The Future of Nuclear Power After Fukushima

Michael Corradini

American Nuclear Society
Vice President / President-Elect
http://ans.org

University of Wisconsin Energy Institute
Chair
http://www.energy.wisc.edu

ANS Special Committee On Fukushima

The special committee is to provide a clear and concise explanation of the events surrounding the accident to the general public.

We evaluated needed actions to better communicate with the public.

http://fukushima.ans.org

Co-Chairs: Dale Klein, Univ. of Texas, Michael Corradini, Univ. of Wisconsin

Paul T. Dickman, Argonne National Laboratory

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Craig D. Sawyer, Retired Senior Engineer

Amir Shahkarami, Exelon Nuclear

Akira Tokuhiro, University of Idaho

AMERICAN NUCLEAR SOCIETY

Future of Nuclear Power after Fukushima

Summary of what we know about Fukushima

Japanese and International Situation

Lessons Learned for current U.S. plants

Future of nuclear power in this decade

Future of advanced nuclear power technology

Societal energy policy questions

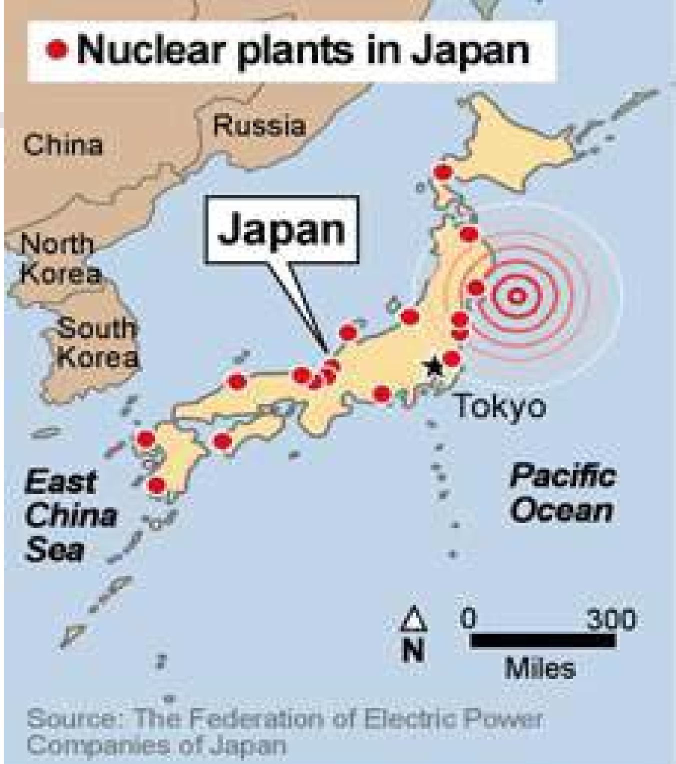
Fukushima-1 Accident Summary

- Basic facts on natural disasters and nuclear power
- Accident progression at Fukushima Daiichi site
- Health effects of radioactive materials release
- Accident cleanup and waste management
- Regulatory safety issues for the U.S.
- Risk communication and future of nuclear

* Info: TEPCO, NISA, MEXT

The Event

- The Fukushima nuclear facilities were damaged in a magnitude 9 earthquake on March 11 (2.46pm JST), centered offshore of Sendai region (Tokyo 250km SW).
  - Plant designed for magnitude 8.2 earthquake.
    A magnitude ~9 quake is much greater in size.
- Serious secondary effects followed including a significantly large tsunami (> factor of 3), significant aftershocks and fires at/from many industrial facilities.
- Over 16,000 dead, 4,000 missing, 80,000 homeless limited resources - over 1000sq.km. land excluded

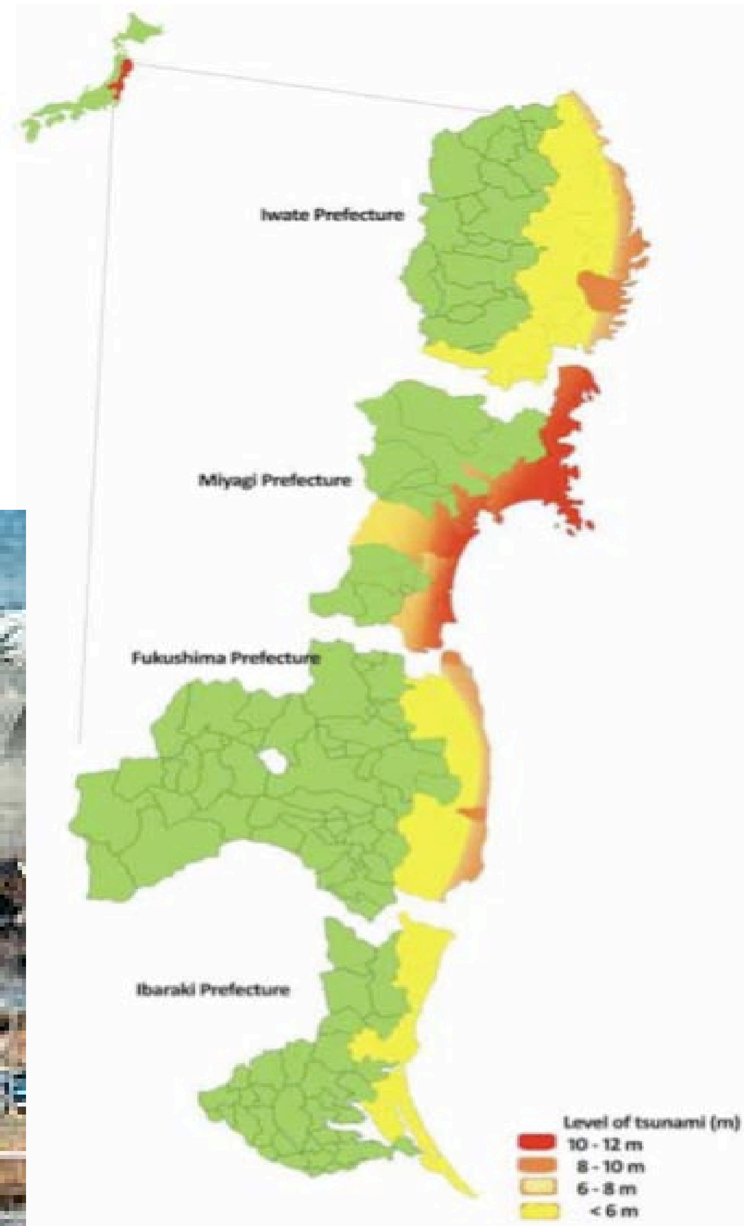


UNIT	MAX OBSERVED MOTION (Direction)	DESIGN EARTHQUAKE MAX MOTION (Direction)
UNIT 1	460 gal* (Horizontal N-S)	487 gal* (Horizontal N-S)
UNIT 2	550 gal (Horizontal E-W)	438 gal (Horizontal E-W)
UNIT 3	507 gal (Horizontal E-W)	441 gal (Horizontal E-W)
UNIT 4	319 gal (Horizontal E-W)	445 gal (Horizontal E-W)
UNIT 5	548 gal (Horizontal E-W)	452 gal (Horizontal E-W)
UNIT 6	444 gal (Horizontal E-W)	448 gal (Horizontal E-W)

Tsunami was historically large but not 'unforeseen'

