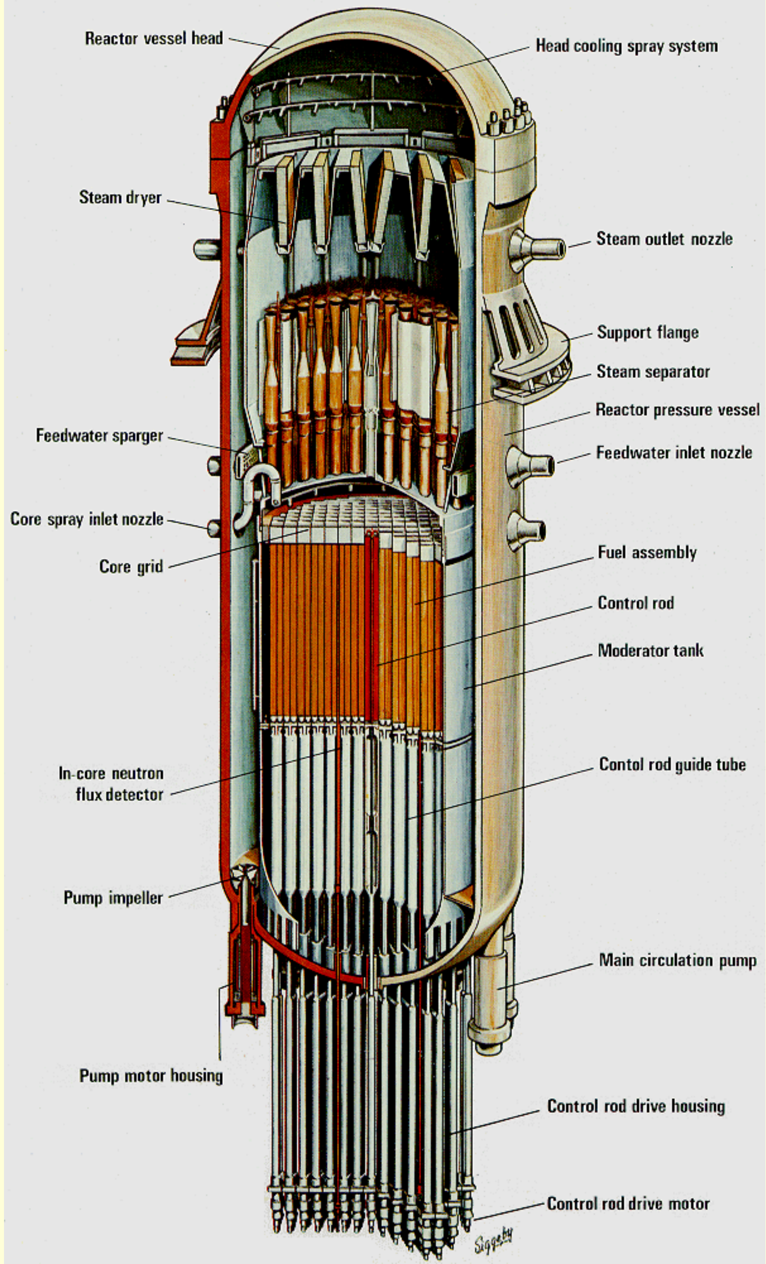
Fukushima Daiichi Event

- Status
  - Much more is still unknown than is known
  - Reasonably firm knowledge on what happened inside the four reactor is likely to take at least couple of years
    - It took two years to get into the TMI core
  - Still high radiation levels inside units and at site boundary
    - Mainly due to Cs-137; water processing should reduce radiation levels considerably

