Effect of 2011 Earthquake on Japanese Nuclear Reactors

March 23, 2011

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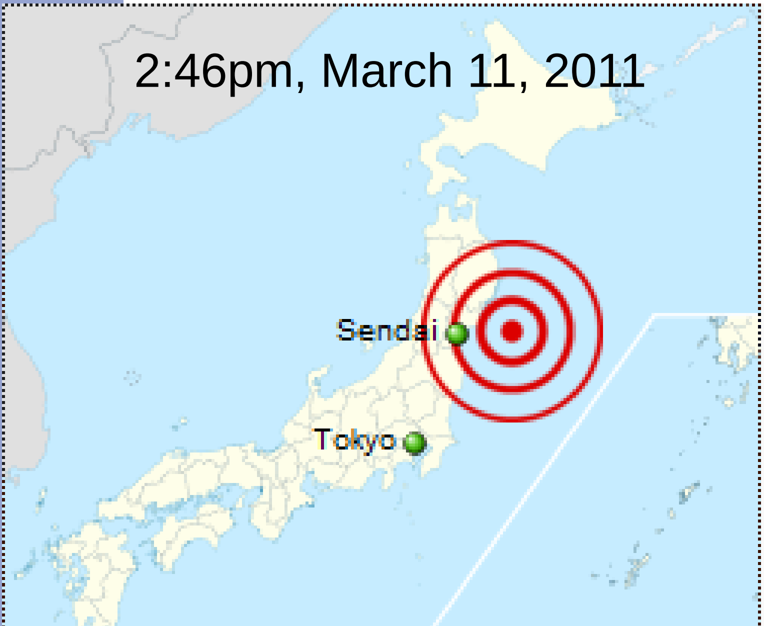
University of Pittsburgh

2011 Sendai Earthquake…



2011 Sendai earthquake and tsunami - Wikipedia, the free encyclopedia
http://en.wikipedia.org/wiki/2011_Sendai_earthquake_and_tsunami

- Magnitude 9.0
- 4th Largest Recorded Earthquake
- Energy release: 9.32 Ttons TNT

Associated Press

- Moved Japan 8 feet
- Shifted Earth 10 cm (on axis)

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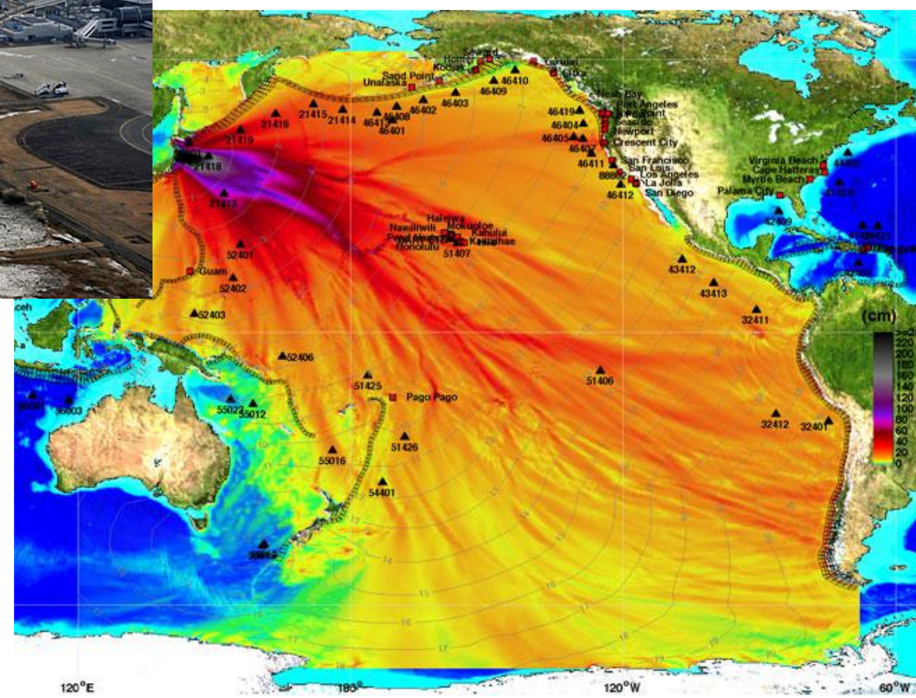
…and Tsunami

Kyodo/Associated Press

- Inundated 420 miles of eastern coast of Japan
- Arrived 10-60 minutes after earthquake



NOAA

- Observed heights: 11-24 feet
- Affected entire pacific ocean

Devastation

Yomiuri Shimbun/AFP/Getty Images

- 8,805 Dead
- 2,628 Injured
- 12,664+ Missing

- 300,000 Homeless
- 4.4M Powerless
- 1.5M Waterless

Yomiuri Shimbun/AFP/Getty Images

Devastation

Yomiuri Shimbun/AFP/Getty Images

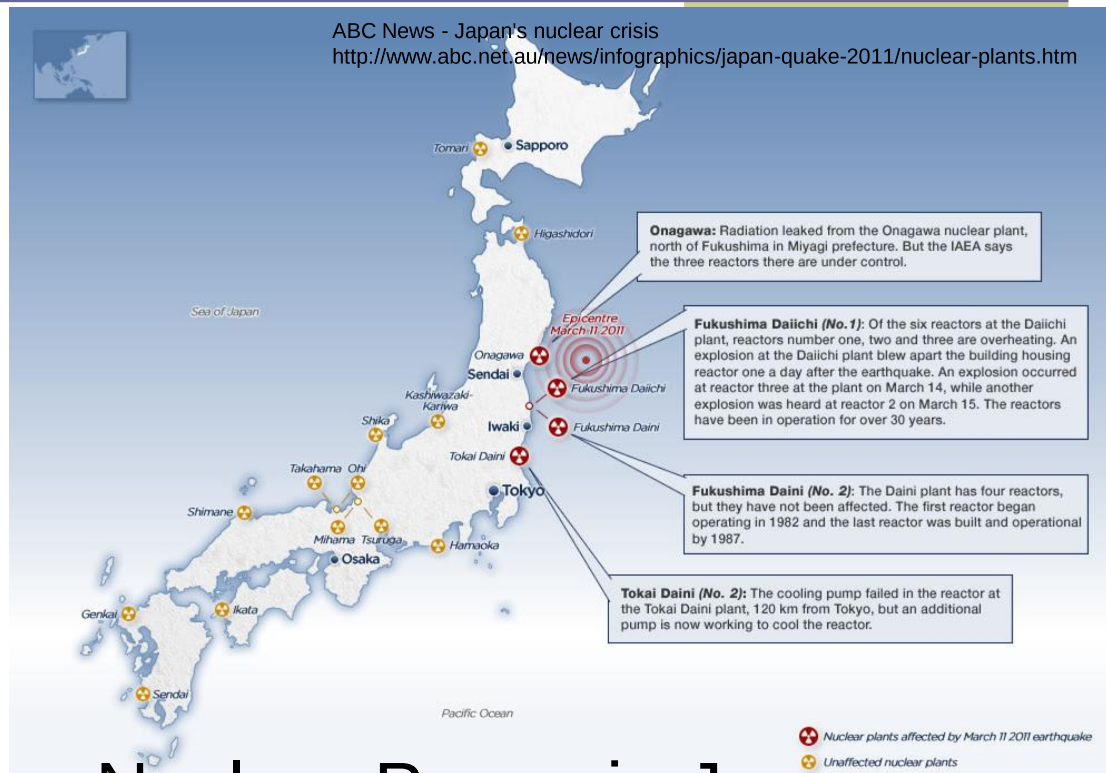
European PressPhoto Agency

- Fujinuma irrigation dam ruptured, destroying 1800 homes
- Several trains in Myagi / Iwate derailed and/or washed away
- Oil refineries in Ichihara and Sendai ablaze
- Entire towns leveled or washed into the ocean

Effects on Nuclear Power Plants

- Since the earthquake the majority of news has focused on damage to 4 nuclear power reactors near the quake epicenter

- We will consider what happened and why



Nuclear Power in Japan

- 55 Power Reactors (17 sites)
- Produces 22.5% of electricity
- 9.7% of total energy consumption

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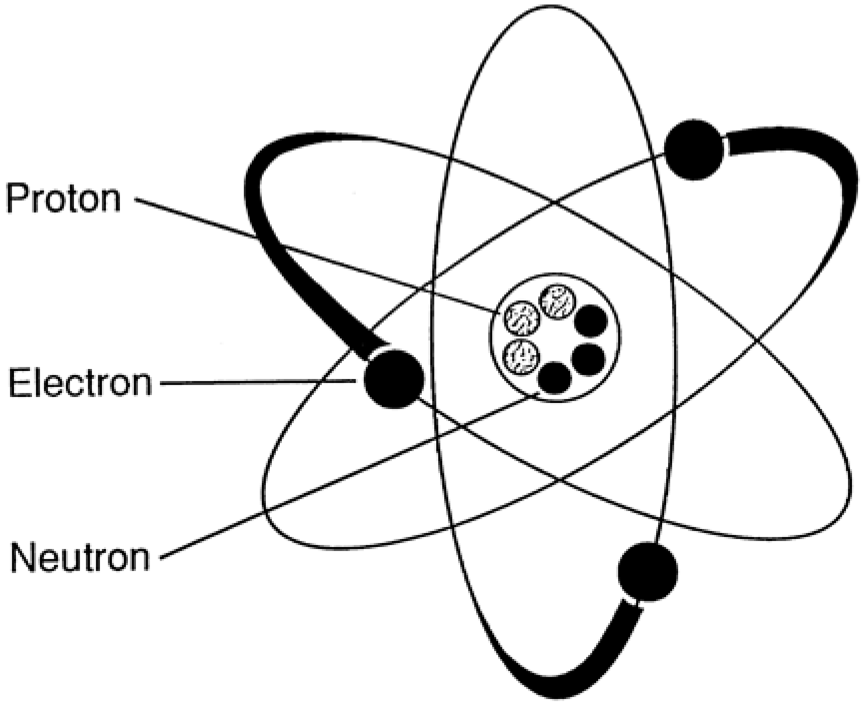
Presentation Objectives

- Before we discuss the ongoing accident at Fukushima Daiichi, it will be useful to understand some basic concepts and terminology about radiation and nuclear reactors.
  - Emphasis on Boiling Water Reactor (BWR) designs found at Fukushima Daiichi

Atomic Structure



- Electrons
  - Negatively charged particles orbiting nucleus
  - Forms chemical bonds with other atoms
- Protons
  - Positively charged particles in nucleus
  - Number of protons determines the element type
- Neutrons
  - Charge-less particles in nucleus
  - Stabilize the nucleus
  - Atoms of the same element may have different numbers of neutrons

Isotopes and Nuclides

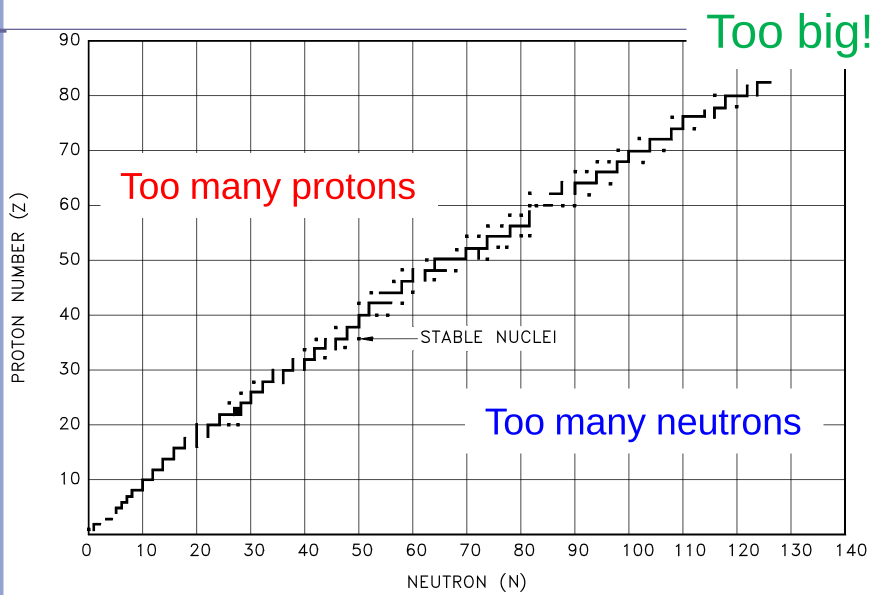
- **Nuclide** – A type of atom characterized by the number of protons and neutrons in the nucleus of every atom of this type.

  Examples: ${}^{1}_{1}H$, ${}^{4}_{2}He$, ${}^{235}_{92}U$

- **Isotopes** – Atoms with the same number of protons (same element) but containing different numbers of neutrons.
  - Nuclides with same atomic number but different atomic masses.

  Examples: ${}^{234}_{92}U$, ${}^{235}_{92}U$, ${}^{236}_{92}U$, ${}^{238}_{92}U$

Radioactive Decay



- Radiation
  - Energy released from an unstable nucleus
    - Subatomic particles
    - Photons

- Not all combinations of neutrons and protons are energetically favorable
  - Nuclei with an unfavorable combination of neutrons and protons will attempt to reach a lower energy state
  - Accomplished by radiating energy out of the nucleus
  - Released energy referred to as **radiation**
  - Changes to nucleus release much more energy than comparable chemical reactions

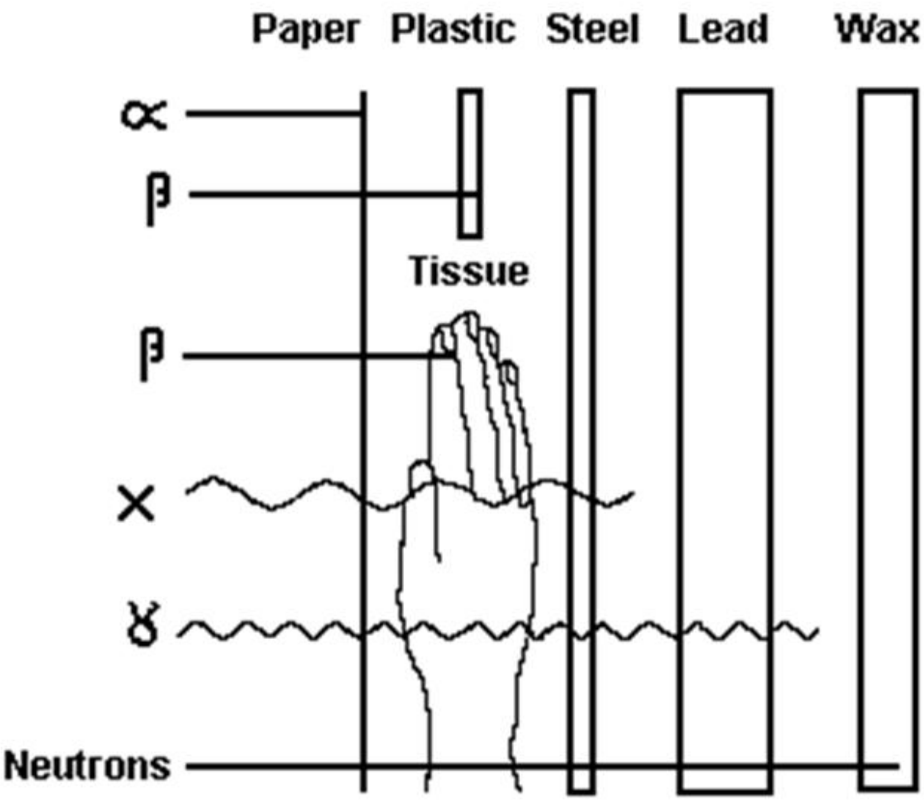
Radioactive Decay

- Any atomic process that releases energy is referred to as **radioactive decay**
  - Energy emitted from the atom is called **radiation**.
  - Unstable nuclides subject to radioactive decay are referred to as **radionuclides** or **radioisotopes**.