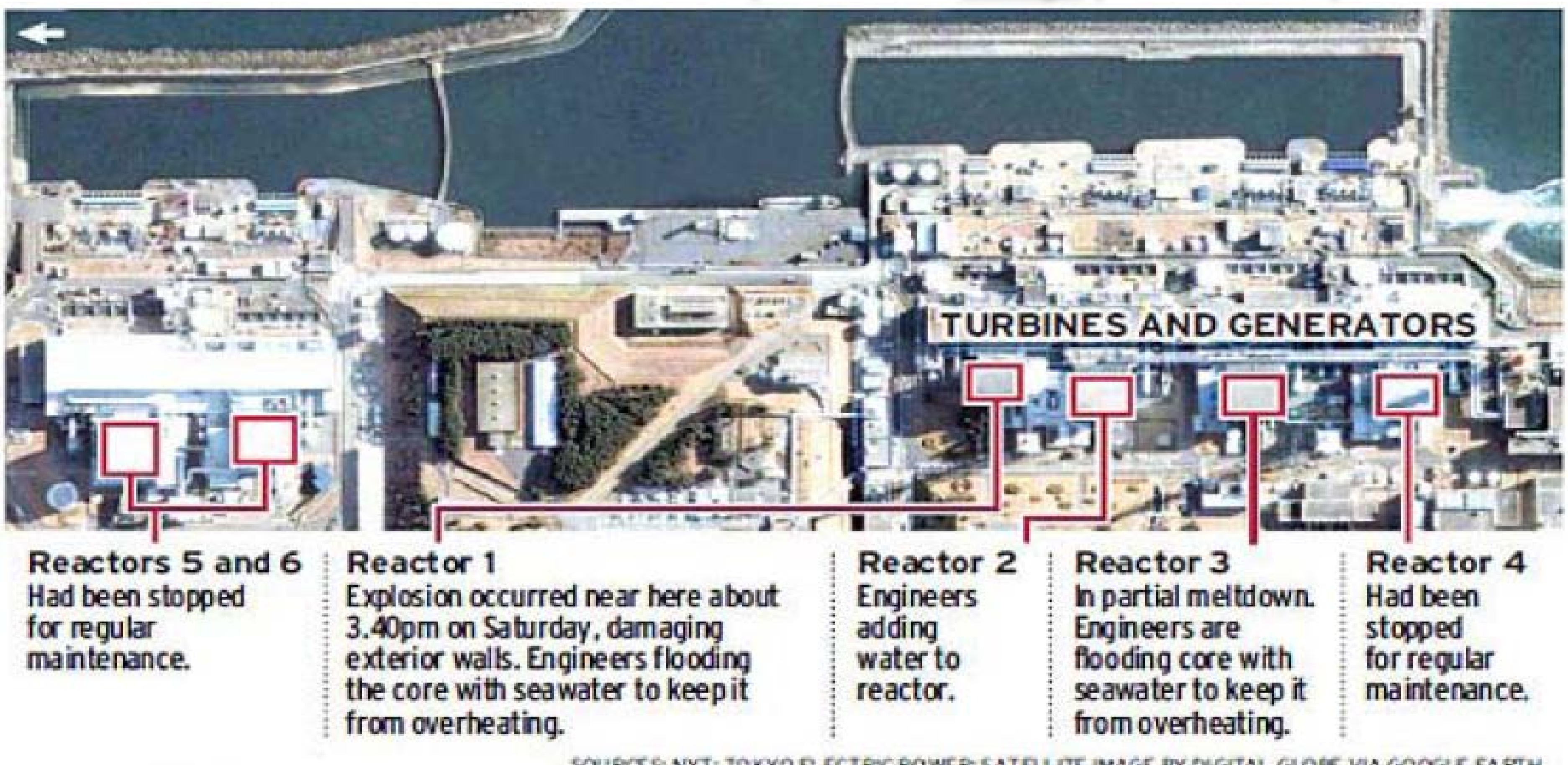
Japanese officials knew of past tsunamis that were above the March event - 869AD - Prob ~10^{-3} (unacceptable event in the US)

Japanese Regulatory restructured



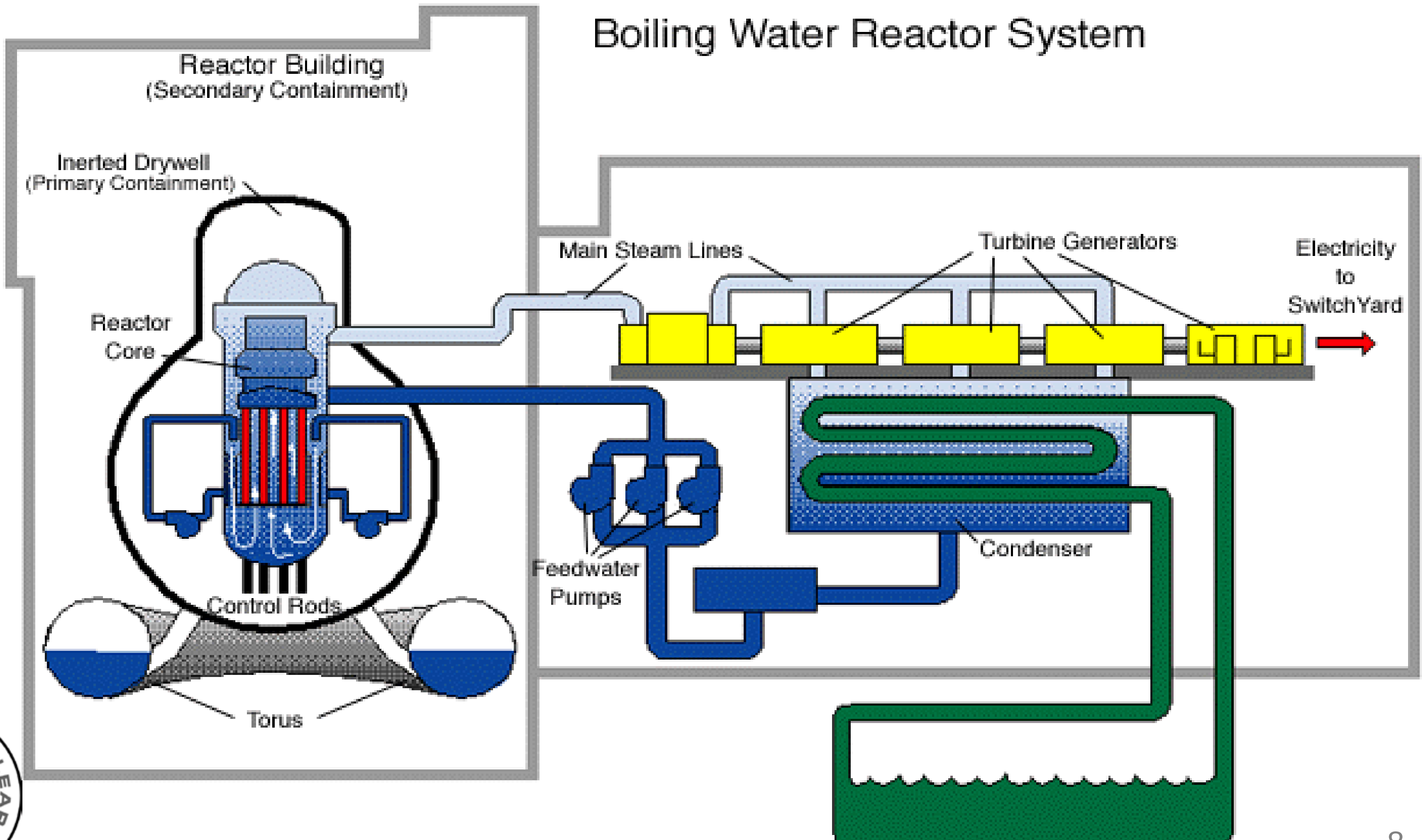
Six BWR Units at the Fukushima Nuclear Station:

- Unit 1: 439 MWe BWR, 1971 (unit was in operation prior to event)
- Unit 2: 760 MWe BWR, 1974 (unit was in operation prior to event)
- Unit 3: 760 MWe BWR, 1976 (unit was in operation prior to event)
- Unit 4: 760 MWe BWR, 1978 (unit was in outage prior to event)
- Unit 5: 760 MWe BWR, 1978 (unit was in outage prior to event)
- Unit 6: 1067 MWe BWR, 1979 (unit was in outage prior to event)

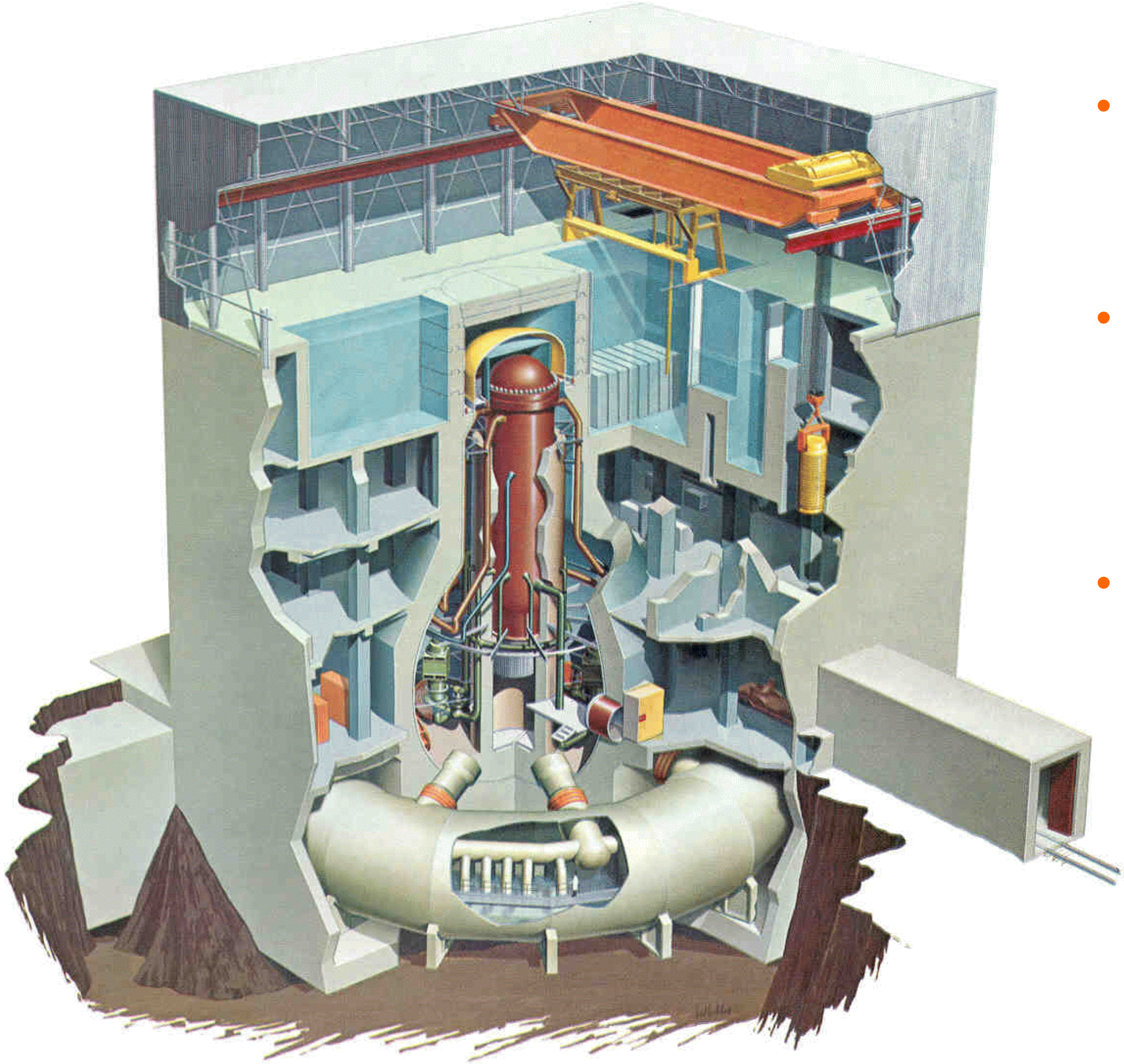


Overview of Boiling Water Reactor

- Typical BWR/3 and BWR/4 Reactor Design
- Similarities to BWR/4 Plants in Midwestern US



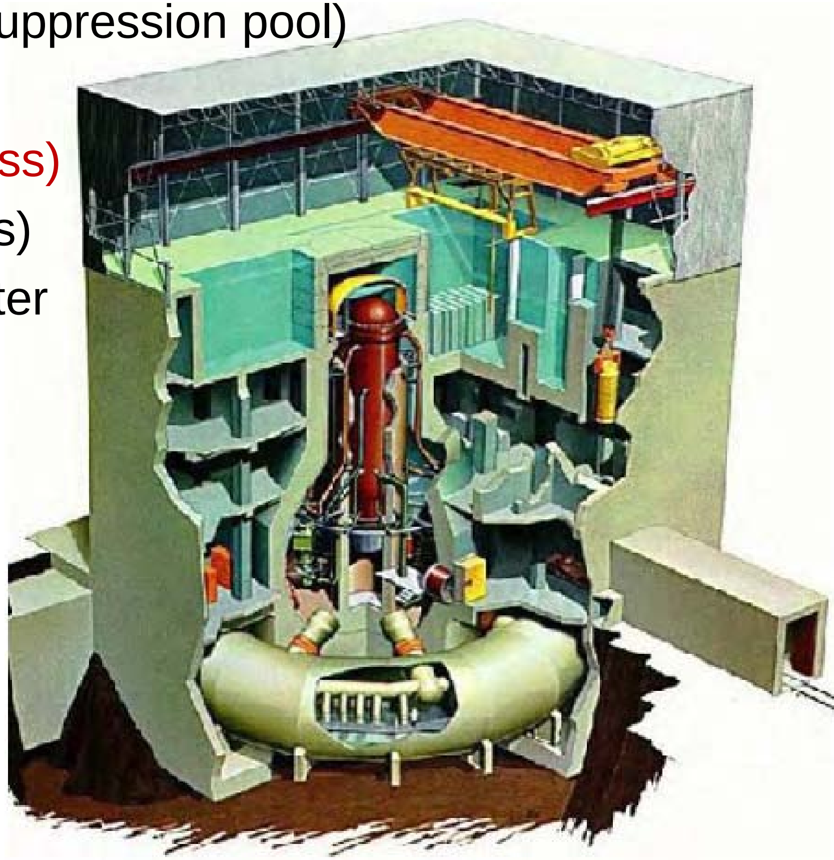
Mark 1 Containment and Reactor Building



- There are 23 reactors in the United States utilizing Mark I containments.
- Available data suggests similarities exist in the design and operation of Japanese and US Mark I containments.
- Following 9/11, the NRC required licensee's to develop comprehensive beyond design basis mitigation strategies (i.e. procedures, staging of portable equipment).