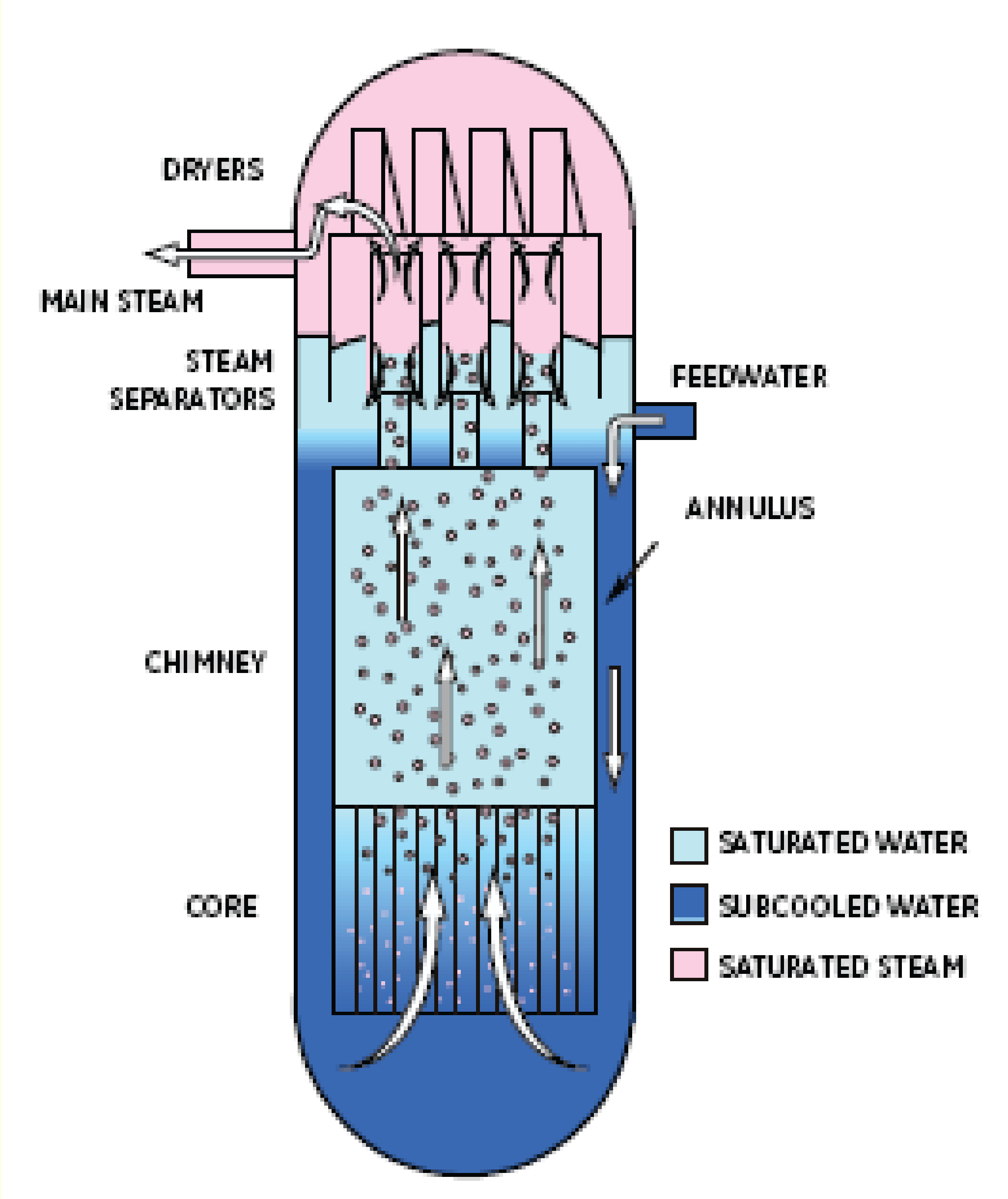
GEN III+ BWRs

- Toshiba/GE: Advanced BWR (ABWR)
  - Thermal efficiency increased to 34.5%
  - Recirculation pumps internalized: no coolant penetrations on lower part of vessel
  - Fine motion control rods for startup
- GE-Hitachi: Economic and Simplified BWR (ESBWR)
  - Thermal efficiency increased to 34.5%
  - Natural circulation during operation and accidents
  - Gravity flooding in an accident
  - Passive containment
- Other improvements similar to PWR

ABWR


Reactor vessel head
Head cooling spray system
Steam dryer
Steam outlet nozzle
Support flange
Steam separator
Reactor pressure vessel
Feedwater sparger
Feedwater inlet nozzle
Core spray inlet nozzle
Core grid
Fuel assembly
Control rod
Moderator tank
In-core neutron
flux detector
Contol rod guide tube
Pump impeller
Main circulation pump
Pump motor housing
Control rod drive housing
Control rod drive motor