- All radionuclides will eventually undergo radioactive decay.
  - Time until decay for any atom is random
  - Rate of decay given by **half-life**
- Any material containing measurable quantities of one or more radionuclides is referred to as **radioactive**.
  - Unintended presence of radioactive material is called **contamination**

Radiation

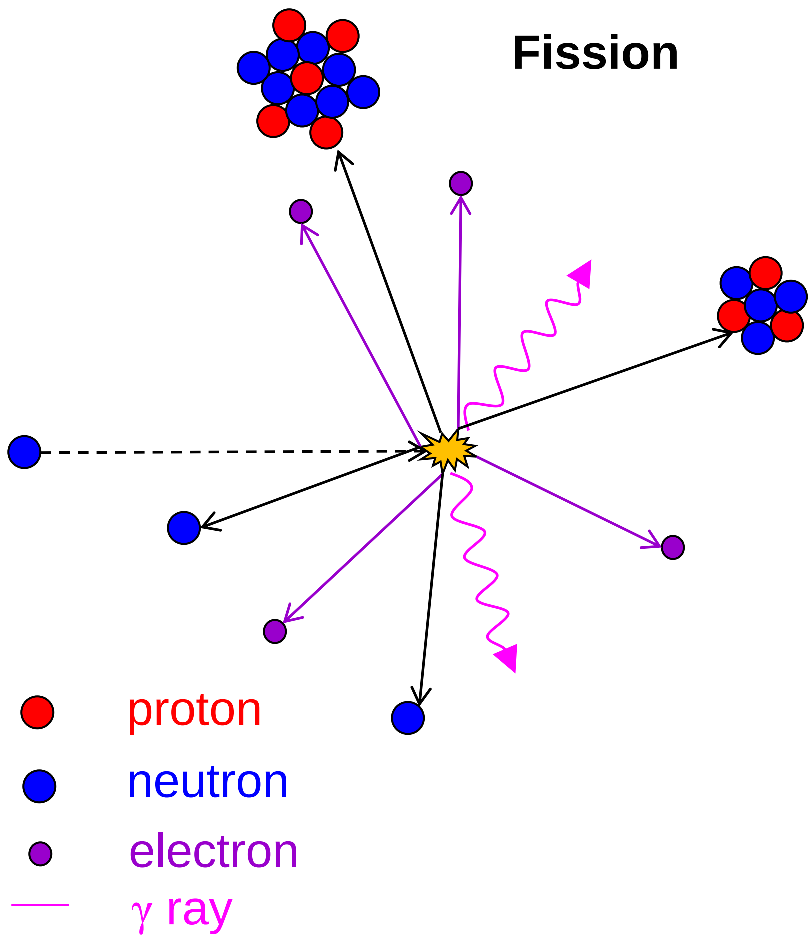
- Several different types of radiation
  - Each has different interaction properties
  - Energy deposition in tissue poses health risks
- External Exposure
  - Radiation enters body and is absorbed by living tissue
- Internal Exposure
  - Radionuclide is ingested or inhaled and retained in tissue
  - Upon decay, radiation is released directly into surrounding tissue



Reproduced from Knief, 1992, *Nuclear Engineering*

- Shielding used to limit external exposure
  - Effective shielding materials depend on type of radiation

Nuclear Fission



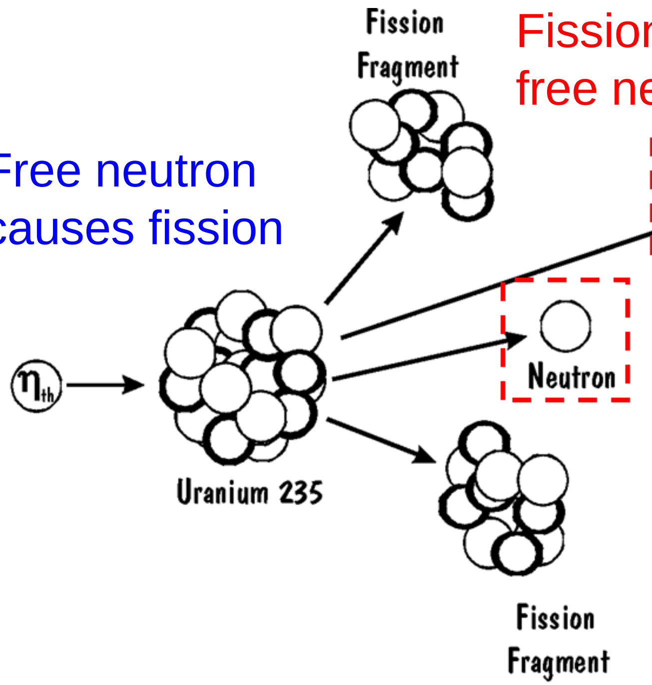
- Some large nuclides are quasi-stable
  - Uranium, Plutonium
  - Addition of 1 extra neutron will cause them to **fission** (split in half)
- During fission an unstable nucleus is split in half
  - 2 new nuclei (referred to as **fission products**)
  - Extra neutrons
  - Gamma rays
- Extremely energetic reaction
  - 200 MeV/fission

Fission Chain Reaction

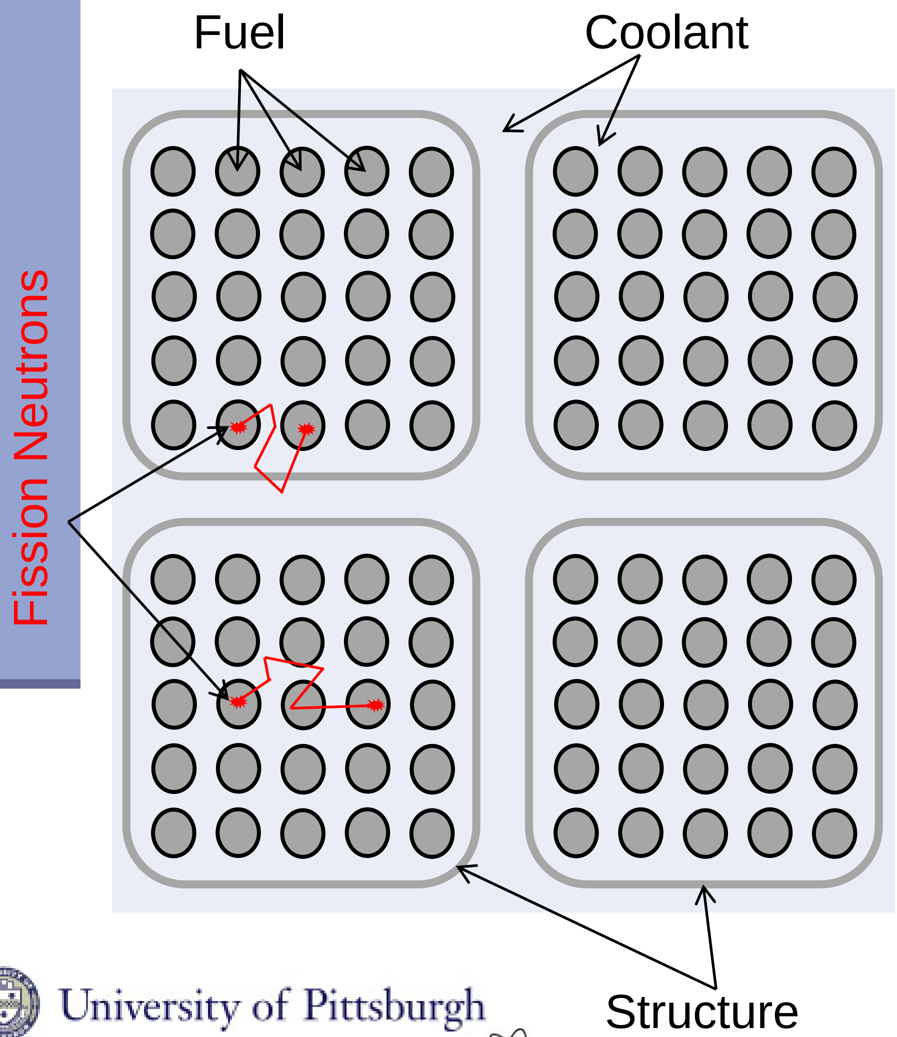
- Free neutrons are key to nuclear fission
  - Caused by neutrons
  - Produces neutrons
- Possible to create a self-sustaining chain reaction
  - Fission neutrons cause additional fission events
  - Basis of fission power reactors

Free neutron causes fission

Fission releases free neutrons

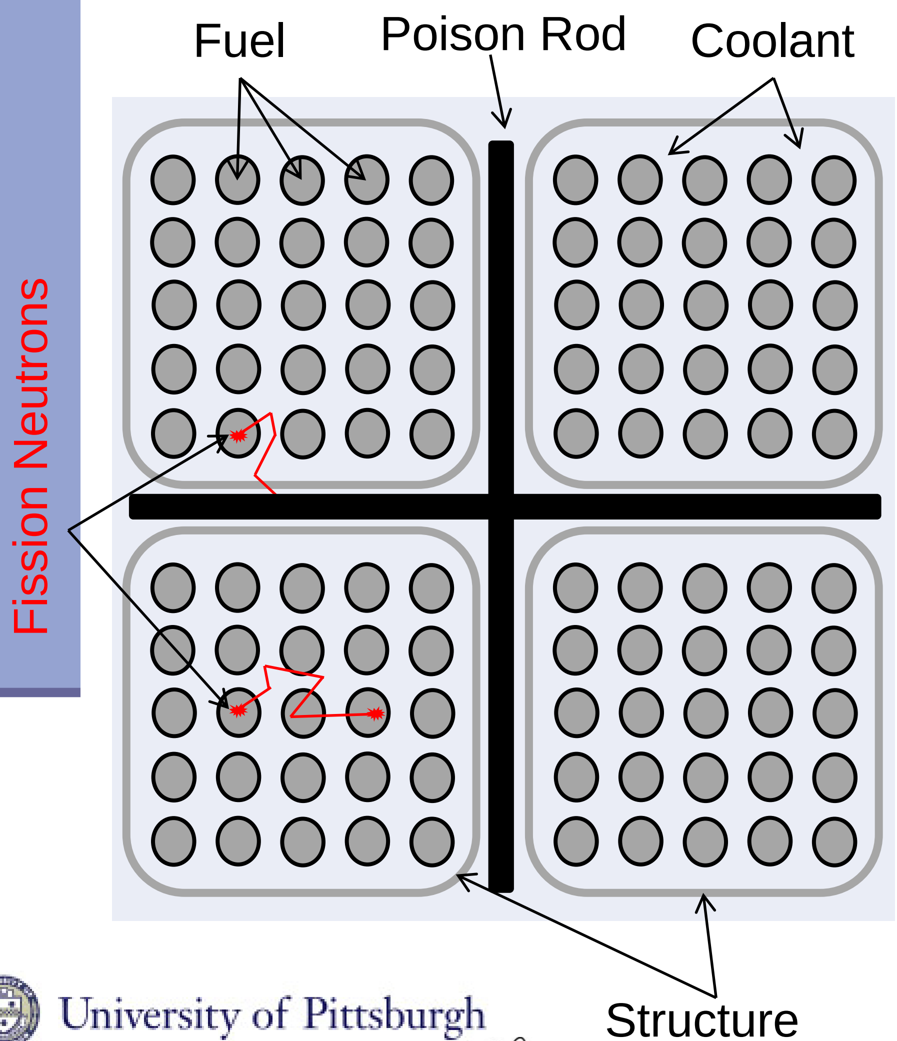


Basic Reactor Design



- Choose materials and arrangement for chain reaction
  - Fuel
  - Coolant/Moderator
  - Structure
- Basic Process
  - Fission neutrons born in fuel rods cause fissions in adjacent fuel
  - Coolant flowing past fuel rods removes heat produced by fission

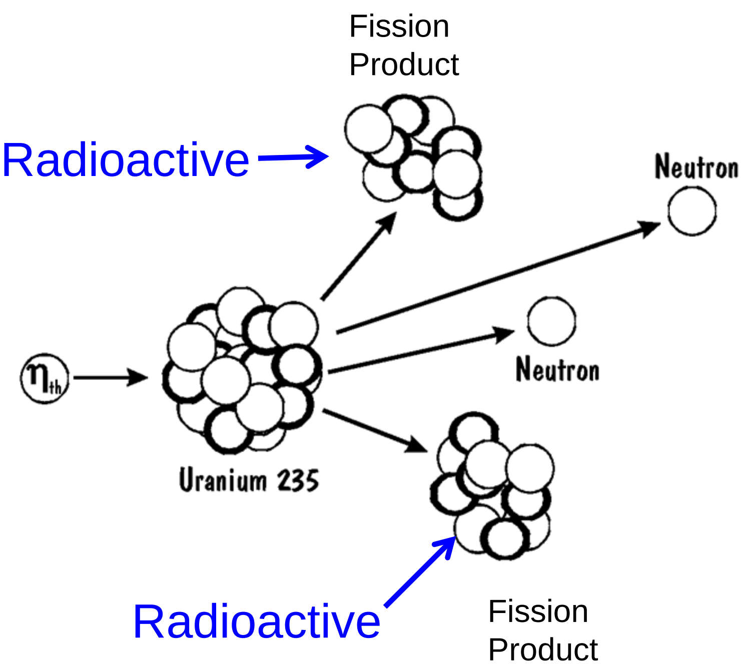
Basic Reactor Design



- Control of chain reaction by movable control rods
  - Neutron poison
  - Absorbs neutrons and stops chain reaction
- Western reactor designs also employ negative feedback effects
  - Temperature increase or loss of moderator stop chain reaction

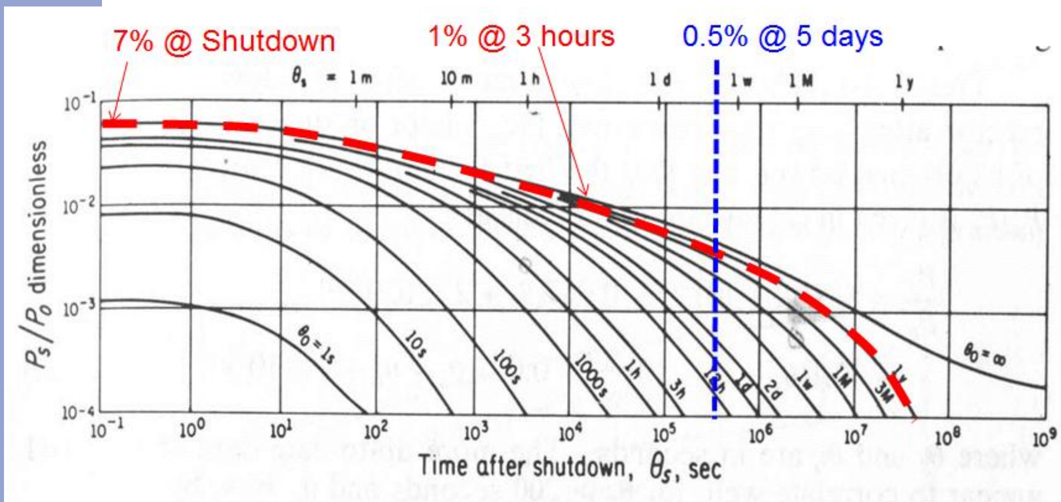
Basic Reactor Design

- Fission reactors have a "tight" neutron economy
  - Design must carefully balance neutron production and absorption for a chain reaction
  - Easy to stop chain reaction with neutron poisons…
  - Inefficient fuel arrangements will not allow a chain reaction…



- What's the problem?
  - Many fission products created in fission are radioactive nuclides
  - After chain reaction stops these nuclides will continue to decay and release energy, which is referred to as **decay heat**.

Decay Heat



- For a 1000 MWt reactor decay heat is:
  - 70 MW immediately after shutdown
  - 10 MW after 3 hours
  - 5 MW after 5 days
  - 1 MW after 2 months
  - 100 kW after 1 year

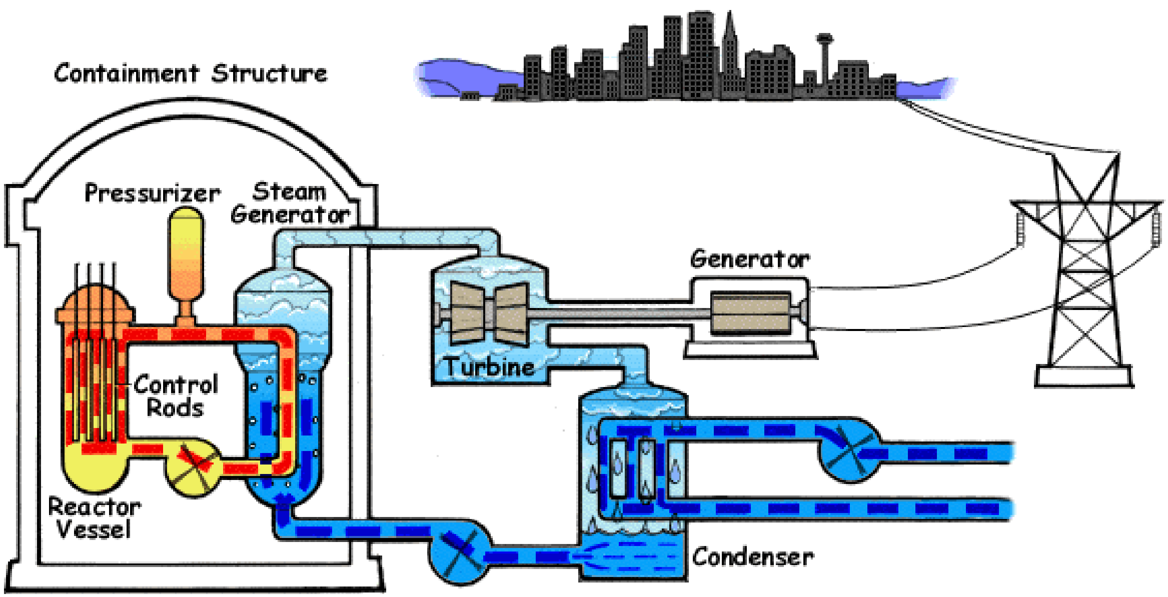
- During operation decay heat accounts for ~10% of reactor power
- After shutdown decay heat decreases as fission products decay away
  - Within hours decay heat is down to 1% of operating power
  - Still a significant source of heat for power reactors
  - Without cooling decay heat can cause fuel to melt

Modern Reactor Designs

- Nuclear reactors are classified by the type of coolant that they use
- Many categories of reactors have been designed and built over the last 60 years
  - Light water reactors (US, Japan)
  - Heavy water reactors (Canada)
  - Gas cooled reactors (UK, Japan, Europe)
  - Liquid metal/liquid salt reactors (US, France)
- Commercial power reactors in the US and Japan are light water reactors
  - Rely on steam cycle and H_2O for coolant
  - Two basic types of light water reactors

Pressurized Water Reactor

- Pressurized Water Reactor [PWR]

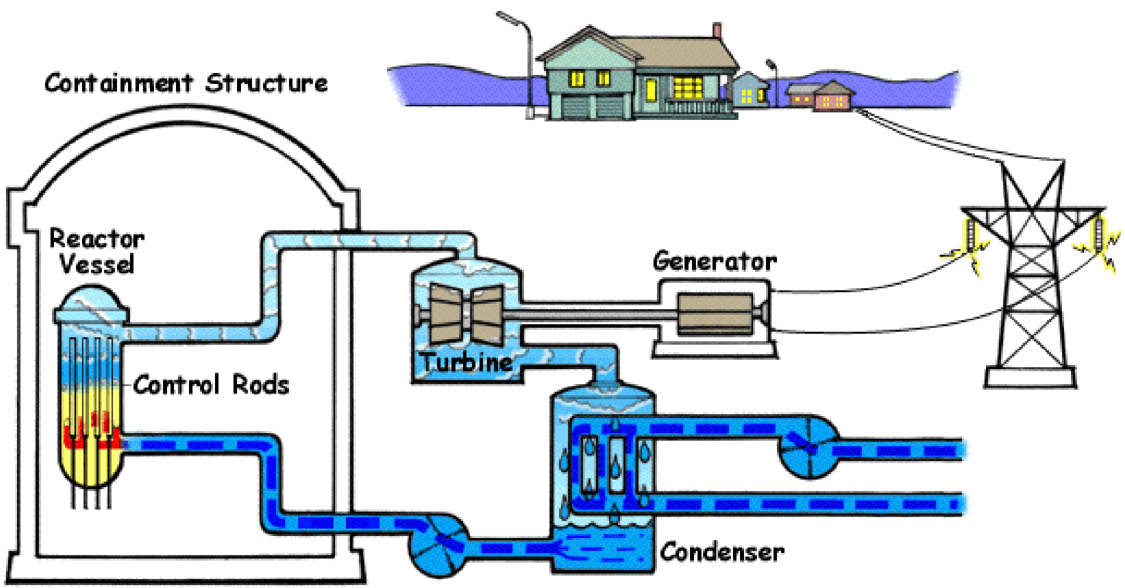


Animated Diagram of a Pressurized Water Reactor.
From the NRC Website. Public Domain.
Wikipedia: "Pressurized Water Reactor", 1-6-2008