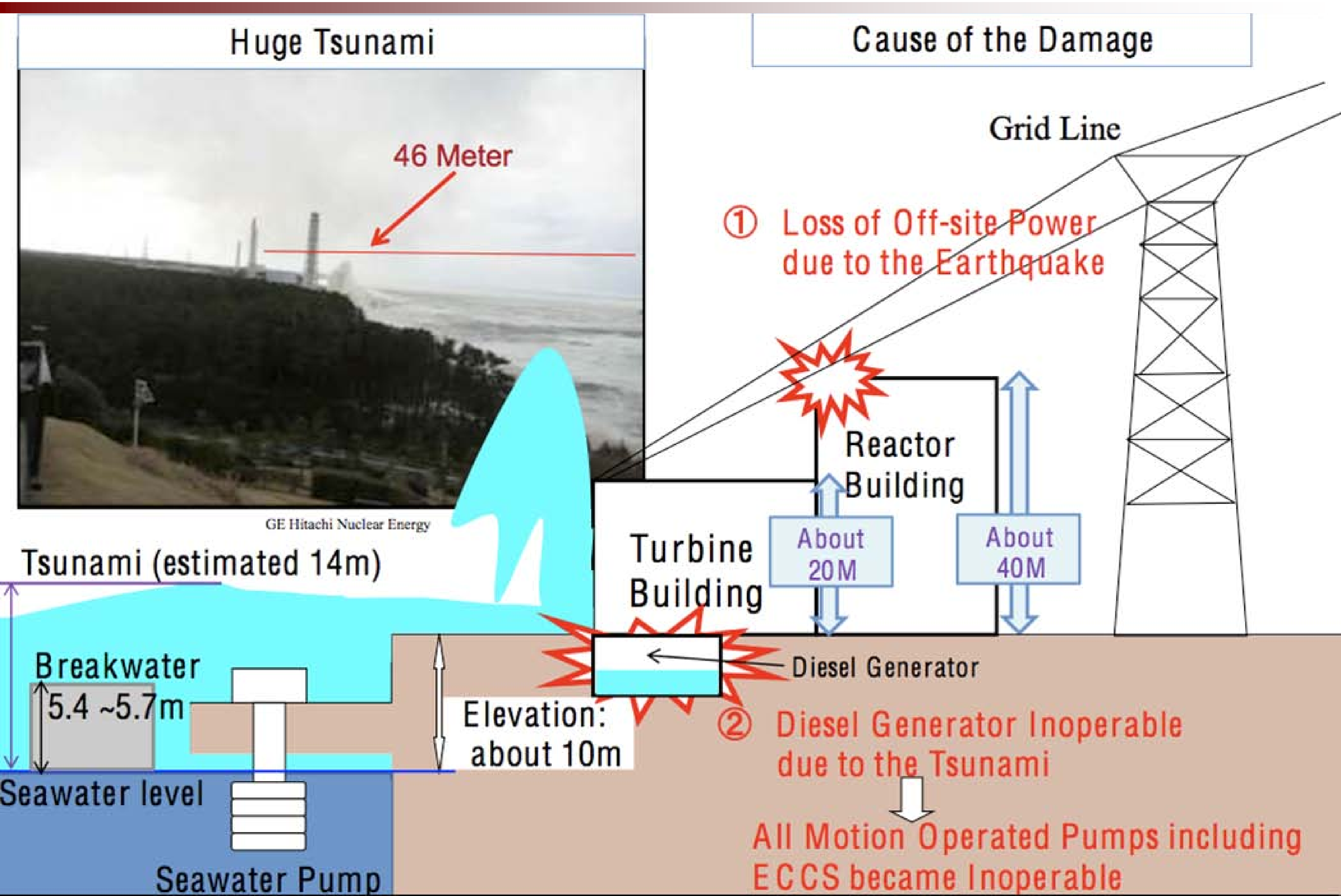
Mark 1 Containment and Reactor Building

- BWR/3 (460 MWe, 1F1)
  - Mark 1 containment (drywell + torus-type suppression pool)
  - SFP on top floor of the R/B
  - Isolation condenser for core cooling (hi-press)
  - HPCI (high pressure core injection, hi-press)
  - Core spray system (CS at low pressure) after depressurization by SRVs



- BWR/4 (784 MWe, 1F2, 3, and 4)
  - Mark I containment (drywell + torus-type suppression pool)
  - SFP on top floor of the R/B
  - RCIC (reactor core isolation cooling) and HPCI (high pressure core injection)
  - CS and RHR/LPCI (at lo-pressure) after depressurization by SRVs