ESBWR

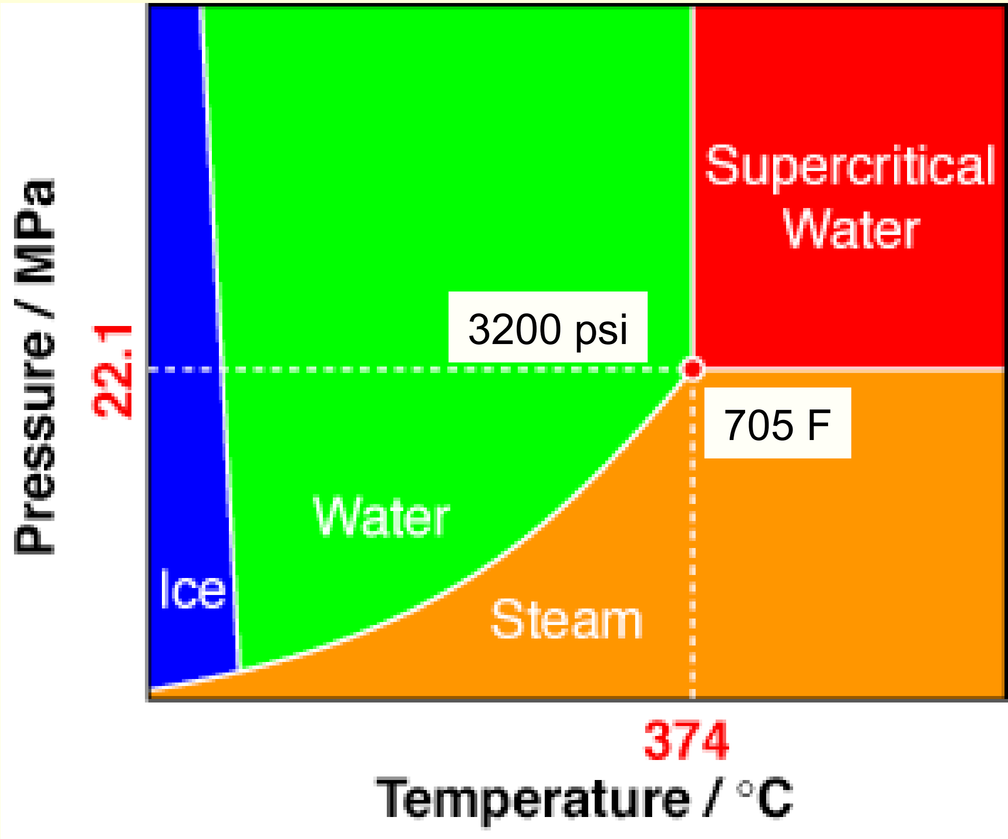

DRYERS
MAIN STEAM
STEAM SEPARATORS
FEEDWATER
ANNULUS
CHIMNEY
CORE
SATURATED WATER
SUBCOOLED WATER
SATURATED STEAM

Backup

Super-Critical Water Reactor

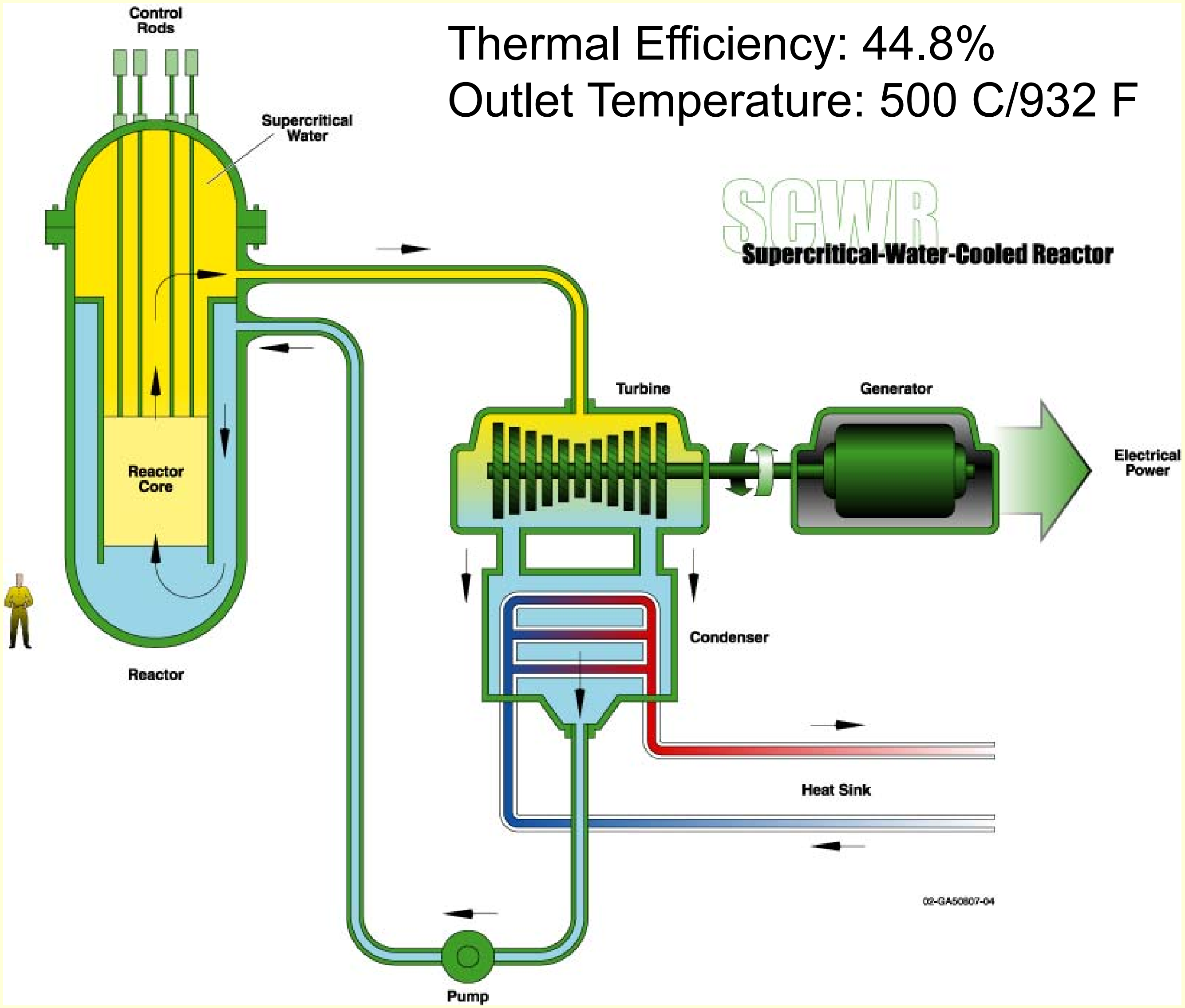
Supercritical Water

- Supercritical water
  - Properties intermediate between a gas and a liquid
  - Single phase
  - Can diffuse through solids like a gas and dissolve materials like a liquid
- Supercritical water is used in fossil electricity production
  - Supercritical CO_2 is used to decaffeinate coffee



SuperCritical Water Reactor (SCWR)

Thermal Efficiency: 44.8%
Outlet Temperature: 500 C/932 F



SCWR: A GEN IV System

- A BWR at high PWR+ pressure
  - Only a primary loop
  - Supercritical water does not change phase
    - Density changes from about 0.9 to 0.1 g/cm^3 in reactor
  - Thermal spectrum but low SCW density will require water rods in fuel
- Advantages
  - High efficiency
  - Simple system
  - Compact