- Water pumped though reactor is pressurized and does not boil
- Intermediate heat exchanger creates steam for generating electricity
- Operating plants
  - US: 69 plants (68 GW electric)
  - Japan: 24 plants (19 GW electric)

Boiling Water Reactor

- Boiling Water Reactor [BWR]



Animated Diagram of a Boiling Water Reactor.
From the NRC Website. Public Domain.
Wikipedia: "Boiling Water Reactor", 1-6-2008

- Water pumped though reactor is allowed to boil and steam passes directly through turbine, generating electricity
- Operating plants:
  - US: 35 plants
    (35 GW electric)
  - Japan: 30 plants
    (28 GW electric)
    - 6 units at Fukushima Daiichi
    - 4 units at Fukushima Daini
    - 3 units at Onagawa

Fukushima Daiichi

Yomiuri/Reuters

- Ohkuma, Fukushima
- Tokyo Elec. Power Co.
- 6 BWR Reactors
  - 4546 MWe Capacity
  - Built 1970-1979

Fukushima I Nuclear Power Plant - Wikipedia, the free encyclopedia
http://en.wikipedia.org/wiki/Fukushima_I_Nuclear_Power_Plant

Unit	Type[12]	First criticality	Electric power	Reactor supplier
Fukushima I – 1	BWR-3	October 1970[11]	460 MW	General Electric
Fukushima I – 2	BWR-4	July 18, 1974	784 MW	General Electric
Fukushima I – 3	BWR-4	March 27, 1976	784 MW	Toshiba
Fukushima I – 4	BWR-4	October 12, 1978	784 MW	Hitachi
Fukushima I – 5	BWR-4	April 18, 1978	784 MW	Toshiba
Fukushima I – 6	BWR-5	October 24, 1979	1,100 MW	General Electric
Fukushima I – 7 (planned)	ABWR	October 2016[13]	1,380 MW	
Fukushima I – 8 (planned)	ABWR	October 2017[13]	1,380 MW	

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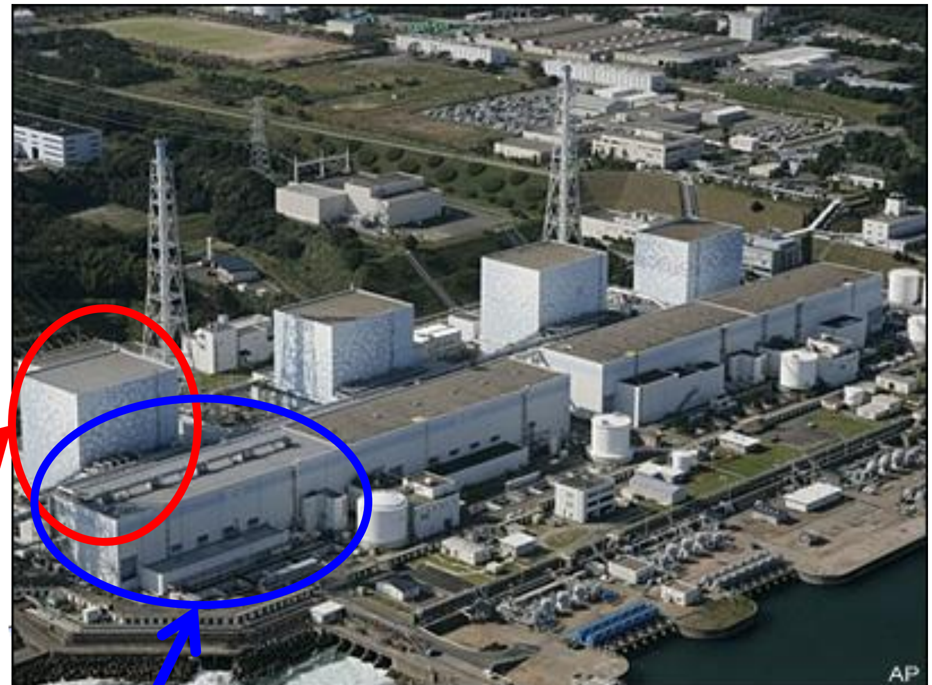
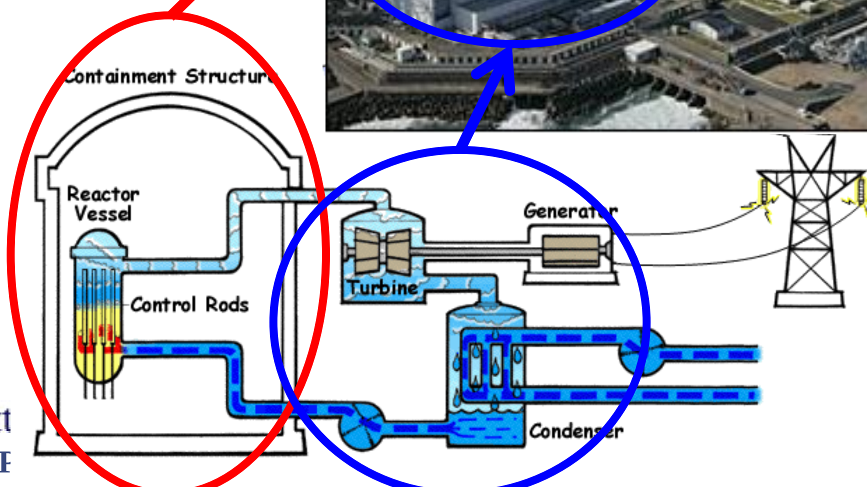
Fukushima Daiichi



Reactor Building

- Containment
- Reactor
- Safety systems



Auxiliary Building

- Turbine/Condenser
- Generator
- Safety systems

Reactor Safety

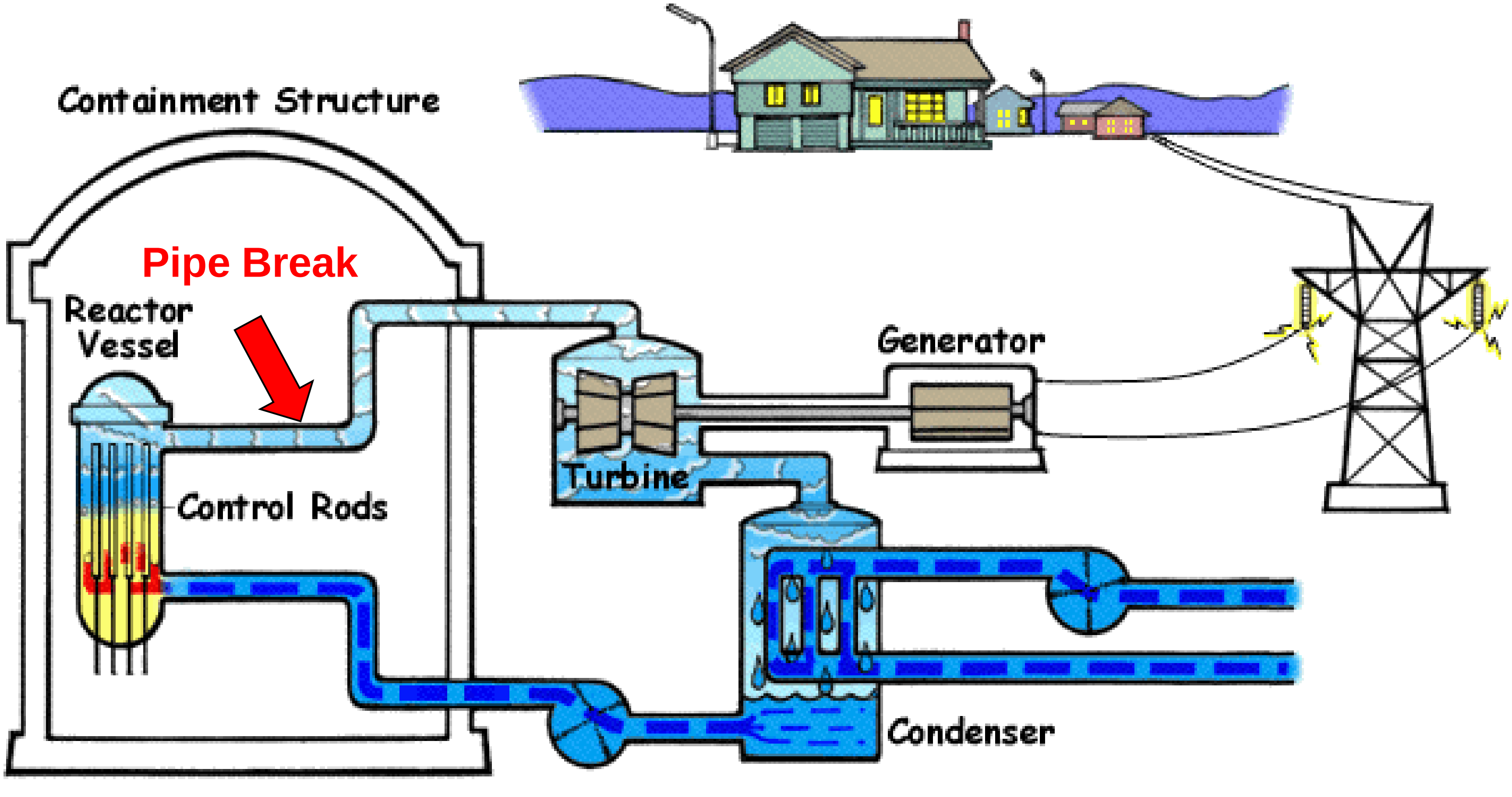
- During reactor design a tremendous amount of effort is spent on safety analysis
  - Understanding how plant will behave in off-normal situations
  - Designing active and passive safety systems to ensure plant can respond to abnormal conditions
- Before construction every plant design must be approved by regulatory agency
  - Builder must prove (via analysis) that plant can withstand a set of site-specific **design-basis accidents** set defined or approved by the regulator.

Design Basis Accidents

- Design basis accidents (DBAs) are a set of specific accident scenarios postulated by the regulatory agency.
  - Intended to represent the most severe credible accident that the plant could encounter.
  - DBAs are events for which the safety systems are designed to remain functional both during and after the event, thus assuring the ability to shut down and maintain a safe configuration.
    - The design basis earthquake for Fukushima was 8.0
    - The design basis tsunami for Fukushima was 5.7 meters (19')
    - Other DBAs include specific failures of systems (pumps, pipe breaks, etc.) in the plant, as well as combinations of failures.

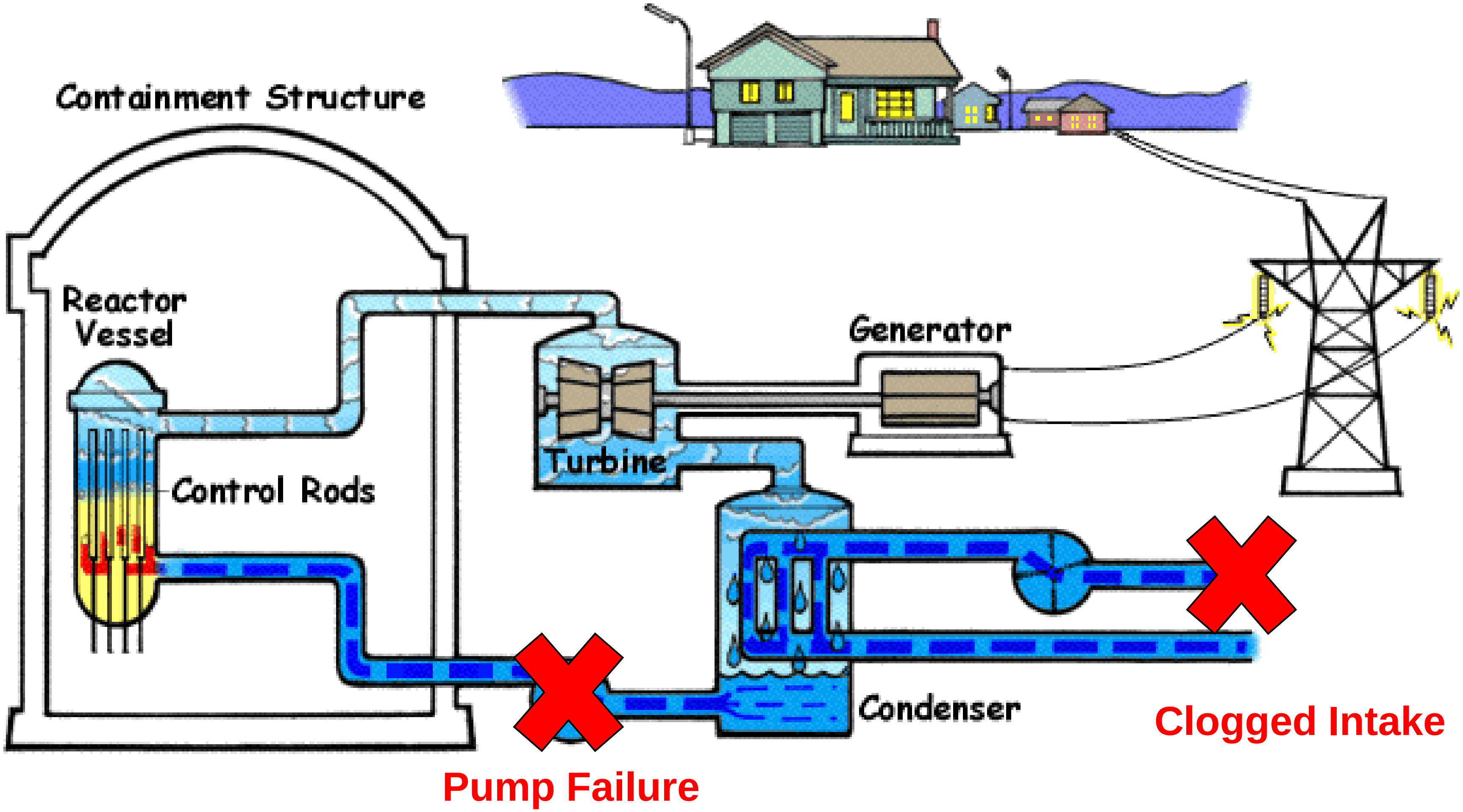
Design-Basis Accidents

- Loss of Cooling [LOCA]



Design-Basis Accidents

- Loss of Flow (Cooling Capacity) [LOFA]



Reactor Safety Systems

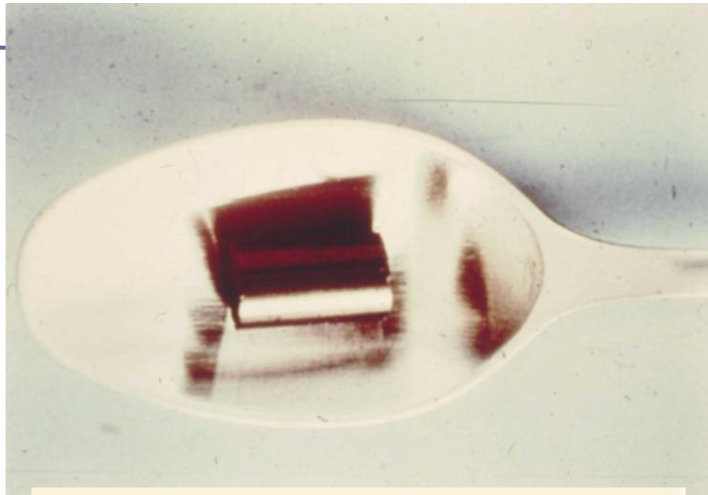
- In order to satisfy DBA requirements, reactors are designed with a wide variety of active and passive safety features to:
  - Ensure that the chain reaction can be stopped in all credible scenarios
  - Prevent fuel from melting in all credible scenarios
- Reactor designs also employ a **Defense-in-Depth** philosophy to prevent (or minimize) the release of radioactive material in severe accidents
  - Defense-in-Depth is inherent in the reactor design itself
    - Choice of materials
    - Plant designed with physical “layers” of defense
    - Layout of plant itself

Defense-in-Depth Design I

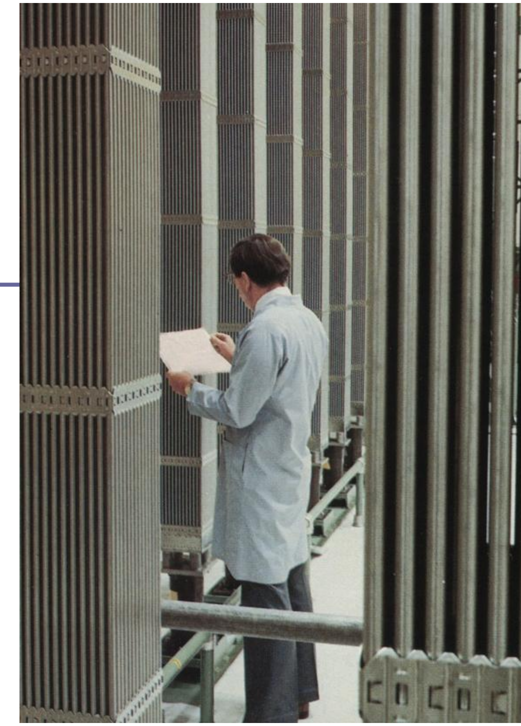
- The first defense layer begins with the uranium fuel rods, which contain
  - Ceramic UO_2 pellets…
    - High melting temperature
    - Will not easily dissolve or disintegrate into a fine powder
    - Trap non-gaseous fission products
  - …sealed in a Zirconium alloy cladding
    - Corrosion resistant
    - Air-tight
    - Captures any gaseous fission products escaping fuel rods