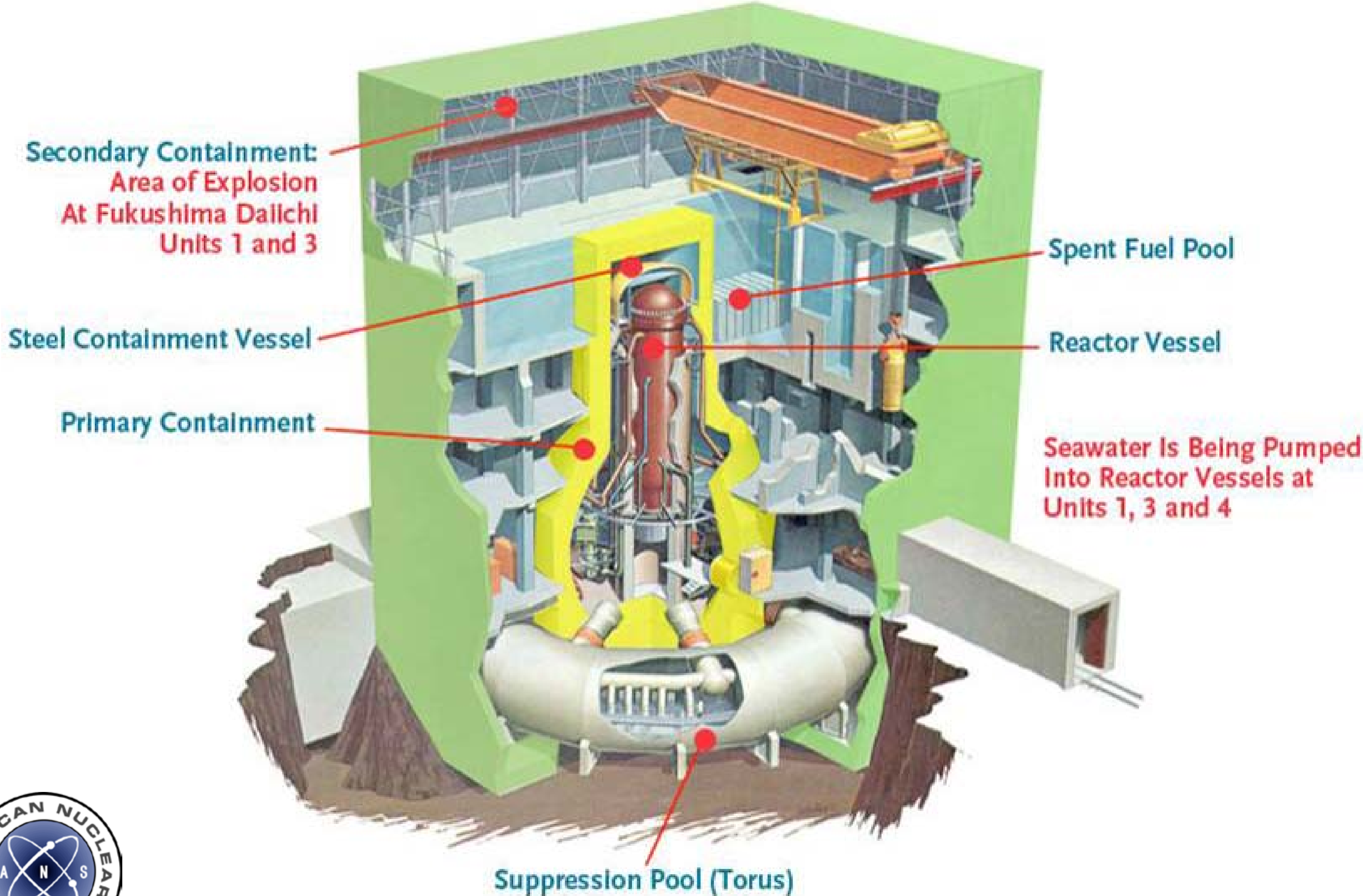
Fukushima Accident Initiation



Fukushima Accident Summary

- Reactors were shutdown based on detection of seismic activity
- Earthquake resulted in the loss of offsite power due to transmission line damage.
- Emergency Diesel Generators powered emergency cooling systems.
- An hour later, the station was struck by the tsunami. The tsunami took out all multiple sets of the Emergency Diesel generator, AC buses, DC batteries (U1) and damaged service water that provide heat rejection to the sea.
- Delayed cooling caused substantial fuel damage as portable power supplies and pumps were being brought on-site to re-establish cooling with fresh & seawater.
- Containments leakage (U1-3) occurred as fuel cladding oxidized and hydrogen released from these processes combusted in the surrounding buildings
- Spent fuel pools didn't suffer direct damage although it was incorrectly assumed

Fukushima Containment System

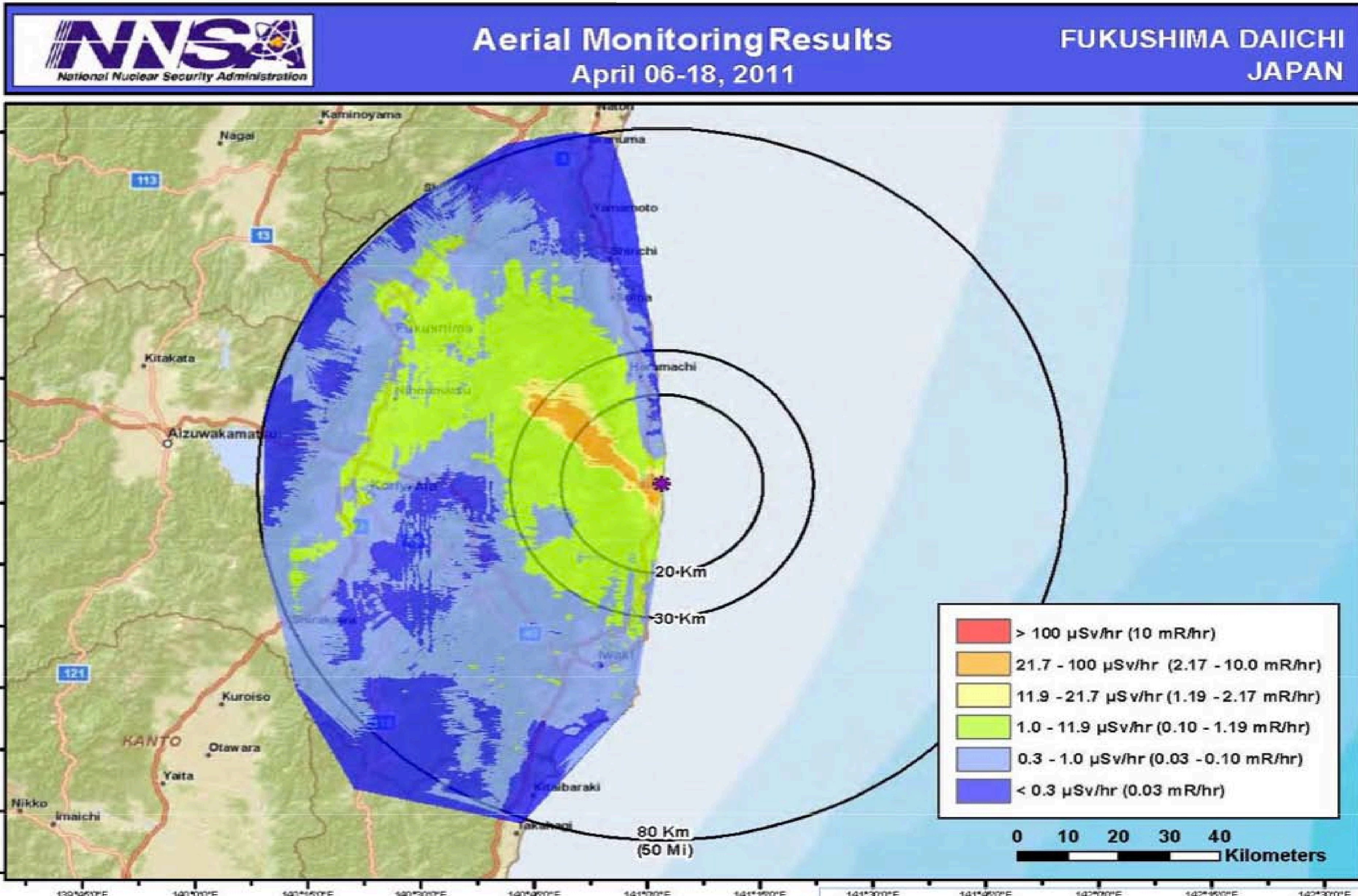


Accident Comparison

- Chernobyl released over 10 times more radioactive material over a few days due to the prompt criticality and explosion
- TMI released over 10 times less radioactive material
- Earthquake and Tsunami damage was extensive (over 20,000 dead/missing; costs range ~ $500b, 5-10% at F1)
- F1 accident caused no loss of life (estimate of latent cancers <100 out of 10's millions) but with land contamination
- Chernobyl accident early fatalities were over 50 with ~5000 cases of children treated with thyroid cancer w unknown cost
- TMI cost ~$2b on-site with off-site damages $150m, and no deaths or no statistically significant latent health effects

Radiological Release

Nuclide	NISA[1]	NSC[2]	Chernobyl
I-131	$1.3X10^{17}$ Bq	$1.5X10^{17}$ Bq	$1.8X10^{18}$ Bq
Cs-137	$6.1X10^{15}$ Bq	$1.2X10^{16}$ Bq	$8.5X10^{16}$ Bq