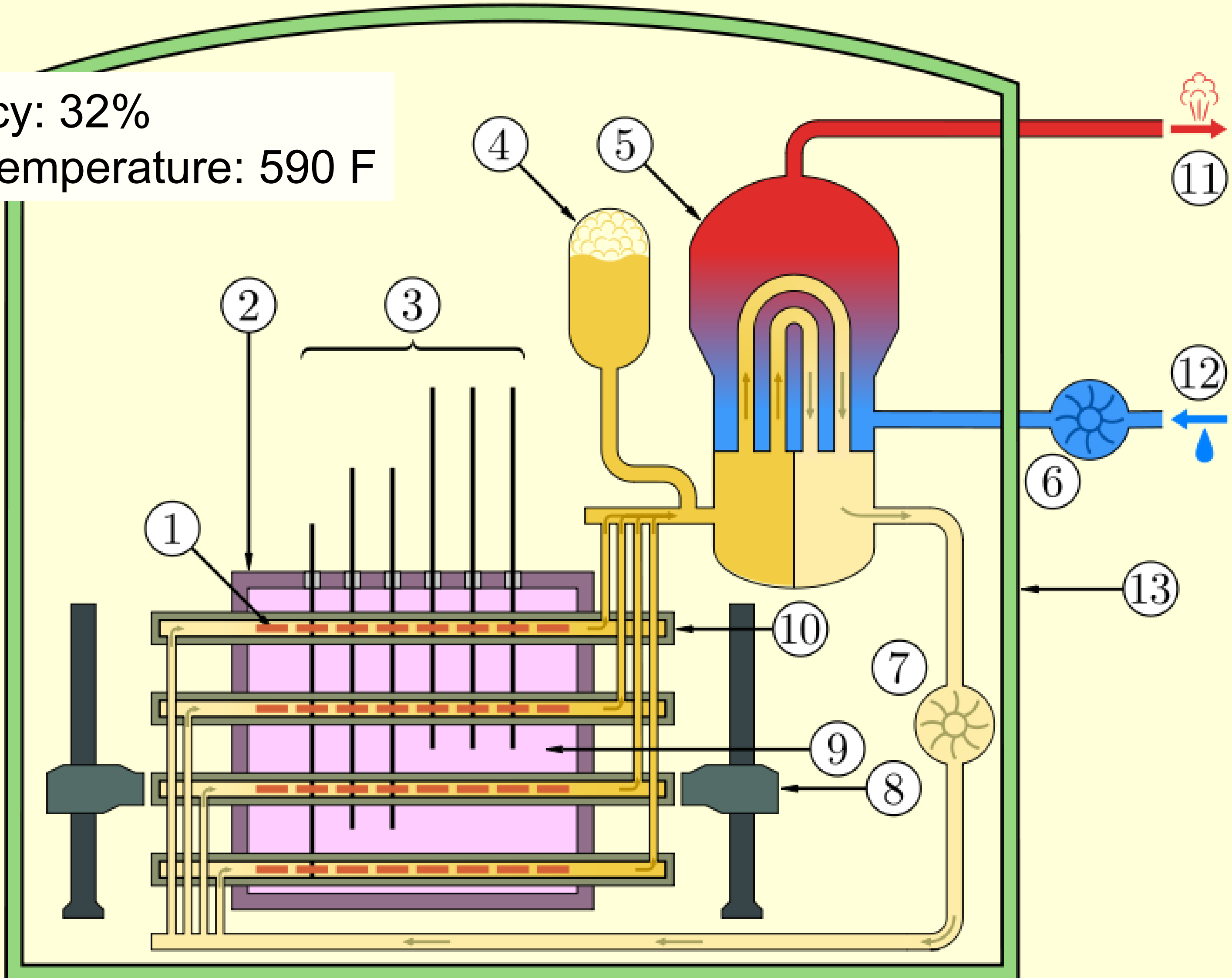
SCWR Status

- R&D project, lower priority
- Major R&D issues
  - Materials of construction: SCW is very corrosive
  - Understanding SCW physical properties and radiolytic chemistry
  - Accident phenomena and mitigation
  - Design optimization

CANDU

Canada Deuterium-Uranium (CANDU) Reactor

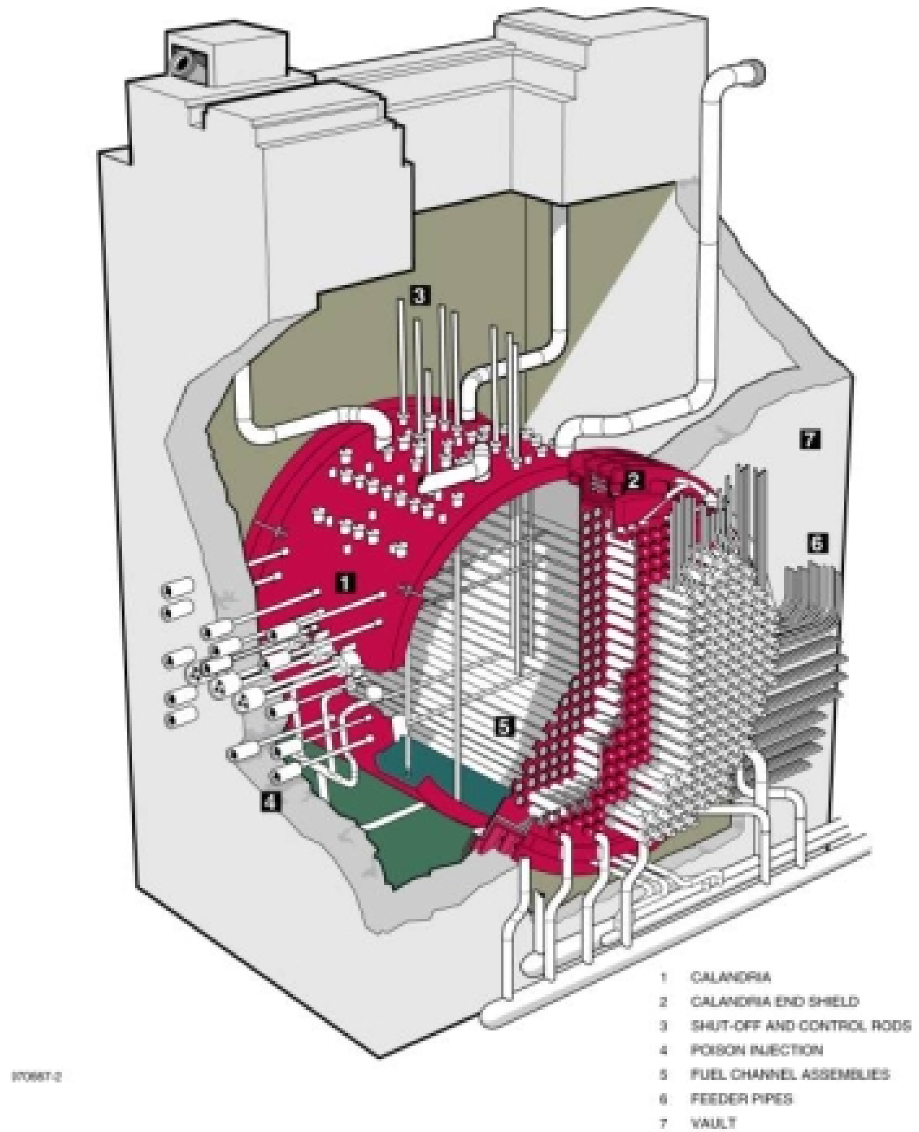
Efficiency: 32%
Outlet Temperature: 590 F