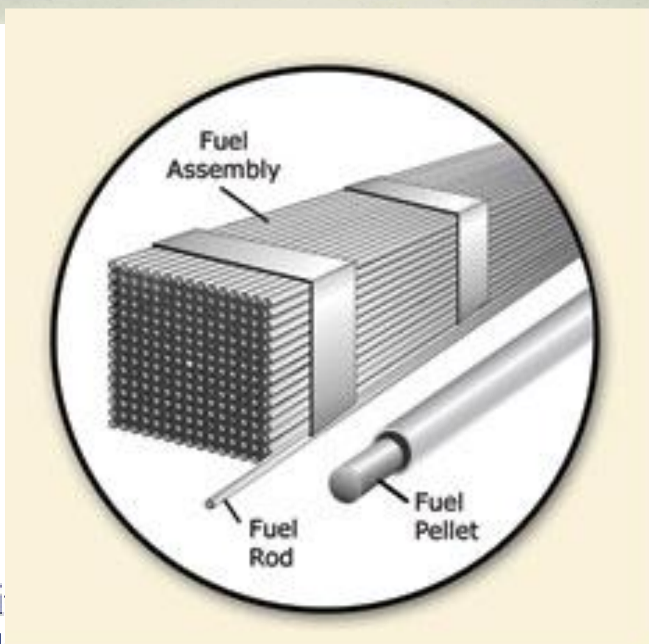
Reactor Fuel

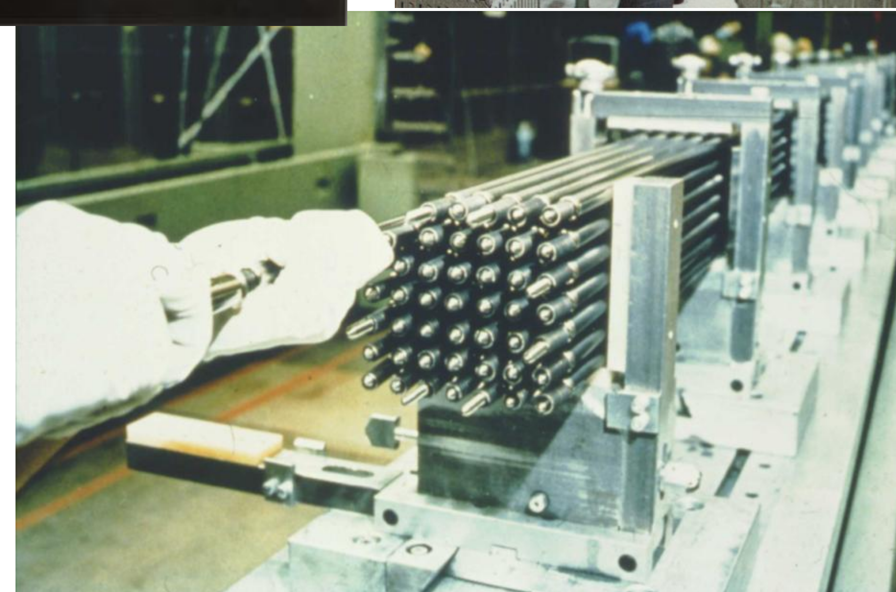
UO_2 Pellet



PWR Fuel Assembly



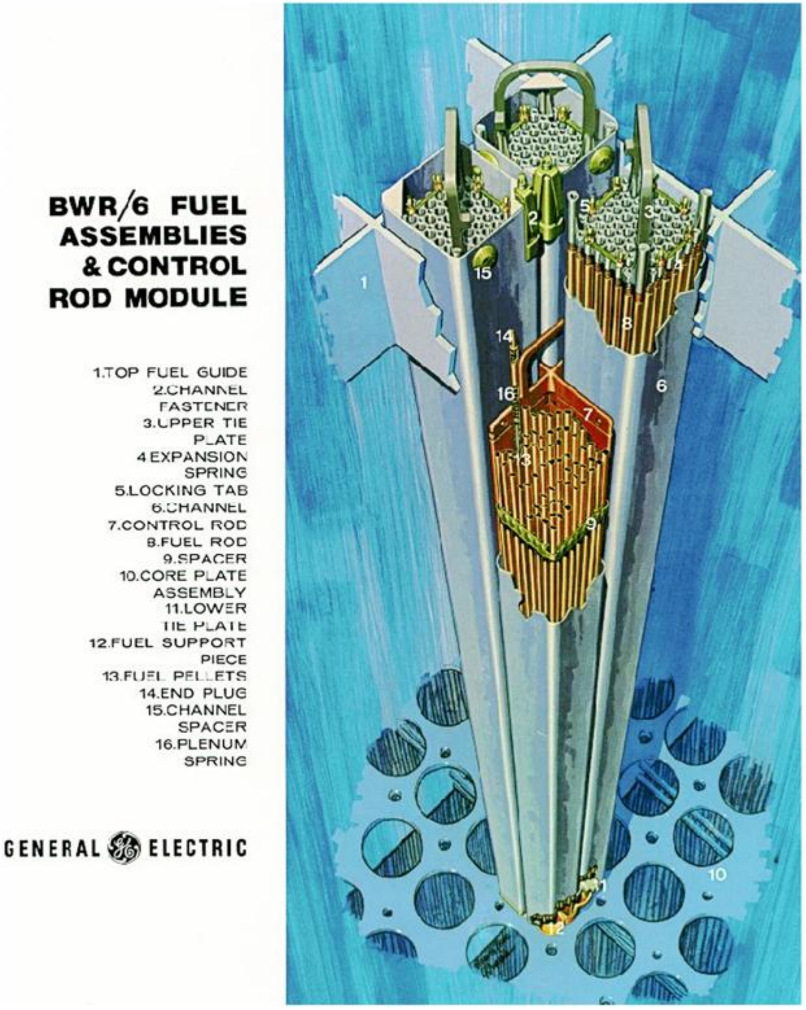




BWR Fuel Bundle

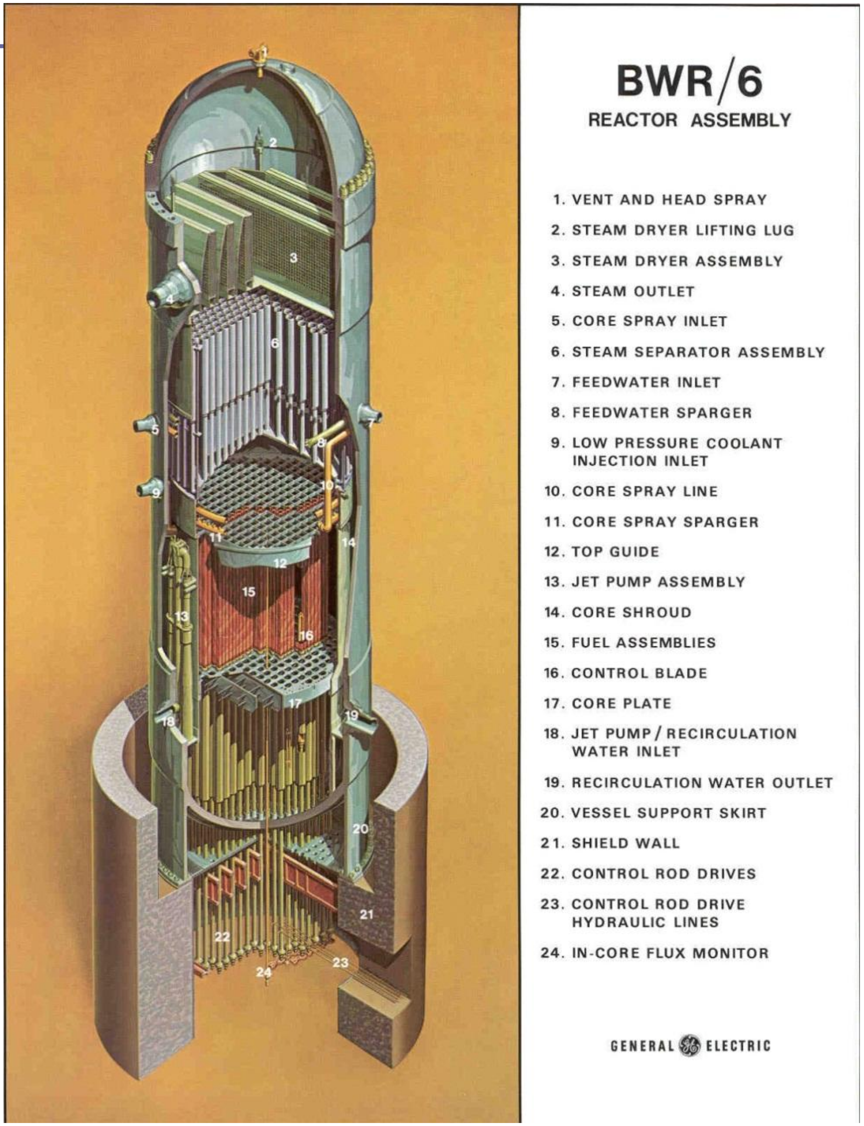
Defense-in-Depth Design II

- Fuel rods are bundled into assemblies for easy transport
  - 64 rods per bundle
  - Assemblies are surrounded by Zirconium alloy sleeves
  - Control rods are positioned between each set of 4 bundles.

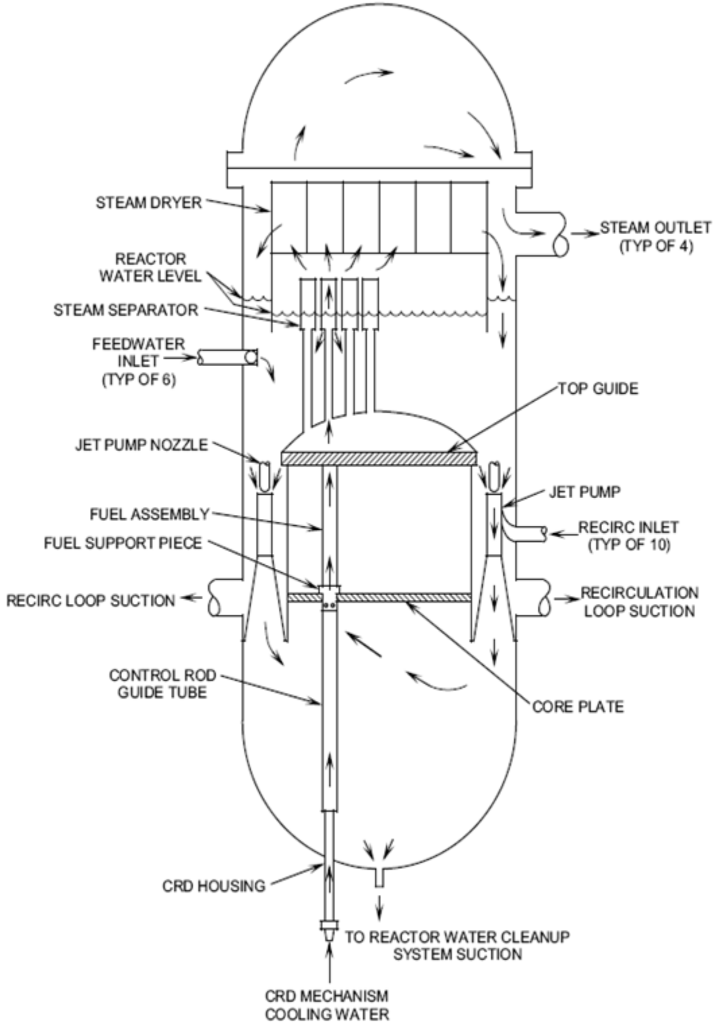


Defense-in-Depth III

- Fuel assemblies are loaded into cylindrical pressure vessel
  - Stainless steel clad
  - Contains 732 fuel assemblies
  - Water is pumped upward through fuel to remove heat
  - Sealed vessel contains debris in accident scenario
  - Designed to withstand high pressures in case of reactor overheating



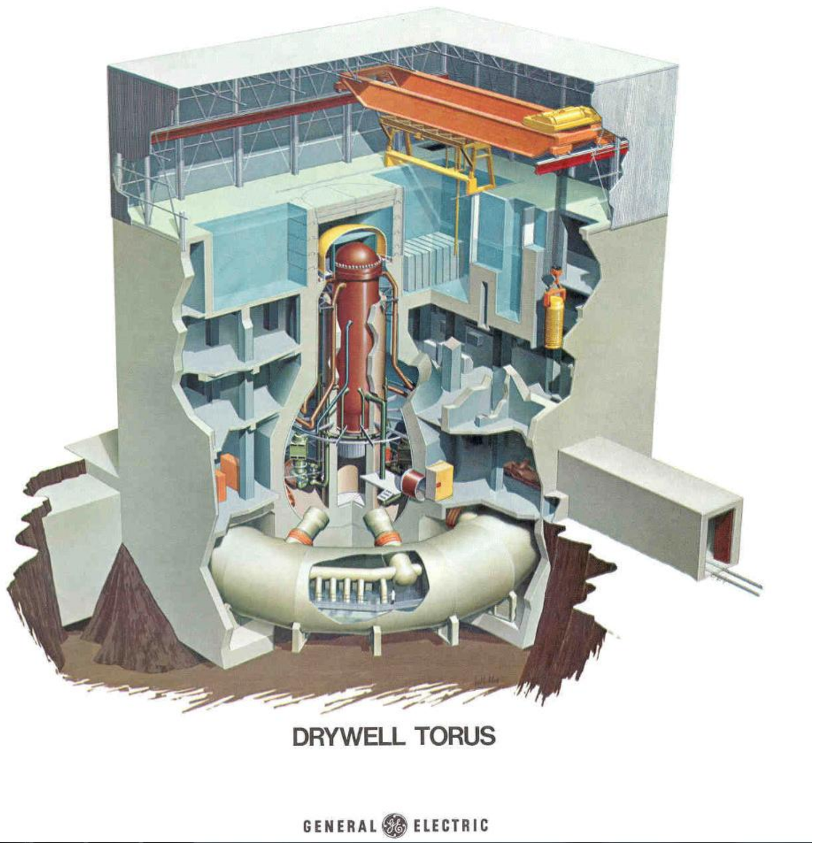
Defense-in-Depth IV



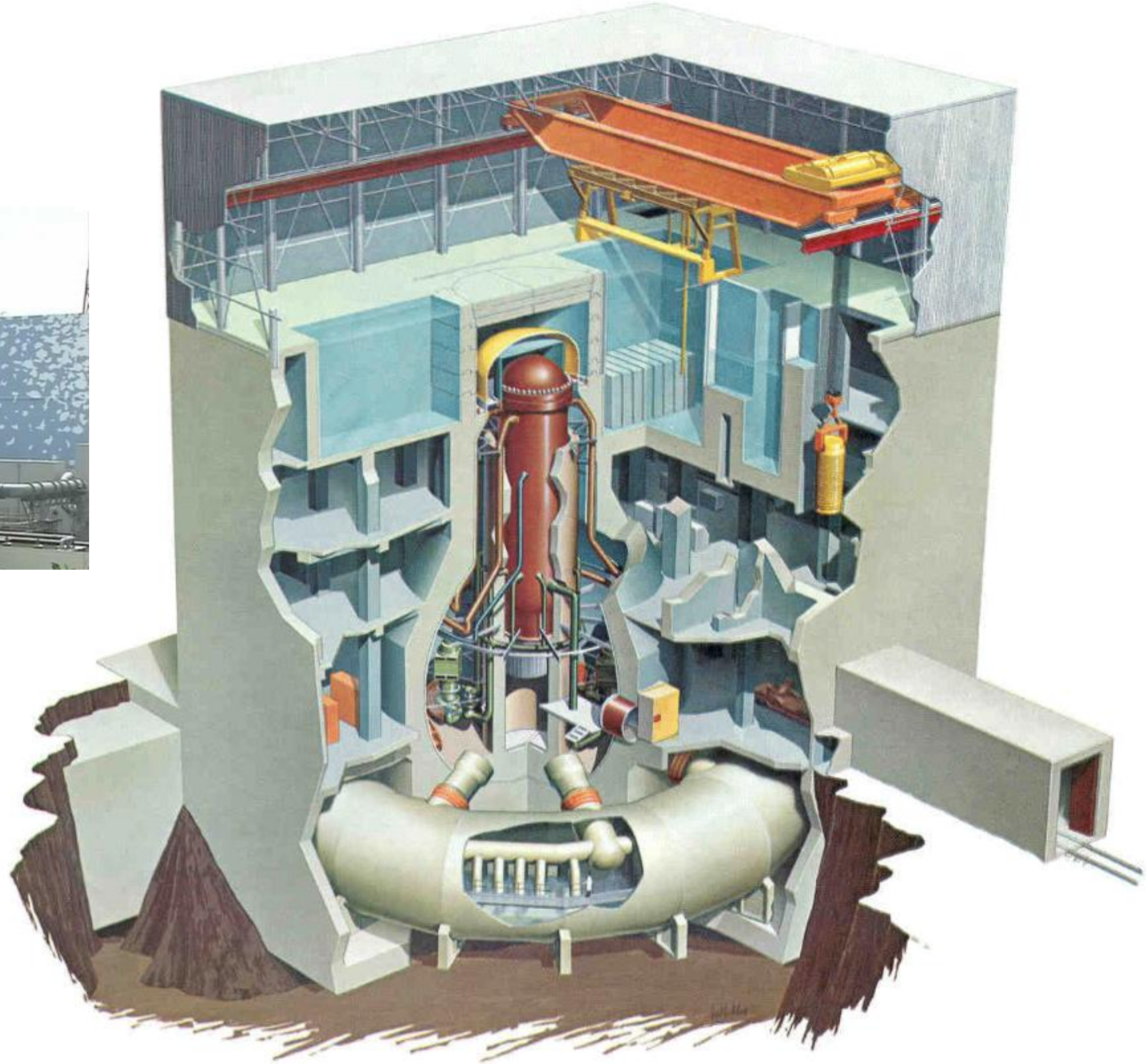
- Design Features (Passive)
  - Water level far above top of fuel
  - Coolant flows upward through fuel
    - These features promote natural circulation of coolant through system
  - Core vessel penetrations located above fuel in core
    - Prevent water from leaving core in accident

Defense-in-Depth V

- Containment
  - Core vessel is enclosed in a larger containment vessel
  - Sealed steel container shaped like an inverted light-bulb (drywell).
  - Prevents escape of material leaking out of reactor core or connected piping
  - Includes suppression pool filled with water (wetwell)
    - Excess steam in reactor core can be condensed by venting through pool to reduce pressure.