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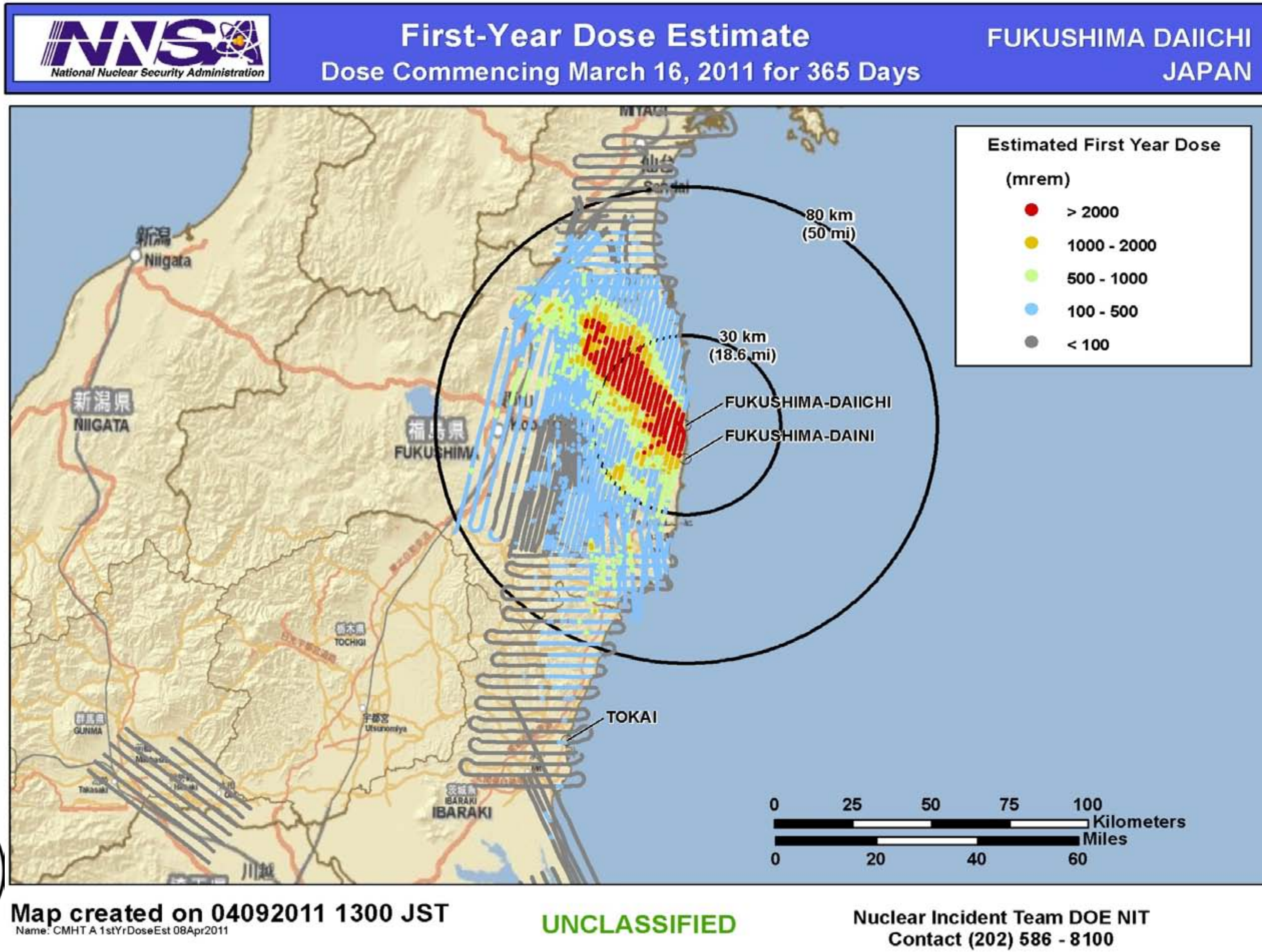
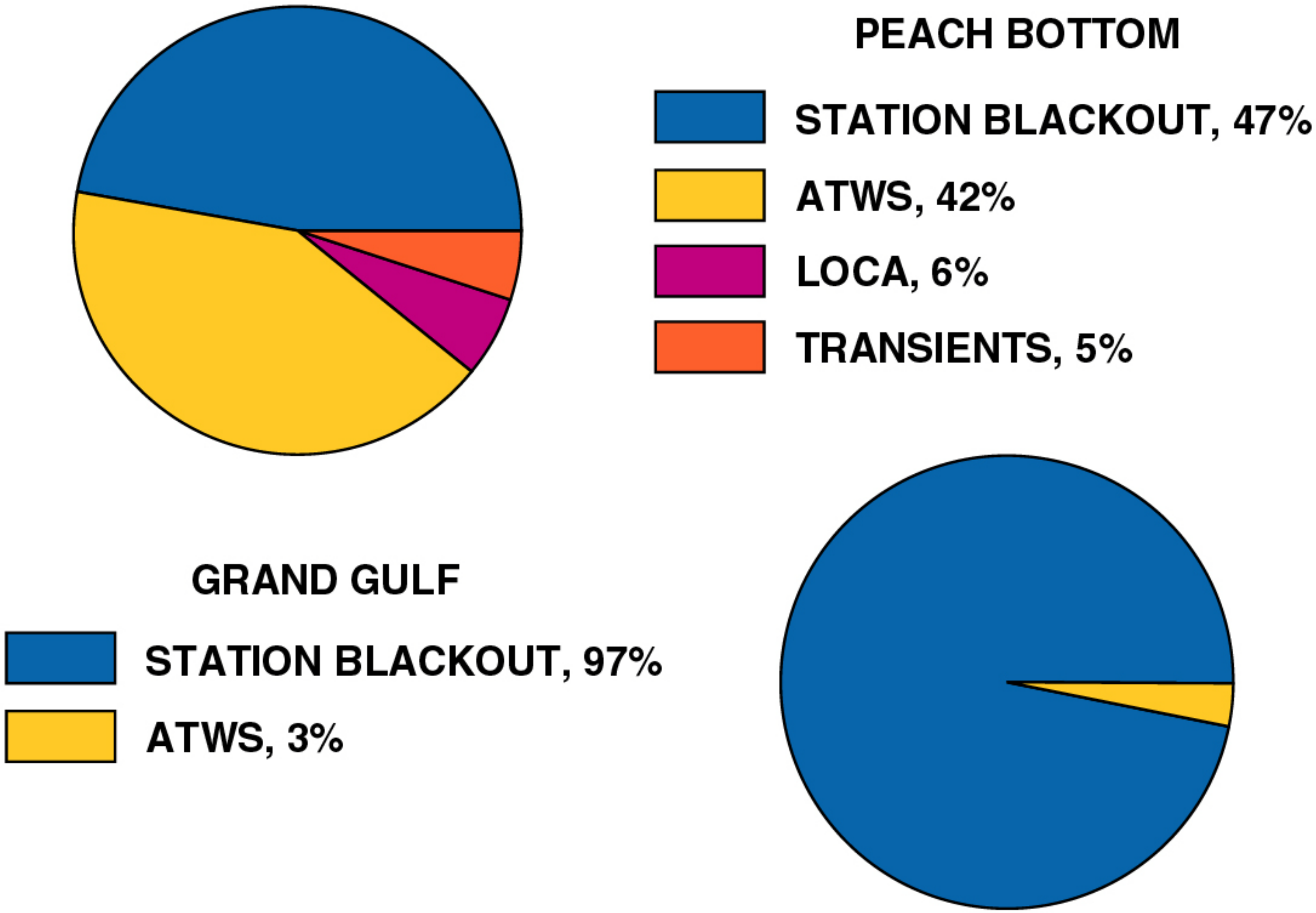


Safety-Related Issues

- Safety approach should evolve to risk-informed regulation
- Command/control of an accident needs to reside as close to the accident location as possible; plant manager on-site needs to retain control to assure safety is ‘main focus’ during any event
- Confirm that plants have consistent and appropriate design base for natural disasters (reassess on a periodic basis w/ new info)
- Cope with a station blackout with a plan for longer periods (flexible approach: automatic systems, on-site actions, off-site aid)
  - Protection of DC batteries and switchgear from natural disasters
  - Ability to reroute water sources with robust steam-driven pumps
  - Logistically position fuel, generators and pumps to move onto plant site

Boiling Water Reactor Contributors to Core Damage Frequency – NUREG-1150



Safety-Related Issues (cont.)