CANDU Features

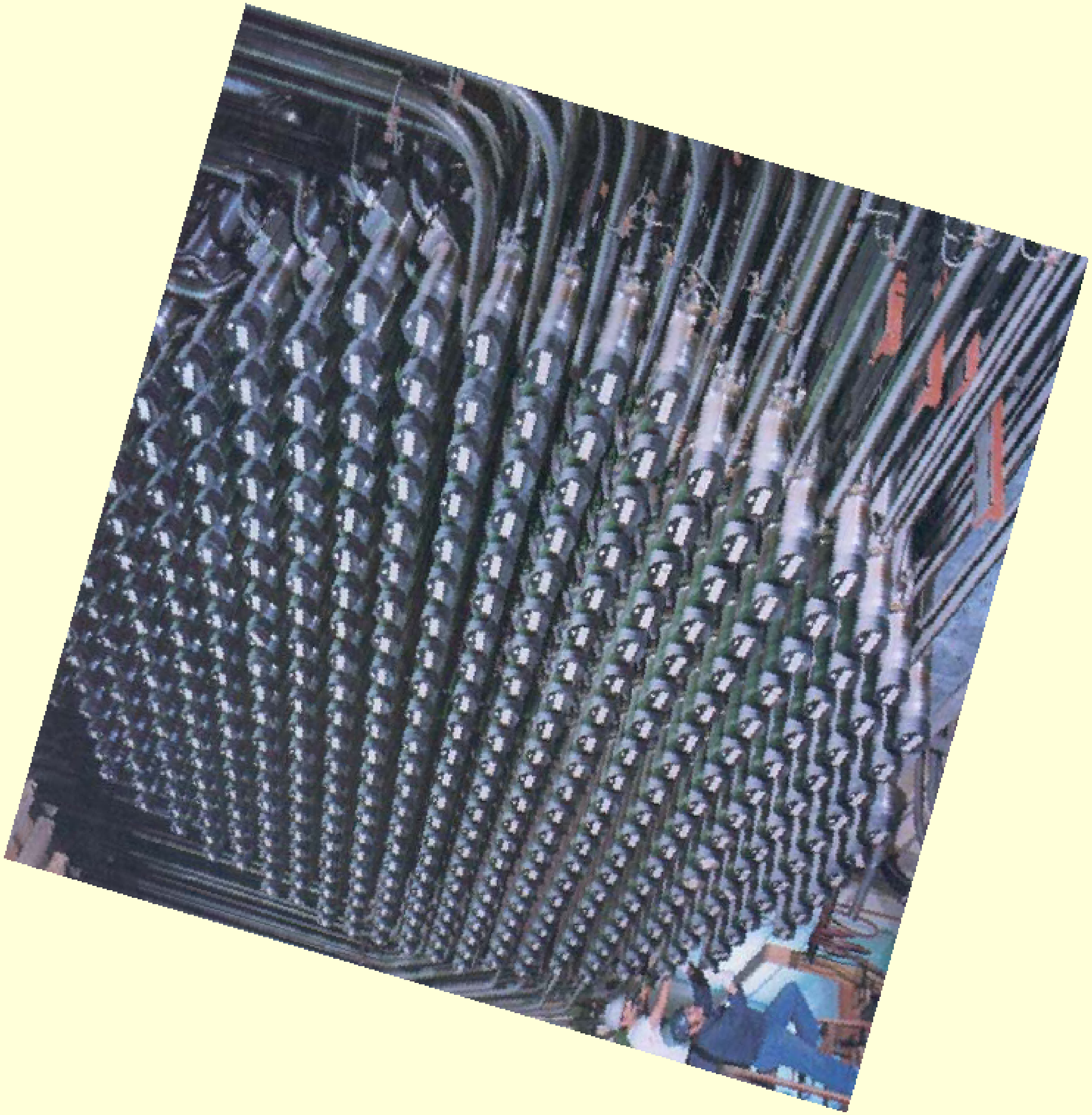
- Conceptually very similar to a PWR
- Major differences
  - Cooled and moderated by heavy water
  - Can operate on natural uranium as well as slightly enriched uranium
  - Online refueling
  - Horizontal pressure vessel
  - Does not use boron for control