Fukushima Dai-Ichi 3

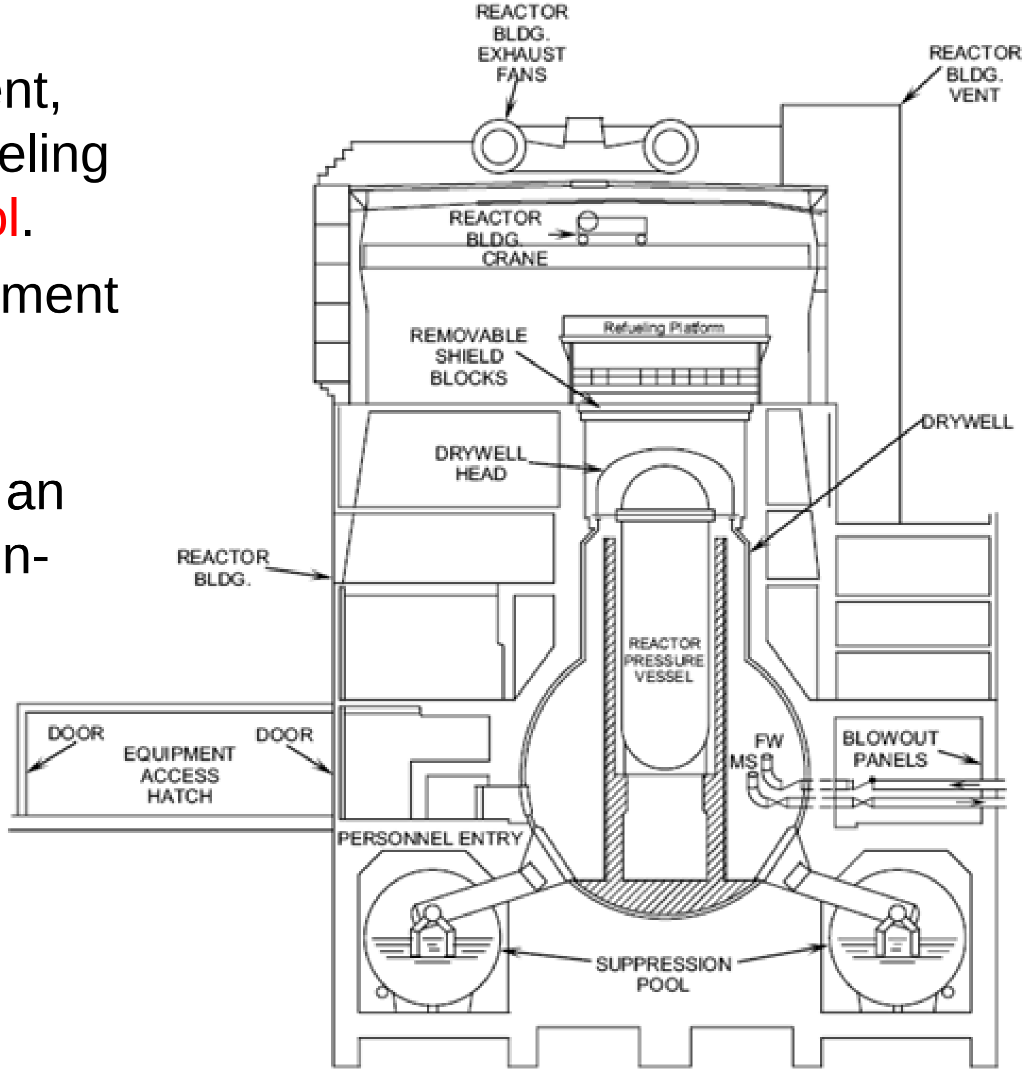


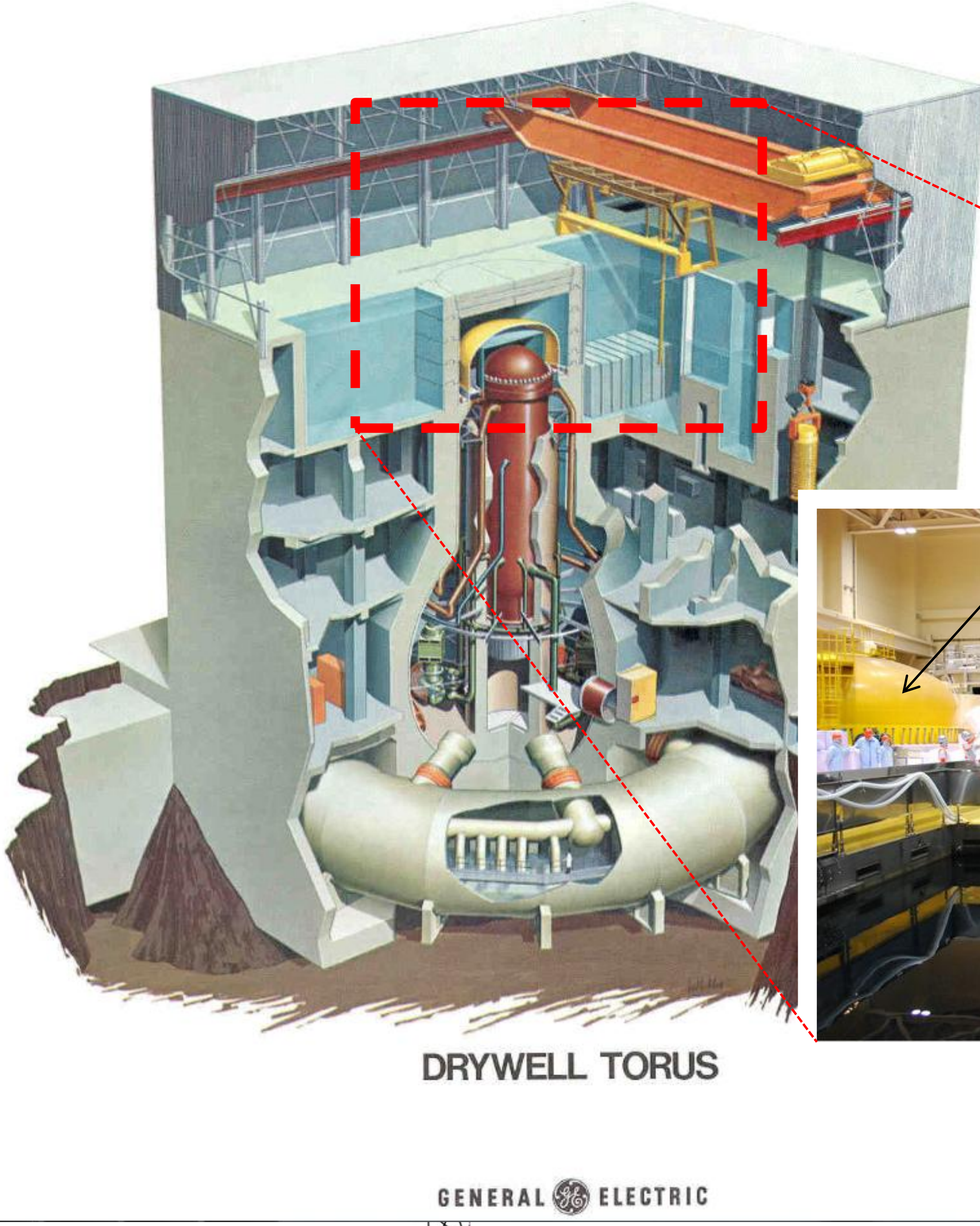
DRYWELL TORUS

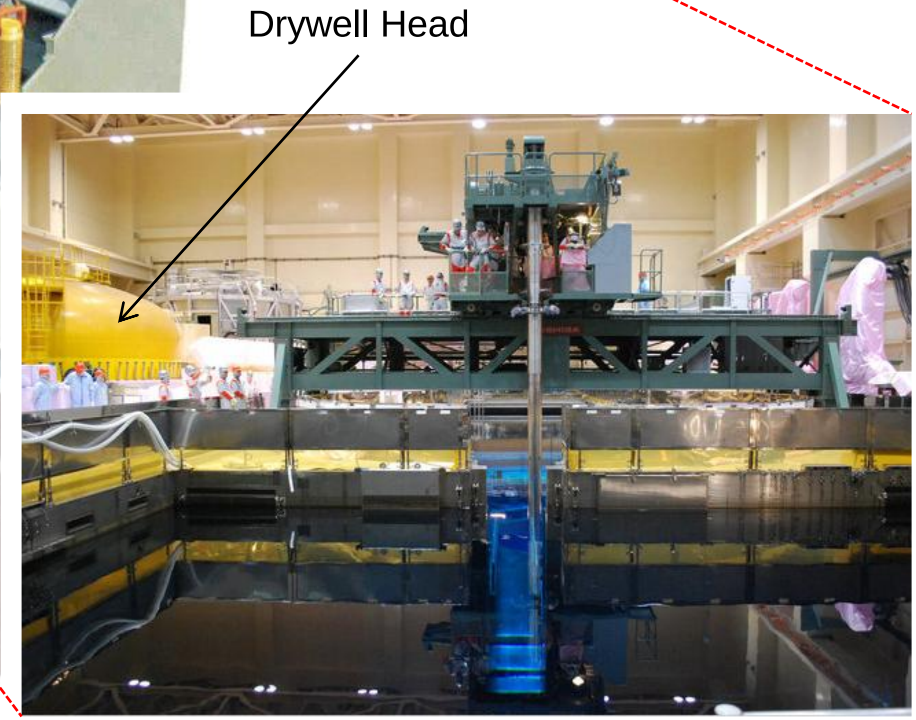
GENERAL ELECTRIC

Defense-in-Depth V

- Reactor Building
  - Surrounding containment, intended to shelter refueling floor and spent fuel pool.
  - Contains support equipment
    - Including air handling equipment and filters
  - Not usually considered an official part of defense-in-depth







Jiji Press/Agence France-Presse – Getty Images

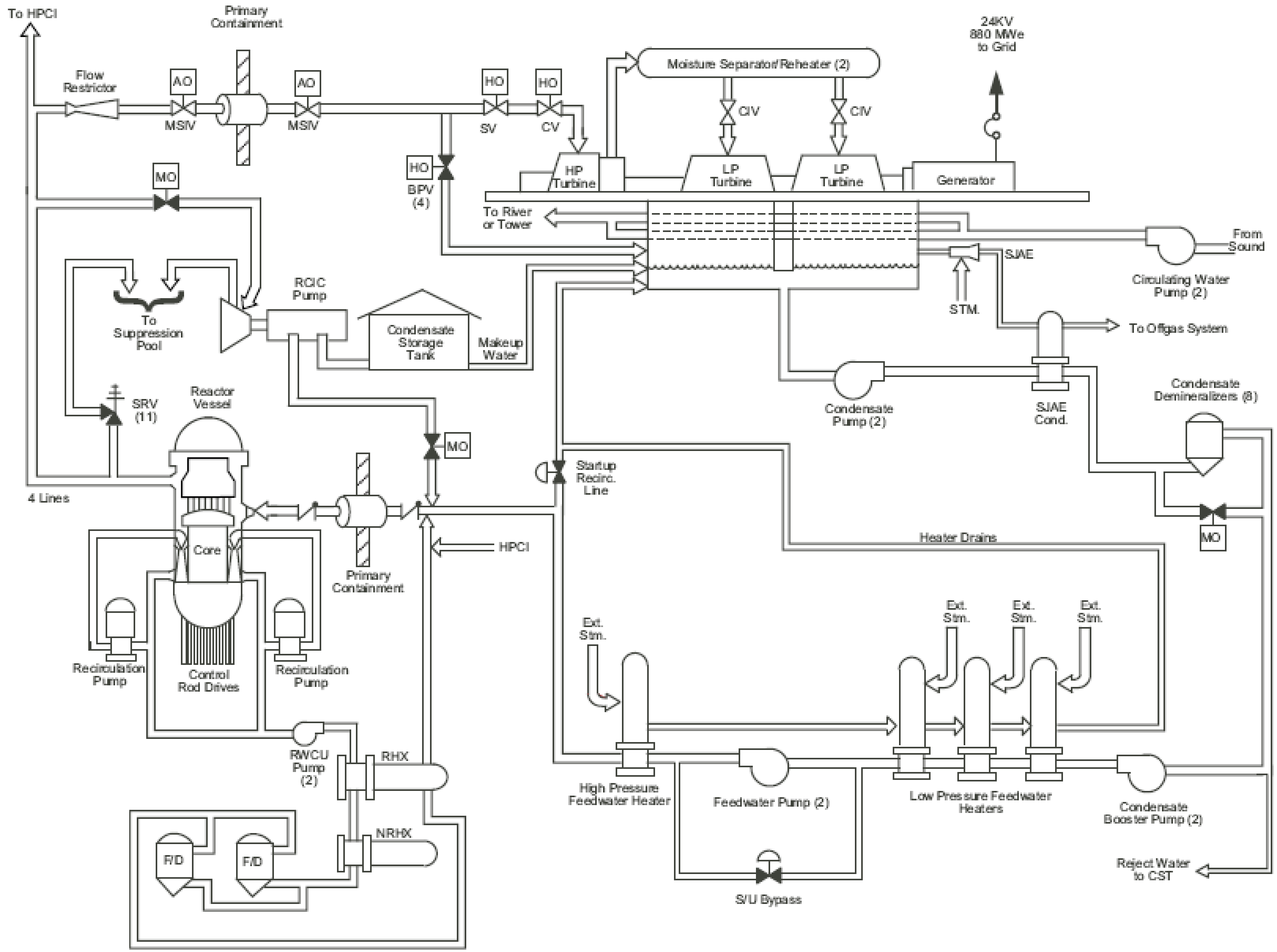
Fukushima Spent Fuel Pool / Refueling Crane

Engineered Safety Systems

- Engineered safety systems in a reactor are designed to stabilize the reactor and prevent fuel melting in accident scenarios
- Reactors include a variety of active and passive systems
  - Passive safety systems
    - Systems that respond naturally without operator intervention or external power
  - Active safety systems
    - Systems that rely on mechanical equipment and electrical power (pumps, motors, motor operated valves, etc.)

Engineered Safety Systems

- In order to minimize the risk of engineered safety systems failing, nuclear plant designs emphasize
  - Redundancy / Flexibility
    - Is there a back-up component that can do the task if the primary fails to start? Can the system be reconfigured to handle unusual conditions or multiple failures?
  - Diversity
    - Having multiple different types of active safety systems provides extra insurance
  - Physical Separation
    - Making sure that safety systems are spread around the plant reduces the risk that an accident can damage all of the systems



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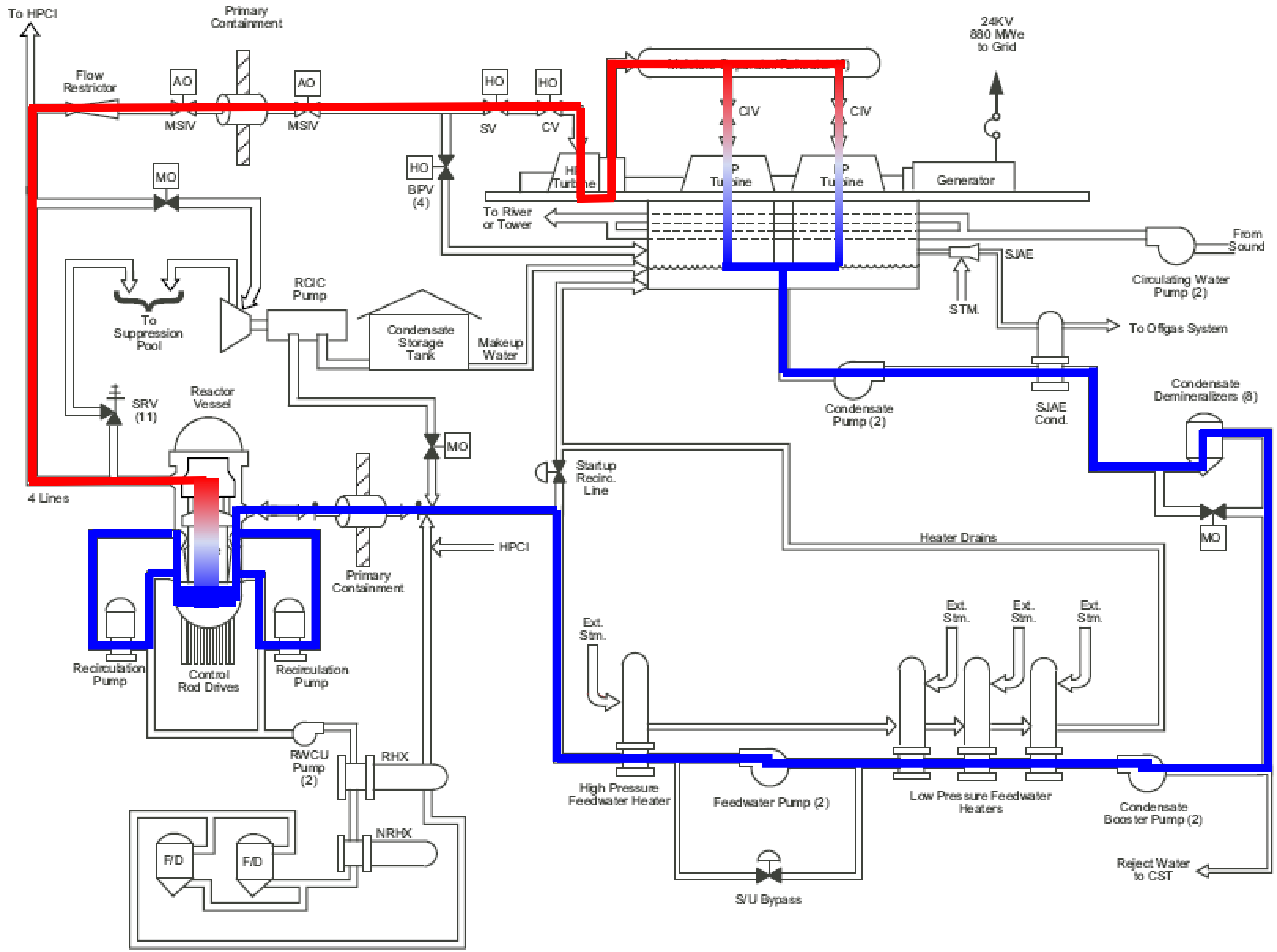