- Modifications after 9/11 could be used as reliable safety systems
- Consider specific hardware changes that have safety benefit (e.g., reliable and uniform system for containment venting)
- Spent fuel cooling was maintained but uncertainty suggests that better instrumentation and assured cooling water refill needed
- Review Emergency Operating Procedures that stabilize plant condition and allow progression to low pressure and temps
- EP decisions in Japan were puzzling - need more clarity wrt risk
- ANS needs to develop a nuclear event communication plan
- Int'l groups need to help develop regulatory structure in emerging countries be made to conform to international standards

International Impact of Fukushima

- Japan is reorganizing its regulatory structure
  - Current nuclear plants likely to restart (case-by-case, not F1)
  - Future plants are deferred until Gov't Commission study
- Germany will be closing current plants early (by 2022)
- Switzerland will revisit new plant construction
- China and India will slow its construction schedule
- Other international plans have not been altered
- IAEA is strongly focused on international safety standards and improving safety review

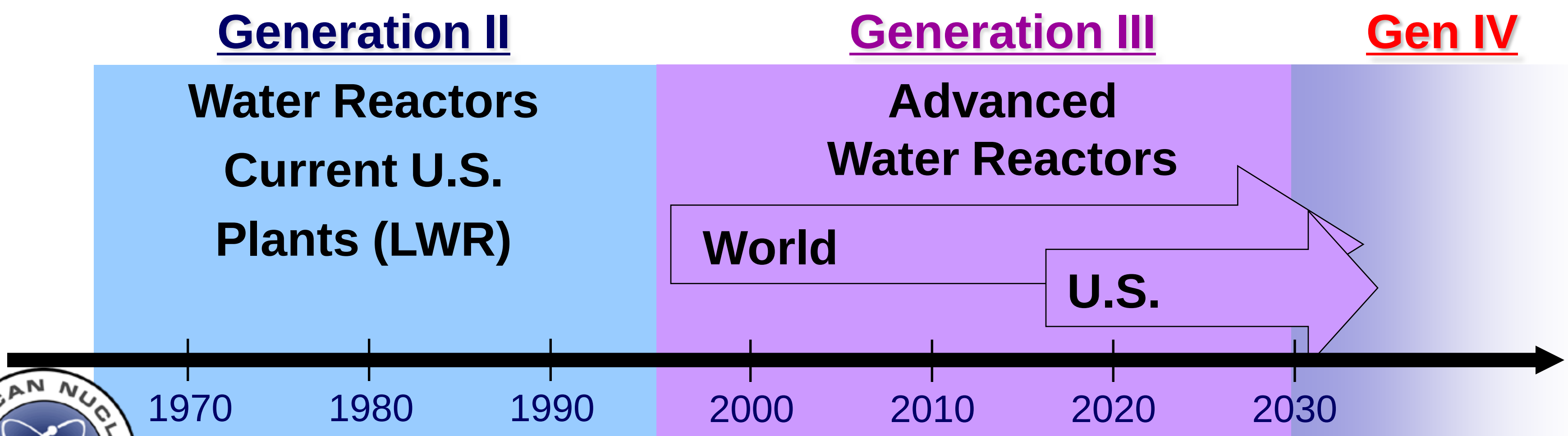
Status of Nuclear Power

Currently all operating U.S reactors [104 + 1 (WattsB)] are Generation II
(70 plants with 20 yr license extension, 14 in queue, 16 planned)
(Power Uprates: 5.7GWe approved + ~4GWe planned)

Currently there are >400 operating reactors worldwide (80% LWR's)

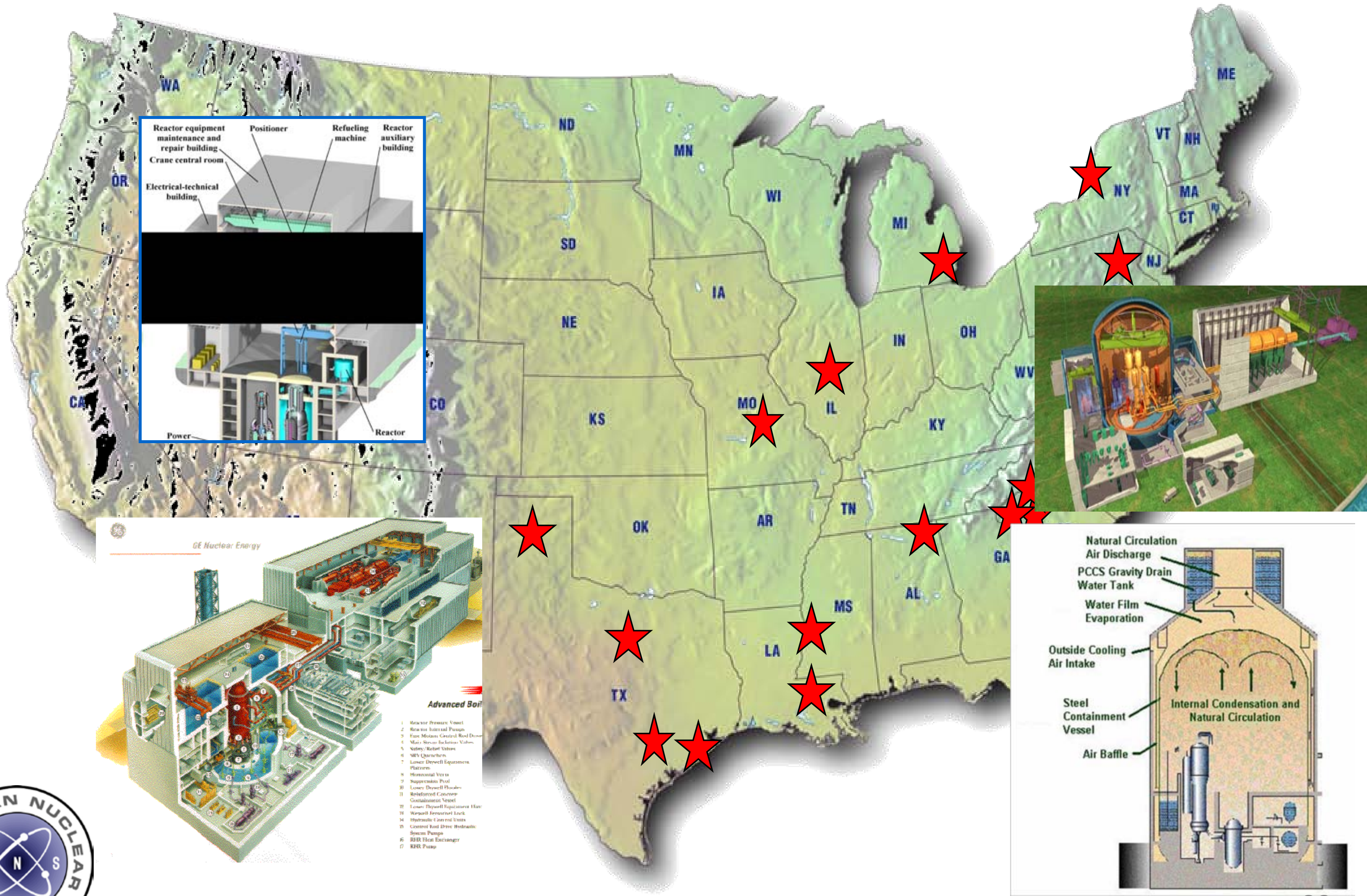
Generation III+: Design changes for improved safety and lower cost
US: 30 proposed, 24 applications received and 4-6 proceeding [1]
World: 12 operating, 63 under construction, >100 planned [2]