CANDU Pressure Vessel: Calandria

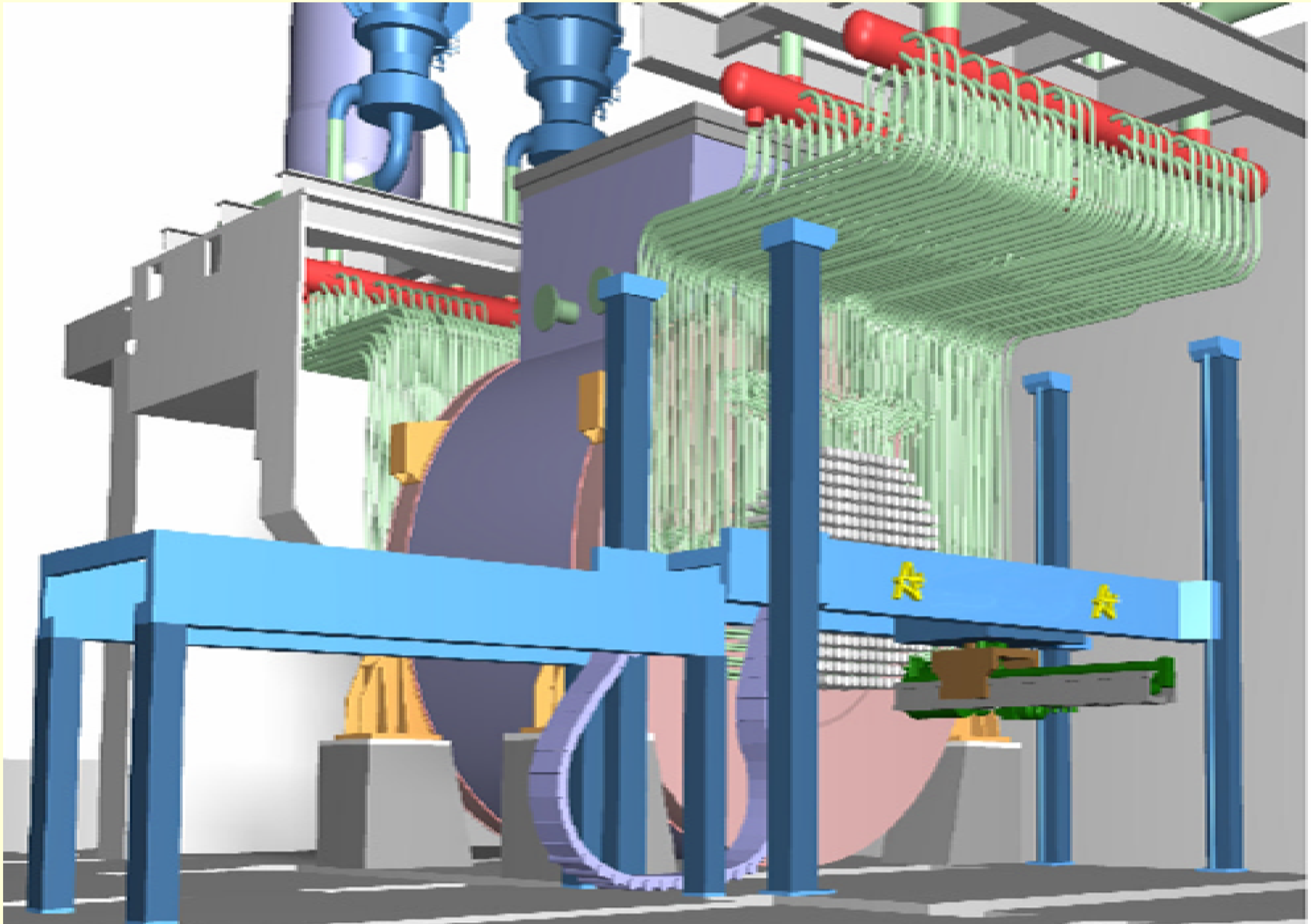


CANDU 6 Reactor Assembly

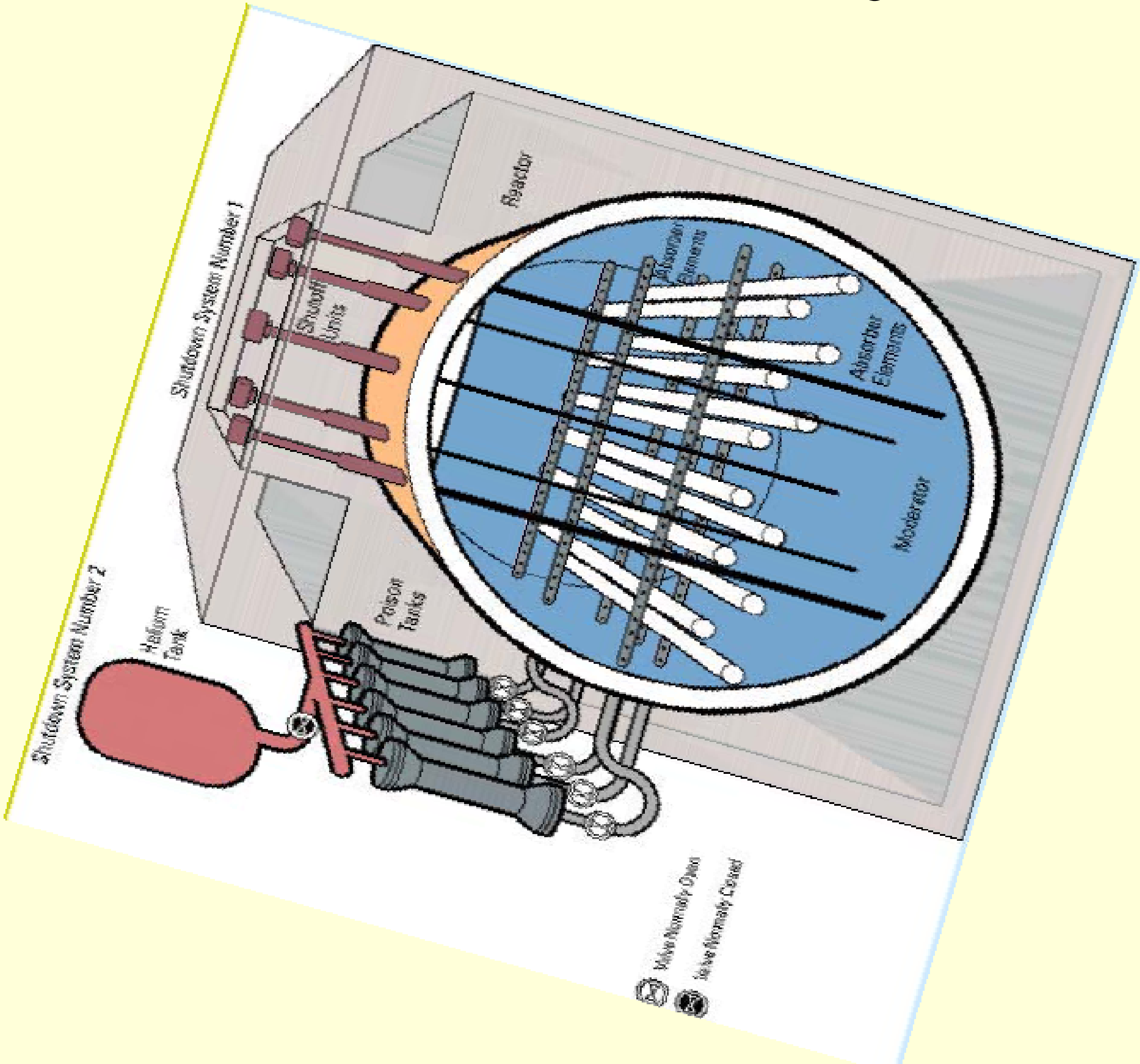
CANDU Reactor Face-1



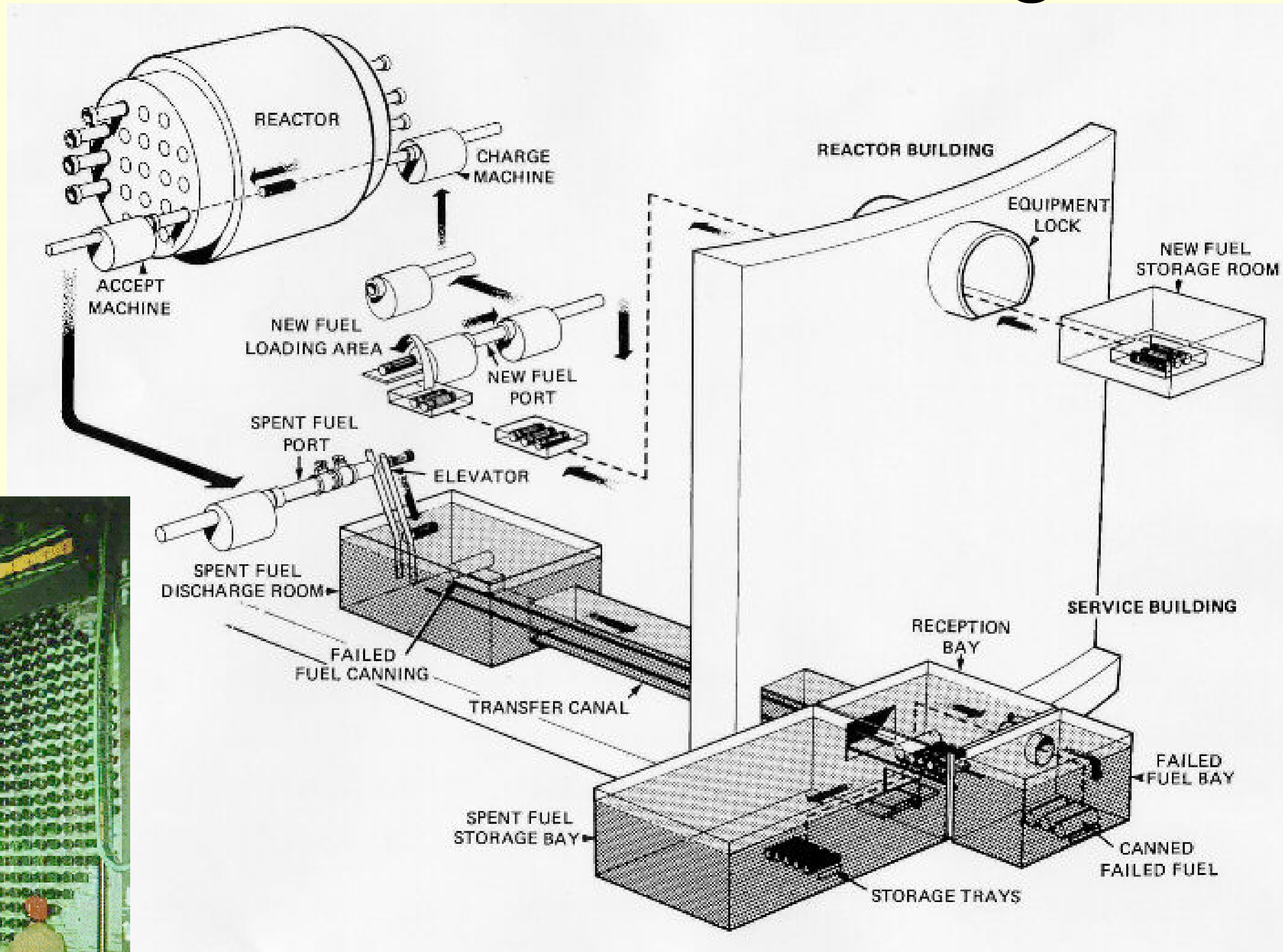
CANDU Reactor Face-2

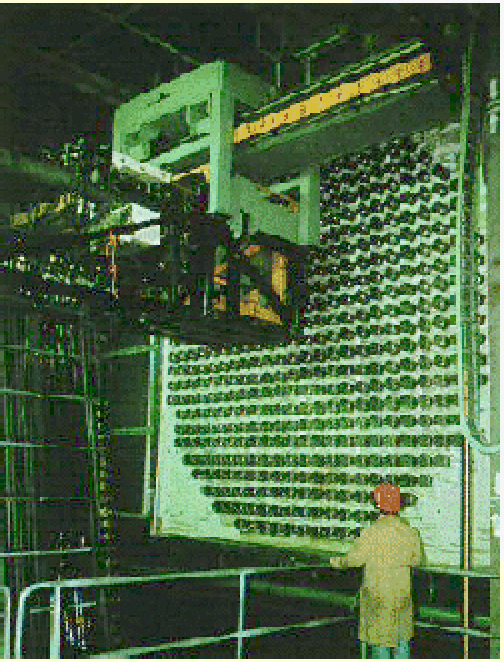


CANDU Control Systems

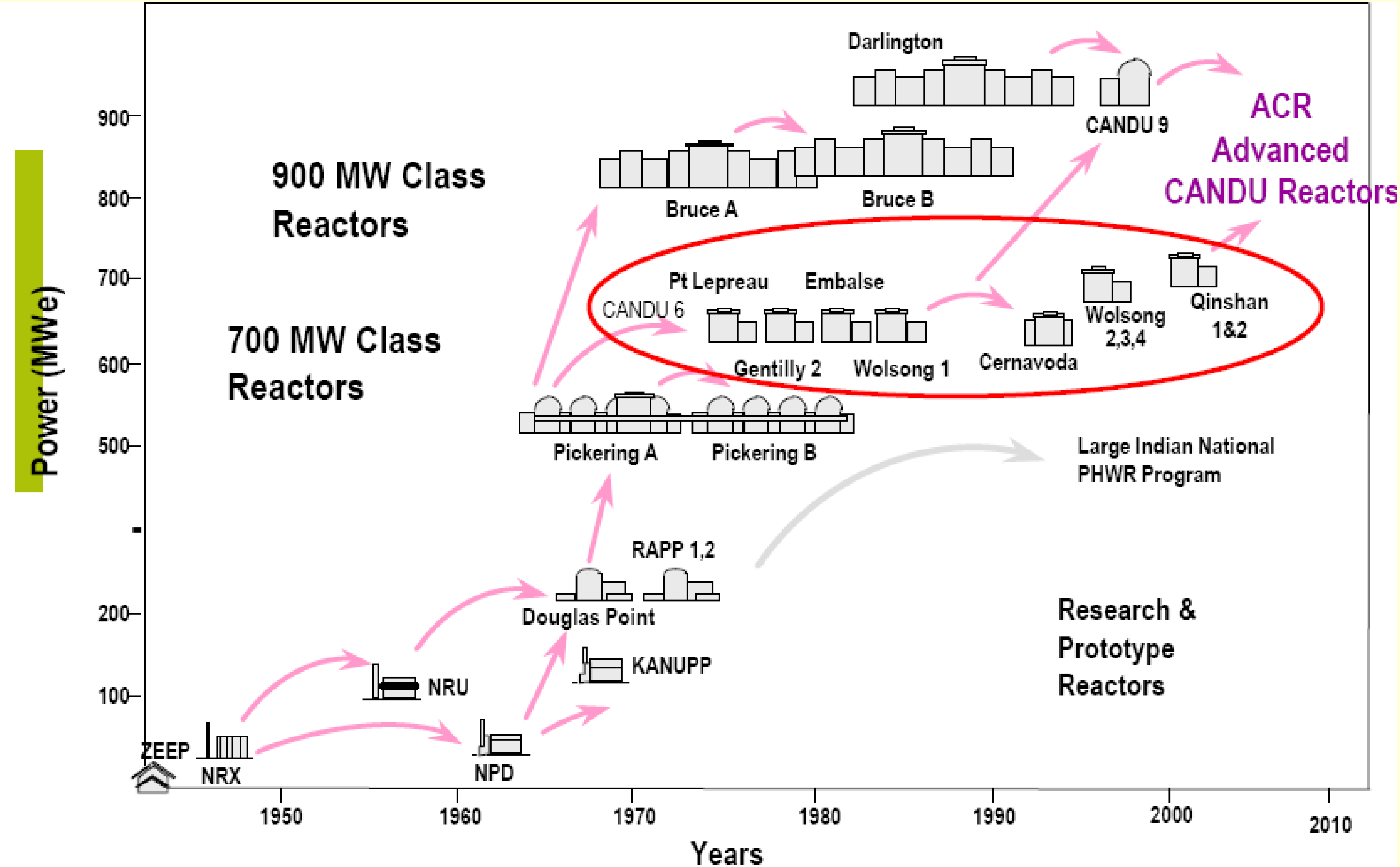


CANDU Online Refueling

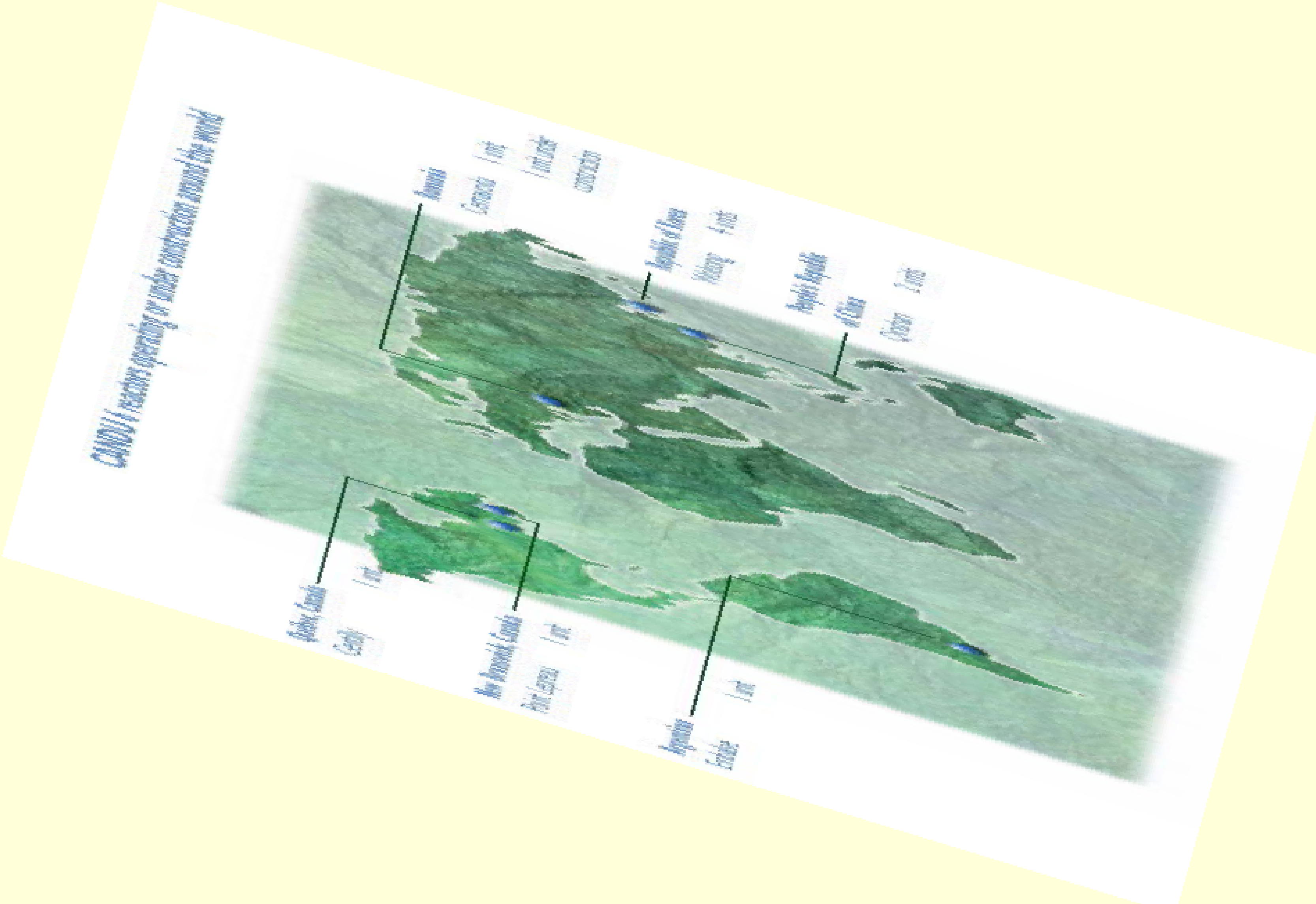




CANDU Evolution



CANDU Deployment



CANDU Observations

- Online refueling
  - May not be a huge advantage: still need to shut down for maintenance
    - Capacity factors no better than LWRs
- Heavy water
  - Copious producer of tritium

CANDU GEN III+

- Advanced CANDU Reactor: ACR-700, 1000
  - Improved fuel to allow significant reduction in size of core and calandria
  - Uses light water coolant; moderator still heavy water
  - Higher coolant water pressure to increase outlet temperature to 605 F and efficiency to 36.5%
  - Other improvements similar to LWRs

Heavy Water Basics

- Deuterium constituted 0.015% of natural water
- Need to enrich it to 99%+ to use in reactors
- Enrichment processes are based on the mass difference between H and D, either directly or through its impacts on chemical exchange rates
- Three processes follow, others have been studied

Heavy Water Production: Girdler

- Based on exchange between water and H_2S capitalizing on differing equilibrium constants at different temperatures
  - Widely used for initial enrichment
  - Uses tall columns to contact water and H_2S

Heavy Water Production: Electrolysis

- Based on exchange between water and hydrogen capitalizing on differing equilibrium constants at different temperatures
  - Used for initial enrichment
  - Only used if very low cost electricity is available, e.g., hydropower
  - Used by Germany in WW II

Heavy Water Production: Distillation

- Based on difference in boiling point of light and heavy water
- Widely used for final enrichment