At Power BWR Cooling

Meltdown

- What if all engineered safety systems fail and the fuel starts to melt? Is this the meltdown?
  - Meltdown is not a technical term so there is no precise definition
- If cooling to the core is lost then the decay heat produced by the fuel will cause coolant to boil off and will leave some (or eventually) all of the fuel uncovered
  - Once the fuel rods are no longer covered by water melting will begin
  - Due to Defense-in-Depth design the melting process should follow a predictable sequence

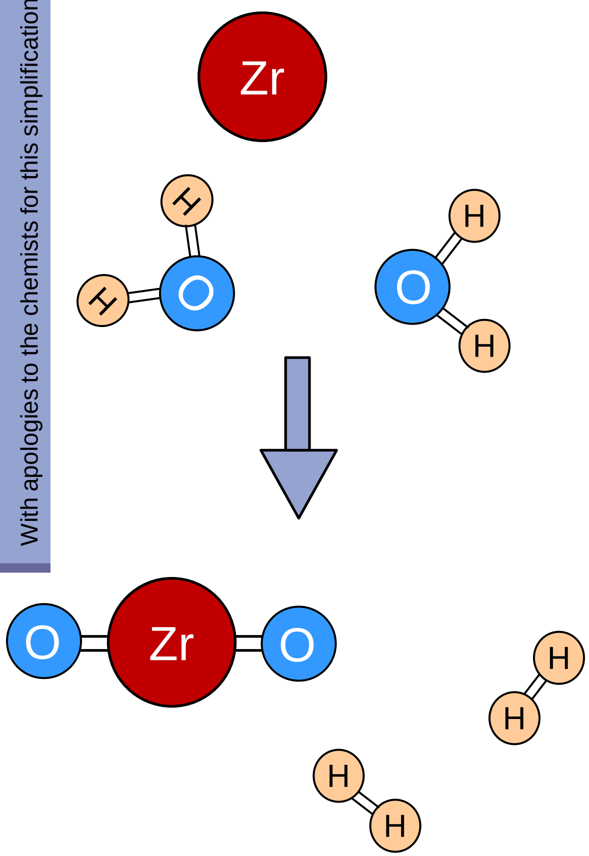
Fuel Melting / Core Degradation

- For an uncooled reactor
  - Zirconium cladding will blister / rupture
  - Zirconium cladding will oxidize away
  - Fuel pellets will fall out of rods, collecting in reactor bottom
  - Fuel pellets will eventually melt, causing molten UO_2 to slump to the bottom of the core vessel
  - After several hours the molten fuel will melt through the bottom of the core vessel and flow into containment
  - Rising temperatures will cause pressure to increase until containment fails via
    - Over-pressurization
    - Fuel melting through the containment wall

Secondary Effects

With apologies to the chemists for this simplification of oxidation

Zirconium Oxidation

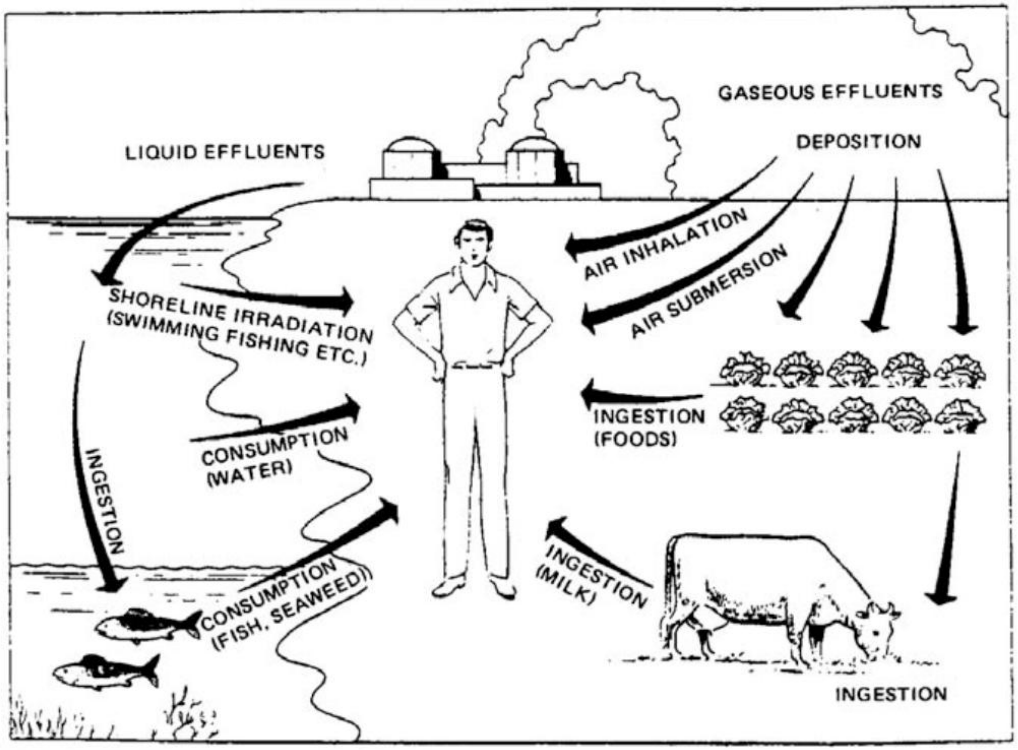


- Additional problems created by fuel melting
  - Over-pressure (mechanical failure)
  - Steam explosions
    - If molten fuel drops into liquid water
  - Exothermic chemical reactions
    - Fuel/concrete interactions
    - Clad/water interactions
      - Zirconium and Stainless Steel readily oxidize at high temperature (highly exothermic)
      - Reactions release hydrogen which can explode

Environmental Release

- Once containment fails, radioactive materials (molten fuel and gaseous fission products) have entered the environment.
- The real dangers:
  - Many fission products are radioactive and others are quite toxic
  - An uncontrolled environmental release means that these nuclides can be inhaled directly or ingested by eating contaminated food

Environmental Release



- Once outside of containment, tracking the transport of radionuclides becomes very complicated
- The study of the release, transport and human effect of radionuclides is covered by a branch of nuclear engineering called **health physics**

Environmental Release

Fission Products of Significance in Internal Exposure from Reactor Accidents†

Isotope	Radio-active half-life $T_{1/2}$	Fission yield (%)	Deposition fraction‡	Effective half-life	Internal dose (mrem/ μCi)	Reactor inventory§ [Ci/kW(th)] 400 Days	Equilibrium
Bone							
^{89}Sr	50 d	4.8	0.28	50 d	413	43.4	43.6
^{90}Sr–^{90}Y	28 y	5.9	0.12	18 y	44,200	1.45	53.6
^{91}Y	58 d	5.9	0.19	58 d	337	53.2	53.6
^{144}Ce–^{144}Pr	280 d	6.1	0.075	240 d	1,210	34.7	55.4
Thyroid							
^{131}I	8.1 d	2.9	0.23	7.6 d	1,484	26.3	26.3
^{132}I	2.4 h	4.4	0.23	2.4 h	54	40.0	40.0
^{133}I	20 h	6.5	0.23	20 h	399	59.0	59.0
^{134}I	52 m	7.6	0.23	52 m	25	69.0	69.0
^{135}I	6.7 h	5.9	0.23	6.7 h	124	53.6	53.6
Kidney							
^{103}Ru–^{103m}Rh	40 d	2.9	0.01	13 d	6.9	26.3	26.3
^{106}Ru–^{106}Rh	1.0 y	0.38	0.01	19 d	65	1.8	3.5
^{129m}Te–^{129}Te	34 d	1.0	0.02	10 d	46	9.1	9.1
Muscle							
^{137}Cs–^{137m}Ba	33 y	5.9	0.36	17 d	8.6	1.2	53.6

- Of primary concern are fission products that are readily absorbed by the body and the actinides, which act as heavy metal poisons

Has Nuclear Fuel Ever Melted?

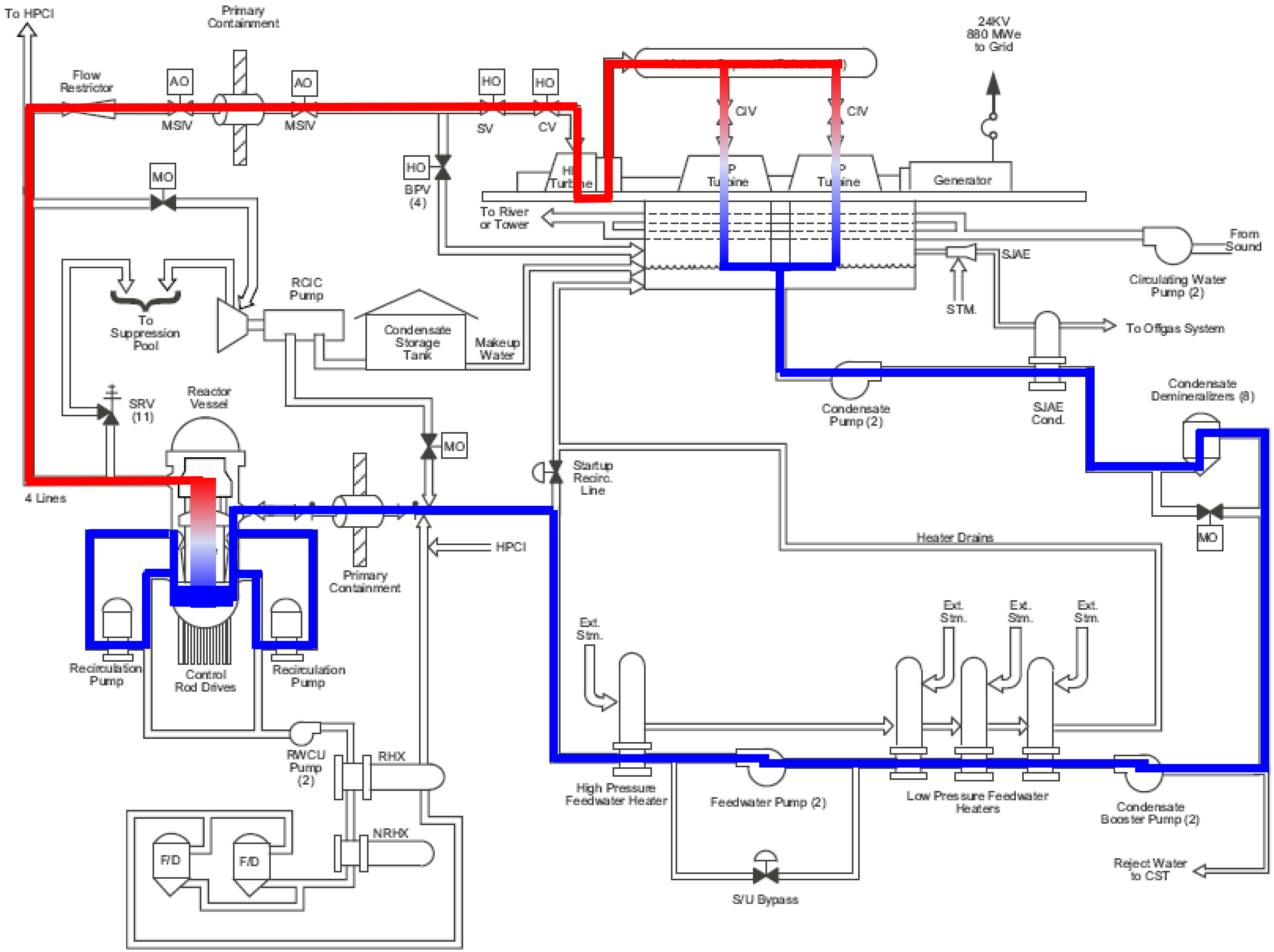
- Unfortunately, yes.
  - There have actually been ~50-100 reactor accidents over the last 60 years
    - Many in Russia, but a surprisingly large number in the US (mostly in research reactors during the first two decades)
    - Most were minor, with a small amount of fuel damage (most reactors were refueled and returned to service)
  - Four accidents stand out above the rest

Notable Reactor Accidents

- SL-1 (Idaho)
  - Criticality excursion destroyed reactor and killed three operators. Little release of contamination in spite of the fact that SL-1 did not have containment.
- Three Mile Island (Pennsylvania)
  - 50-80% of fuel in core melted. Reactor core and vessel was a total loss. Containment held. No fatalities.
- Chernobyl (Russia)
  - Positive void coefficient caused reactivity excursion which created a steam explosion and destroyed the plant. “Containment” was destroyed
  - Spread radioactive debris over a large area
- Fukushima Daiichi (Japan)

Fukushima Daiichi Accident

- Following the March 11th earthquake multiple failures occurred at several units at the Fukushima power station, preventing normal cooling operations.
- Presently units 1, 2, 3, and 4 have suffered damage, including (it is believed) some amount of fuel melting.
- The situation is continually evolving and many of the facts are not yet known.
- The following slides provide the probable sequence of events leading to fuel melting at Fukushima Daiichi Unit I following the earthquake.



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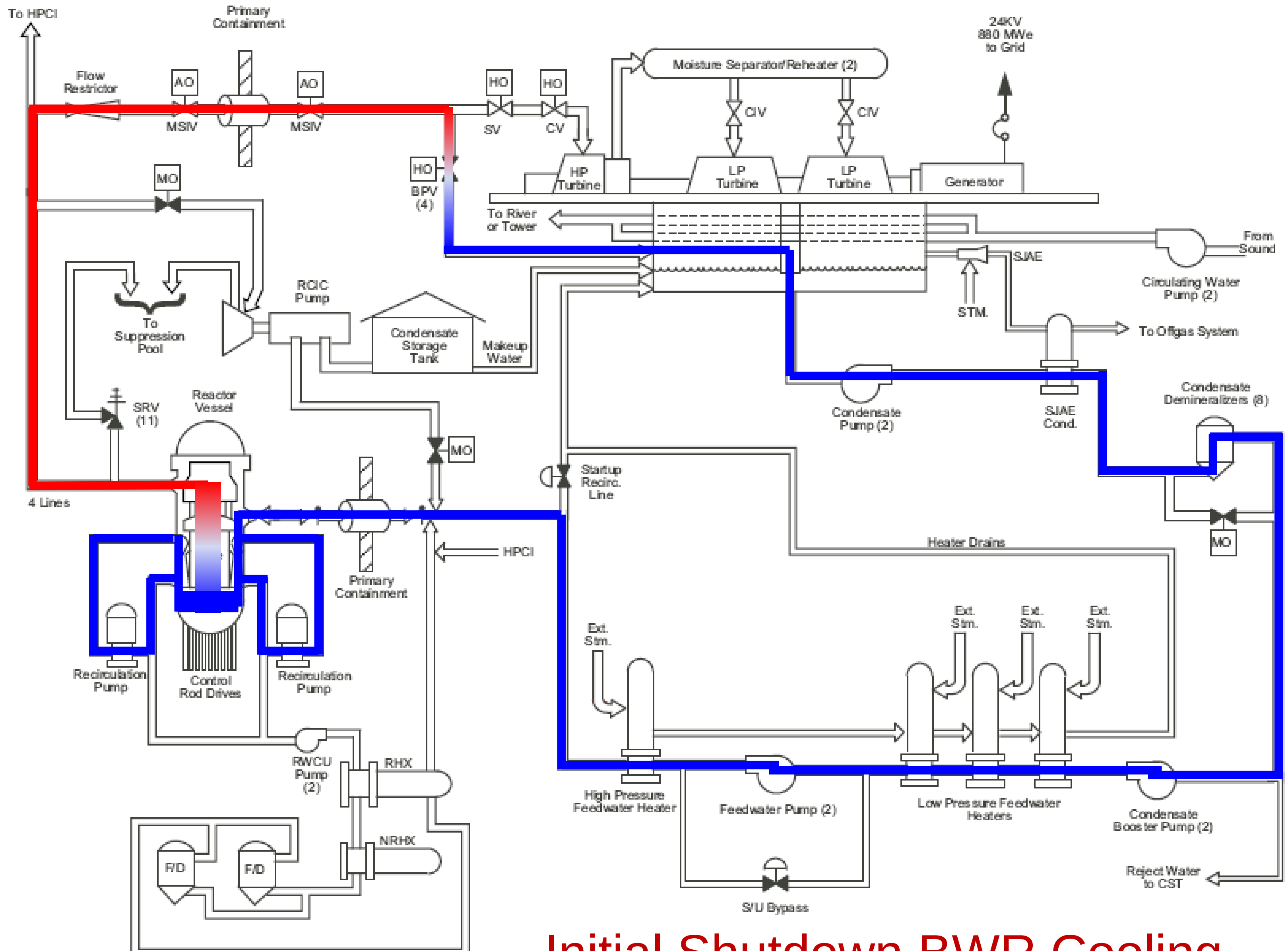
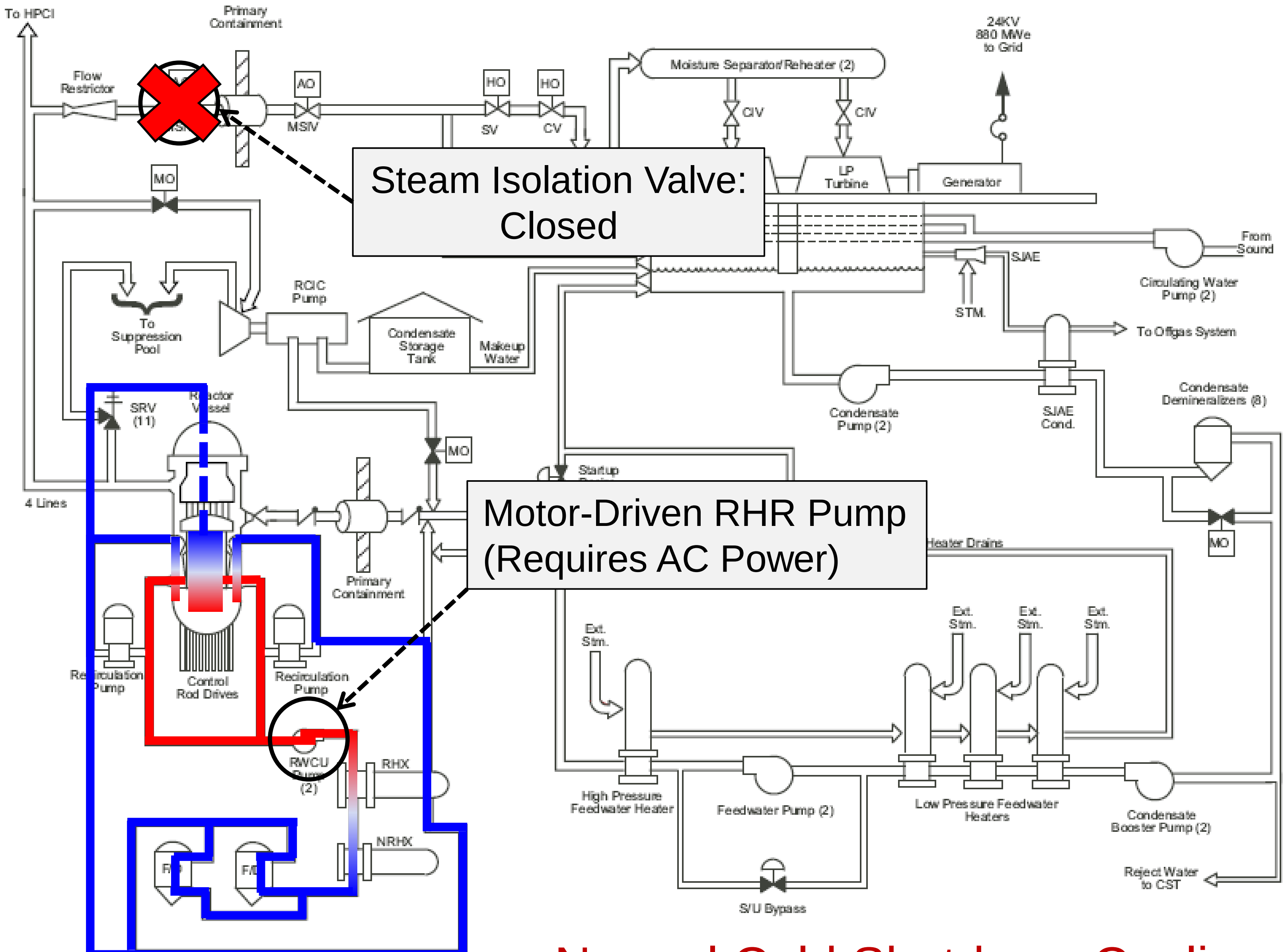
At Power BWR Cooling

Fukushima Timeline

- Prior to earthquake Fukushima I Units 1,2, and 3 were operating at full power.
- Magnitude 9.0 Earthquake hits. All reactors insert control rods and shut down. Chain reaction stops immediately.
- As reactor power coasts down (due to decay of short-lived fission products), steam produced in the reactor is dumped directly into the condenser, bypassing the turbine. This is normal shutdown operating procedure.



Initial Shutdown BWR Cooling (Until pressure below 120 psig)



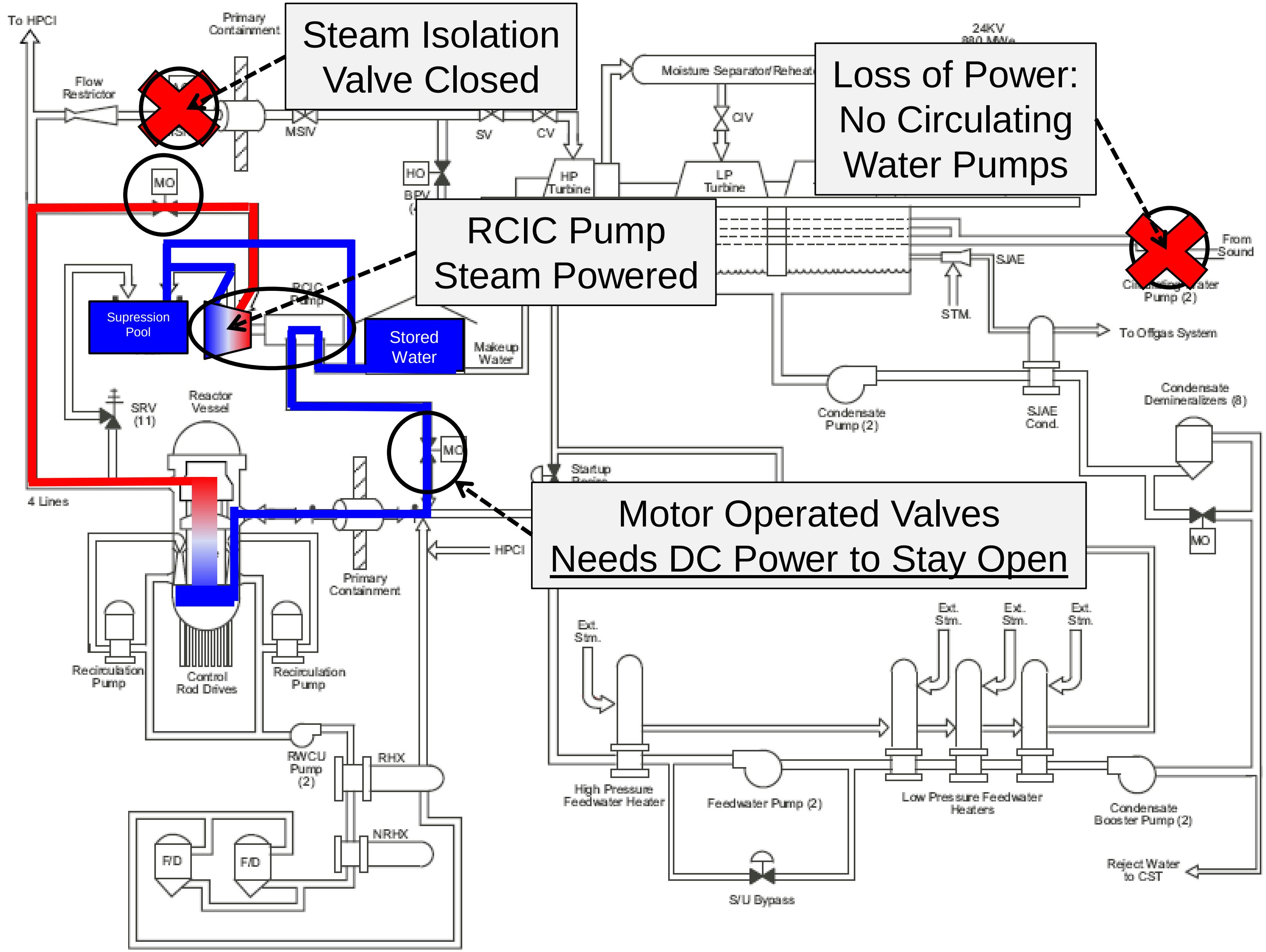
Normal Cold Shutdown Cooling (Residual Heat Removal)

Fukushima I – Unit 1 Timeline

- Power lines and distribution yard are destroyed causing loss of off-site power.
  - First off-normal condition
  - Probably due to shaking from earthquake.
  - Loss of off-site power is an anticipated scenario and nuclear plants are well trained to respond.
- Emergency diesel generators kick in to support in-house electrical loads for core cooling.
- Circulating water pumps (to cool condenser) are not powered by emergency diesel generators.

Fukushima I – Unit 1 Timeline

- During loss of off-site power circulating water pumps (to cool condenser) shut down, as designed.
- Main steam isolation valves are closed, routing steam away from the main condenser
- The Reactor Core Isolation Cooling (RCIC) System, a passive backup cooling system, takes over core cooling, as designed
  - RCIC uses turbine driven pumps powered by steam created in reactor
  - Condenses steam to suppression pool
  - Draws feedwater from suppression pool and external condensate tank
  - RCIC system requires DC power to keep motor operated valves in the open position (fail-safe valve position is closed.)



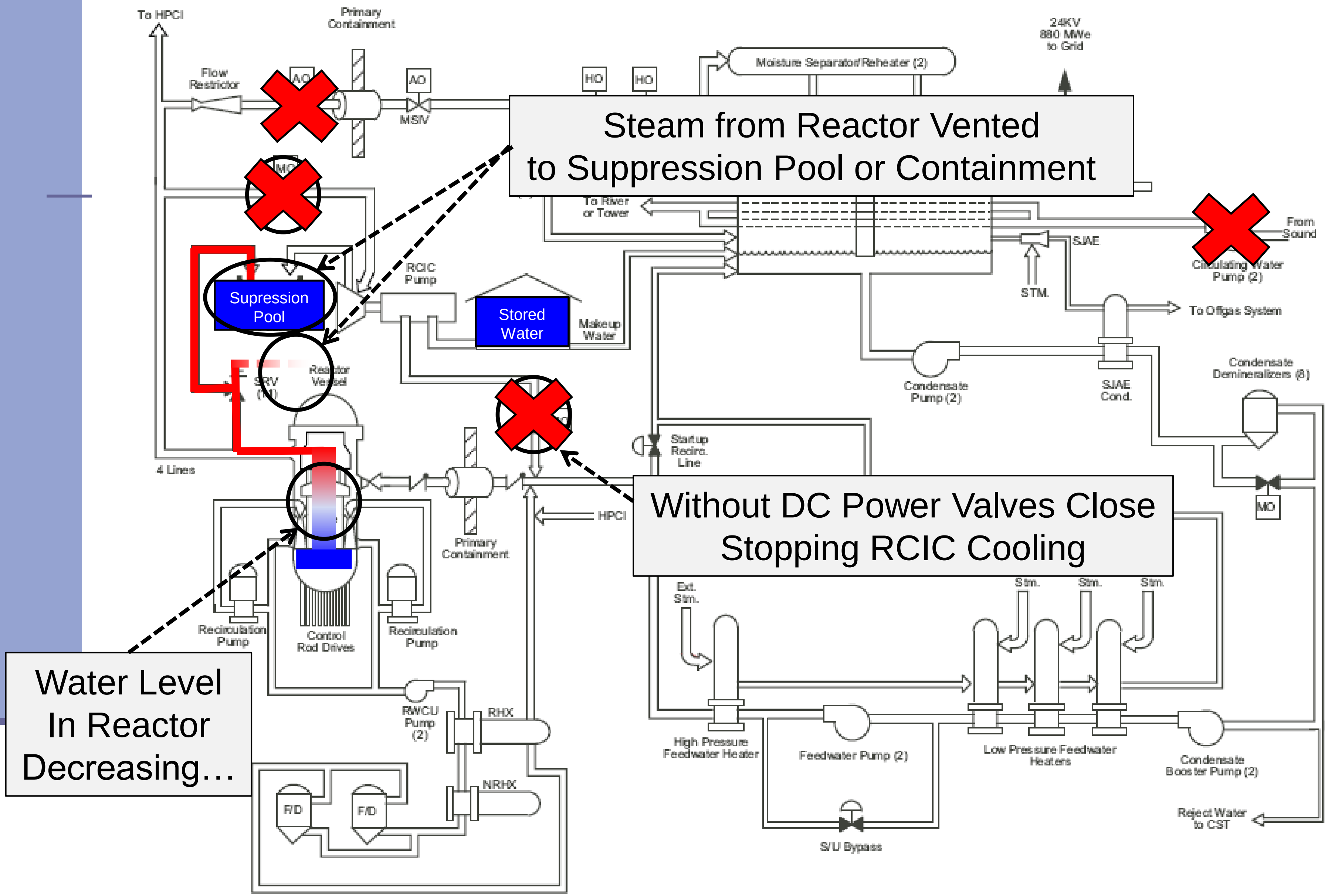
Reactor Isolation Cooling

Fukushima I – Unit 1 Timeline

- One hour after the earthquake a 10+ meter (33') tsunami hits the power station.
- All 13 emergency diesel generators on site (~2 per reactor) are disabled by tsunami damage
  - Diesel generators were located 10-13 meters above sea level
  - Second concurrent failure (along with loss of off-site power)
  - Beyond design basis tsunami / at the limit of the design basis loss of power accident
- Emergency electrical loads in the plant switch to battery backup, as designed
- Core Isolation Cooling (RCIC) system continues cooling the core without interruption, as designed
  - DC power is required to keep valves open so that RCIC can continue working

Fukushima I – Unit 1 Timeline

- After 8 hours backup batteries run out and the RCIC can no longer be used (valves return to fail-safe closed position)
- Complete station blackout.
  - Third failure. No active safety systems remain, just passive design features and defense-in-depth layers.
  - Beyond design basis accident.
- Steam is bubbled through suppression pool, further increasing temperature of water, but condensing steam and keeping pressure at manageable levels, as designed
- Water leaving the core is not replaced, causing the water level in the core to drop.



Station Blackout – No Injection

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Fukushima I – Unit 1 Timeline

- As the water level dropped below the top of the fuel, the temperature in the fuel and cladding began to rise rapidly, causing fuel degradation
  - Clad failure (blister/rupture) allows gaseous fission products in fuel to escape
  - Zirconium in clad oxidizes in the presence of water, releasing hydrogen into containment drywell
- Uncertain how much fuel was uncovered by water or how much melting has taken place.
- During the station blackout, operators focused on the third layer of defense: <u>containment</u>
  - No matter what happens in the core, prevent release of material to the environment

Fukushima I – Unit 1 Timeline

- After a short time pressure levels in containment were at or above the design pressure, raising the risk of a containment rupture due to over-pressurization

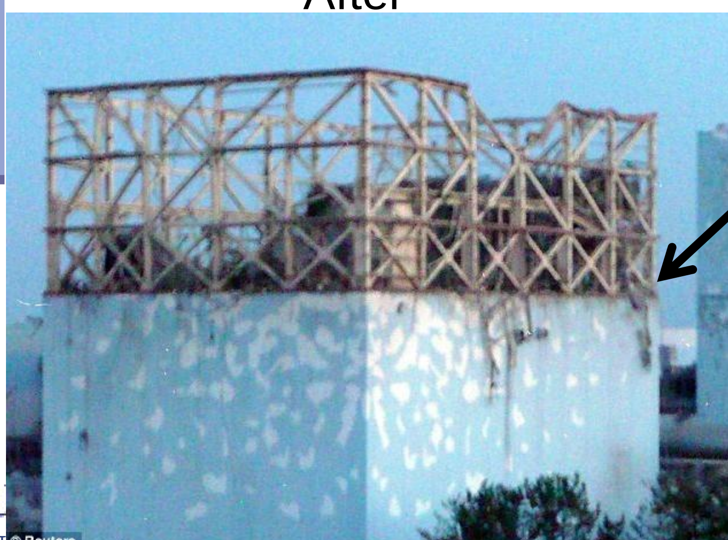
- Operators manually opened a valve to release steam from containment into the reactor building.
  - This was done to prevent an overpressure of containment and the possible uncontrolled release of radioactive material.
  - Vented steam contained hydrogen, which ignited, destroying the reactor building, but not damaging containment…
    - …but, spent fuel pool is now exposed to the elements
  - Units 3 and 4 later suffer similar explosions

Hydrogen Explosion

Hydrogen Explosion

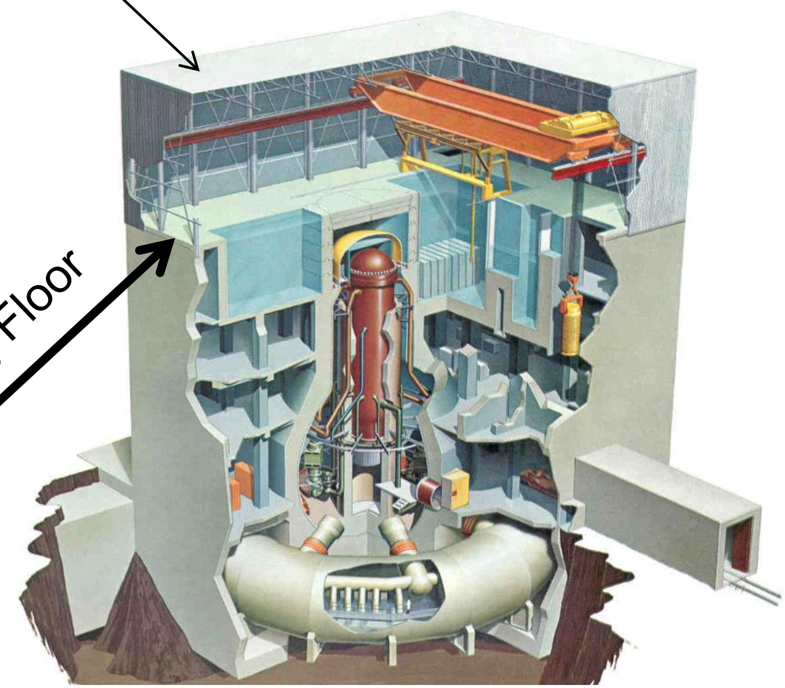
Before

After

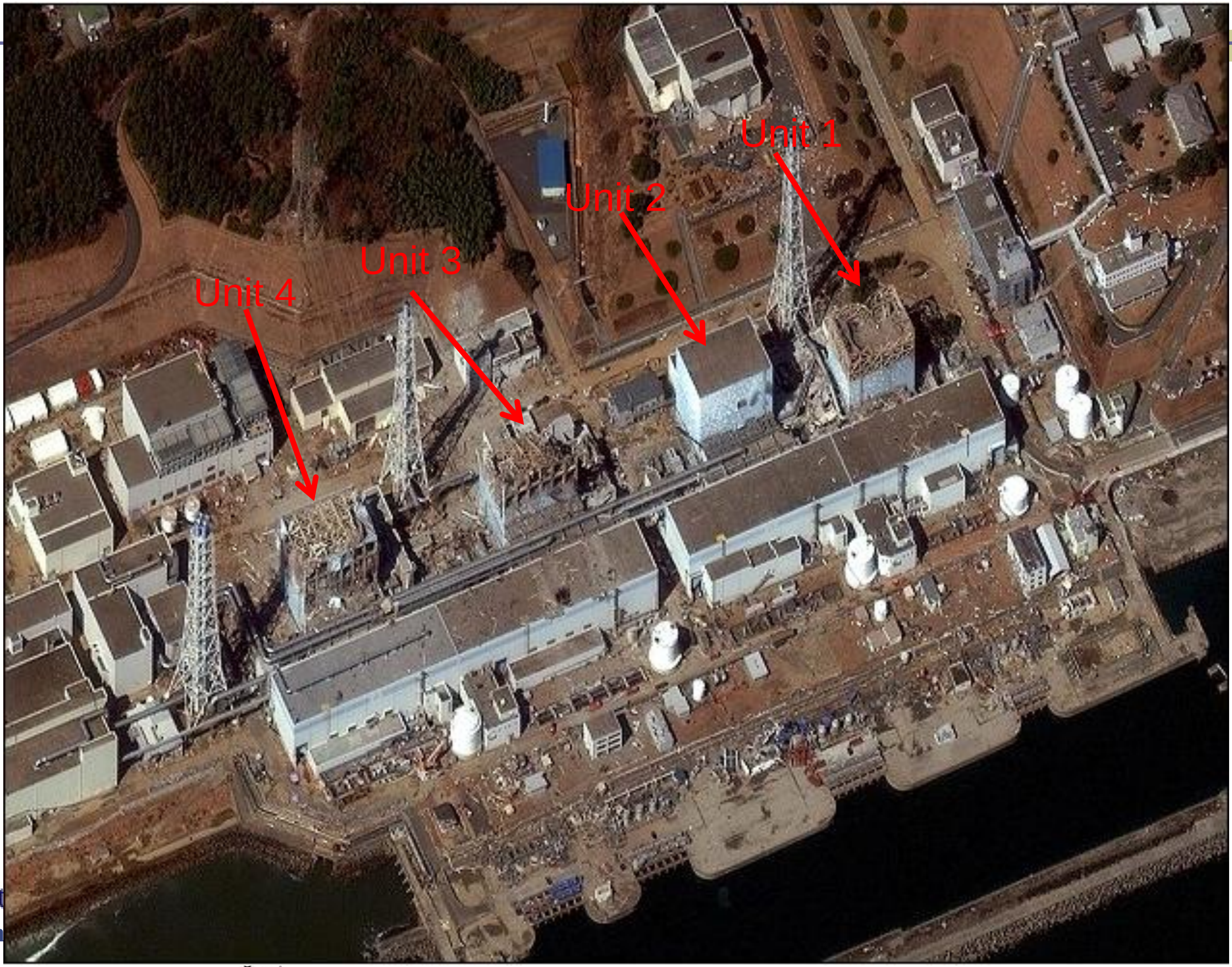


Refueling Floor

Damaged Portion



Hydrogen Explosions

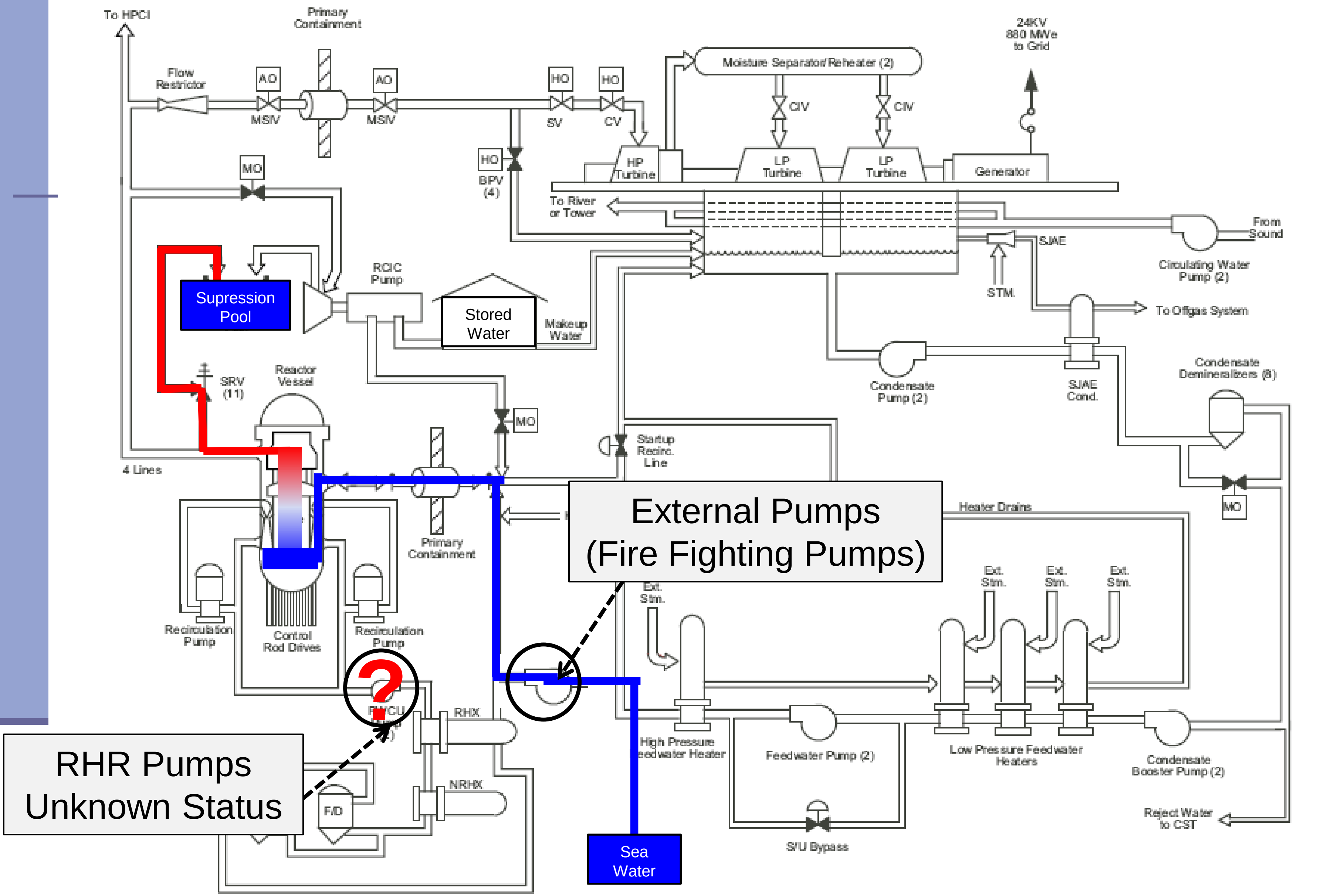


Fukushima I – Unit 1 Timeline

- Following the release elevated radiation levels were detected at the reactor building and at the plant boundary.
- Released steam contained hydrogen and detectable levels of several fission products (Cs-137, I-131)
  - This provided the first indication that some fuel in the reactor had already melted.

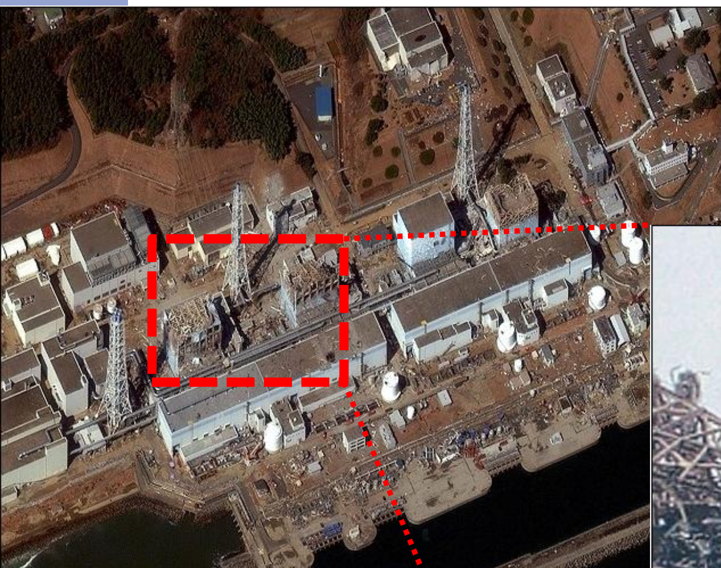
Fukushima I – Unit 1 Timeline

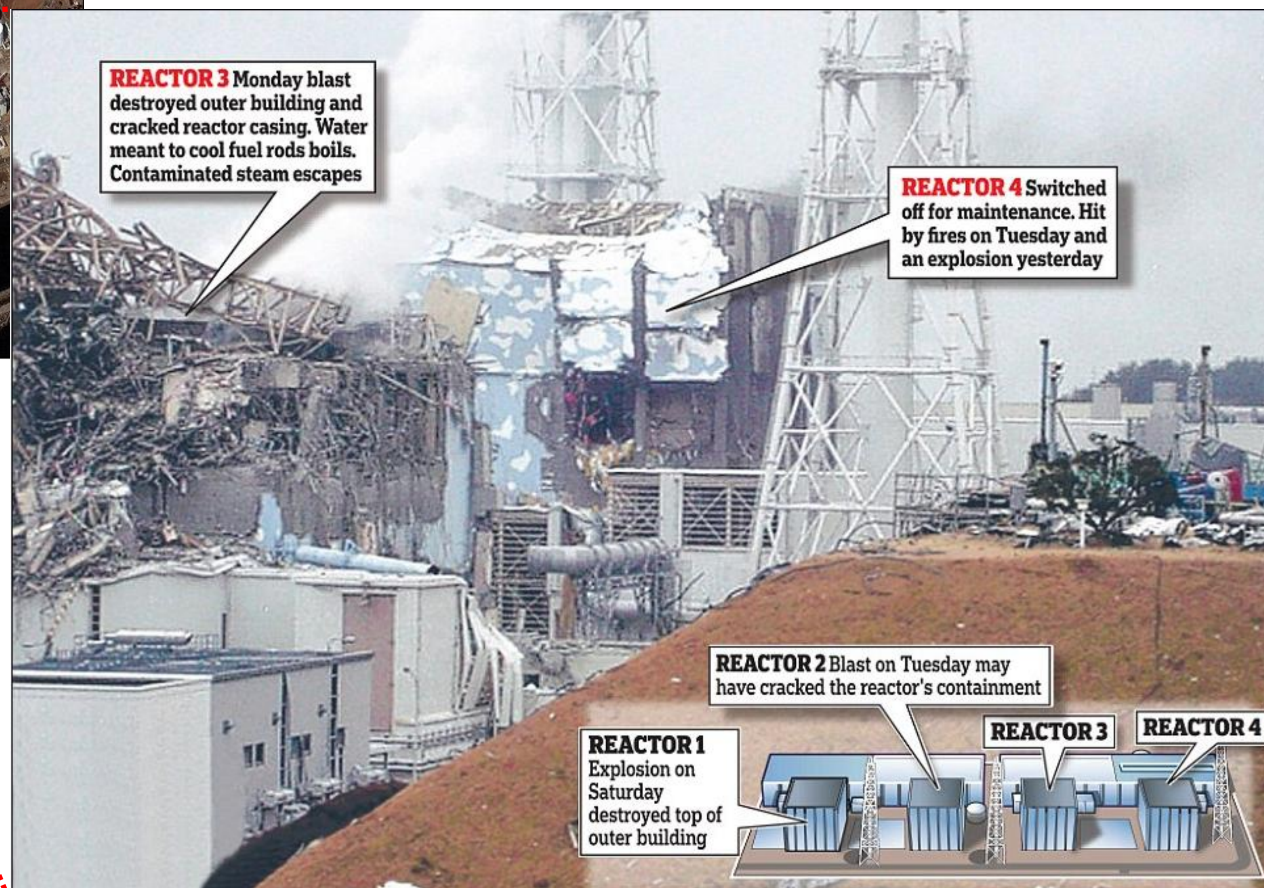
- Backup generators (and batteries) arrived some hours later, restoring partial DC power to plant.
  - It appears that generators were insufficient to power any of the installed cooling system pumps
  - Instead, smaller, portable (fire) pumps were used to pump borated sea water into the reactor core and containment
- Use of sea water guarantees unlimited supply of coolant to pump into reactor.
  - Plants will need to be decommissioned due to corrosion issues from sea water



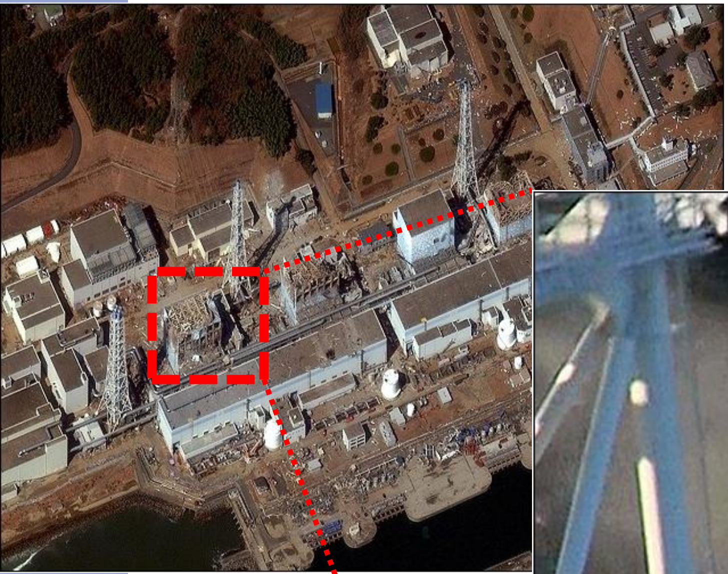
Sea Water Cooling
Temporary On-Site Power

Current Plant Status





Current Plant Status



Fukushima Daiichi Unit 4

Current Plant Status

Status of Fukushima I at 16:00 on 20 March[90]

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Power output (MWe)	460	784	784	784	784	1100
Type of reactor	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
Status at earthquake	In service -> shutdown	In service -> shutdown	In service -> shutdown	Defueled	Outage	Outage
Fuel integrity	70% damaged[44]	33% damaged[44]	Damaged	No fuel rods	Not damaged	Not damaged
Pressure vessel integrity	Unknown	Unknown	Unknown	Not damaged	Not damaged	Not damaged
Containment integrity	Not damaged	Damage suspected	Unknown	Not damaged	Not damaged	Not damaged
Core cooling system 1 (ECCS/RHR)	Not functional	Not functional	Not functional	Not necessary	Not necessary	Not necessary
Core cooling system 2 (RCIC/MUWC)	Not functional	Not functional	Not functional	Not necessary	Not necessary	Not necessary
Building integrity	Severely damaged	Slightly damaged	Severely damaged	Severely damaged	Vent hole opened on rooftop to prevent hydrogen explosion	Vent hole opened on rooftop to prevent hydrogen explosion
Pressure vessel, water level	**Fuel exposed**	**Fuel exposed**	**Fuel exposed**	Safe	Safe	Safe
Pressure vessel, pressure	Stable	Unknown	Stable	Safe	Safe	Safe
Containment pressure	Unknown	**Low**	Stable at higher level after increase	Safe	Safe	Safe
Seawater injection into core	Continuing	Continuing	Continuing	Not necessary	Not necessary	Not necessary
Seawater injection into containment building	Continuing	To be decided	Continuing	Not necessary	Not necessary	Not necessary
Containment venting	**Temporarily stopped**	**Temporarily stopped**	**Temporarily stopped**	Not necessary	Not necessary	Not necessary
Integrity of fuel in Spent Fuel Pool (SFP)	**Water injection to be considered**	(no data)	**SFP level low, Water injection continuing**	**SFP level low, Water injection continuing, Hydrogen from SFP exploded**	Pool cooling capability was recovered	Pool cooling capability was recovered
Environmental effect (NPS border)	At 05:40, 20 March: 269.5 μSv/hour (West Gate); and 3054 μSv/hour to the North of the Service Building (at 15:00, 20 March)					
Evacuation radius	20 km from Nuclear Power Station (NPS). People who live between 20 km to 30 km from the Fukushima I Nuclear Power Station are to stay indoors.					
INES	Units 1-3, Level 5 (estimated by Japanese NISA and accepted by the international IAEA); Level 6 (estimated by the French Nuclear Safety Authority, ASN)[50][51][54]; Unit 4, Level 3.[93]					

Timeline of the Fukushima nuclear accidents - Wikipedia, the free encyclopedia
http://en.wikipedia.org/wiki/Timeline_of_the_Fukushima_nuclear_accidents
Screen clipping taken: 3/21/2011 10:32 PM

What Now?

- Post-Accident Response
  - Coordination with local officials
    - Evacuation
    - Complicated by destruction of infrastructure
  - Radiation Monitoring (air, water, and people)
    - In containment
    - Outside of containment
    - At plant fence
  - Cleanup / Decontamination

Accident Response

- Protection (Short-Term)
  - Evacuations (based on monitoring)
  - Masks to prevent inhalation
  - Hygiene to prevent spread of contamination
  - Iodine tablets

- Protection/Remediation (Long-Term)
  - Monitoring all environmental pathways
  - We can detect radiation, identify radioactive contamination, and remove it from the food chain.
  - Decontamination: Soap and Water
  - Burial of contaminated waste