GenIV will only occur through GenIII+ and only if GenII are reliable

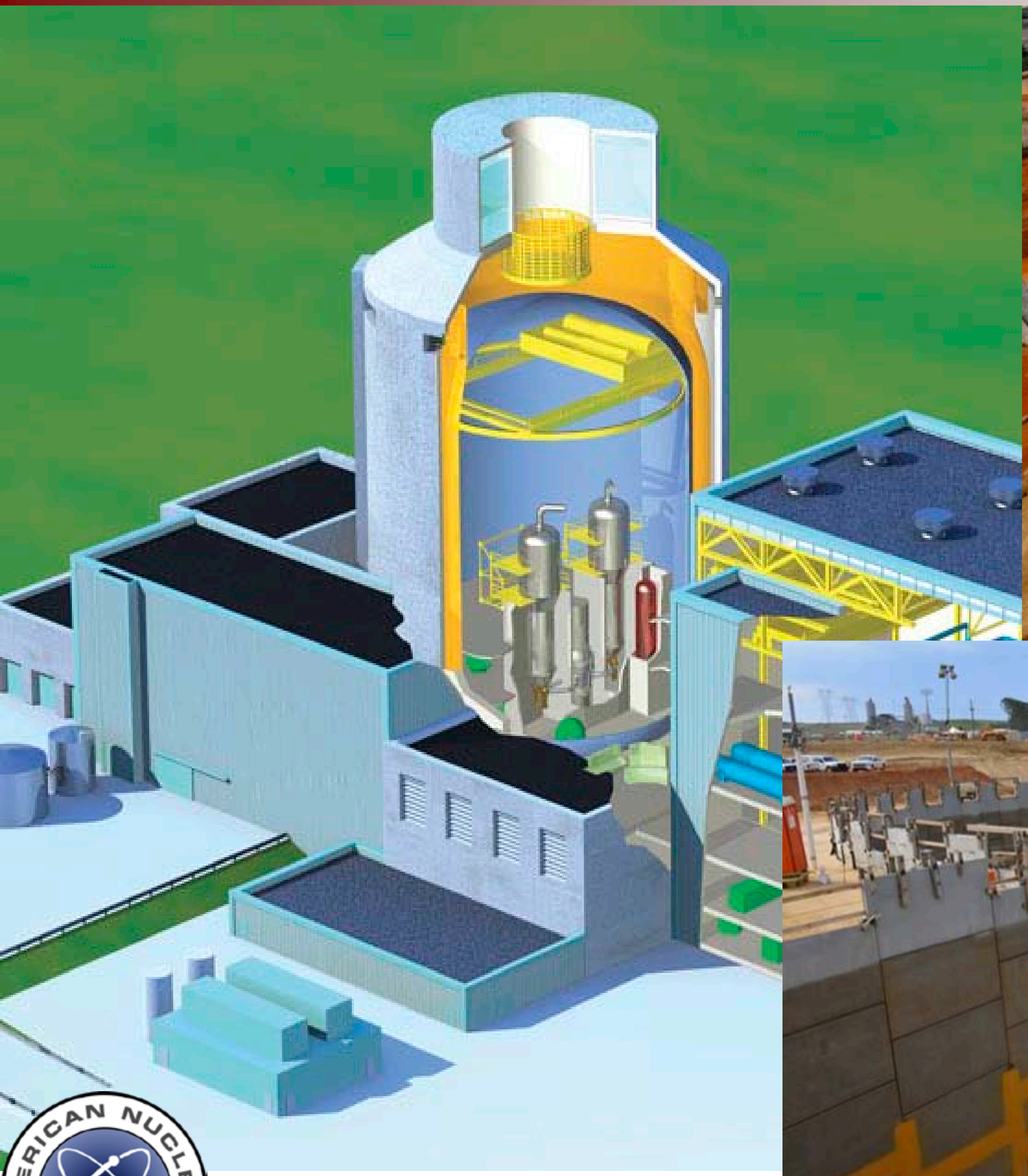


[1] NRC: 2011 [2] IAEA: 2011

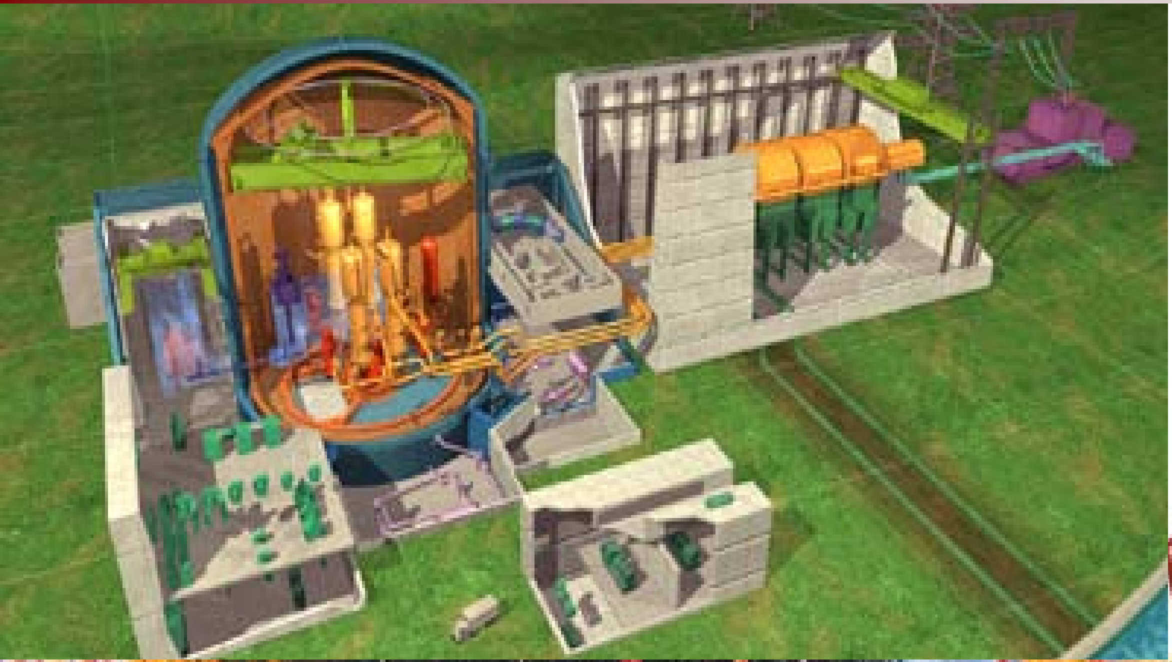
Locations for Advanced Nuclear Plants



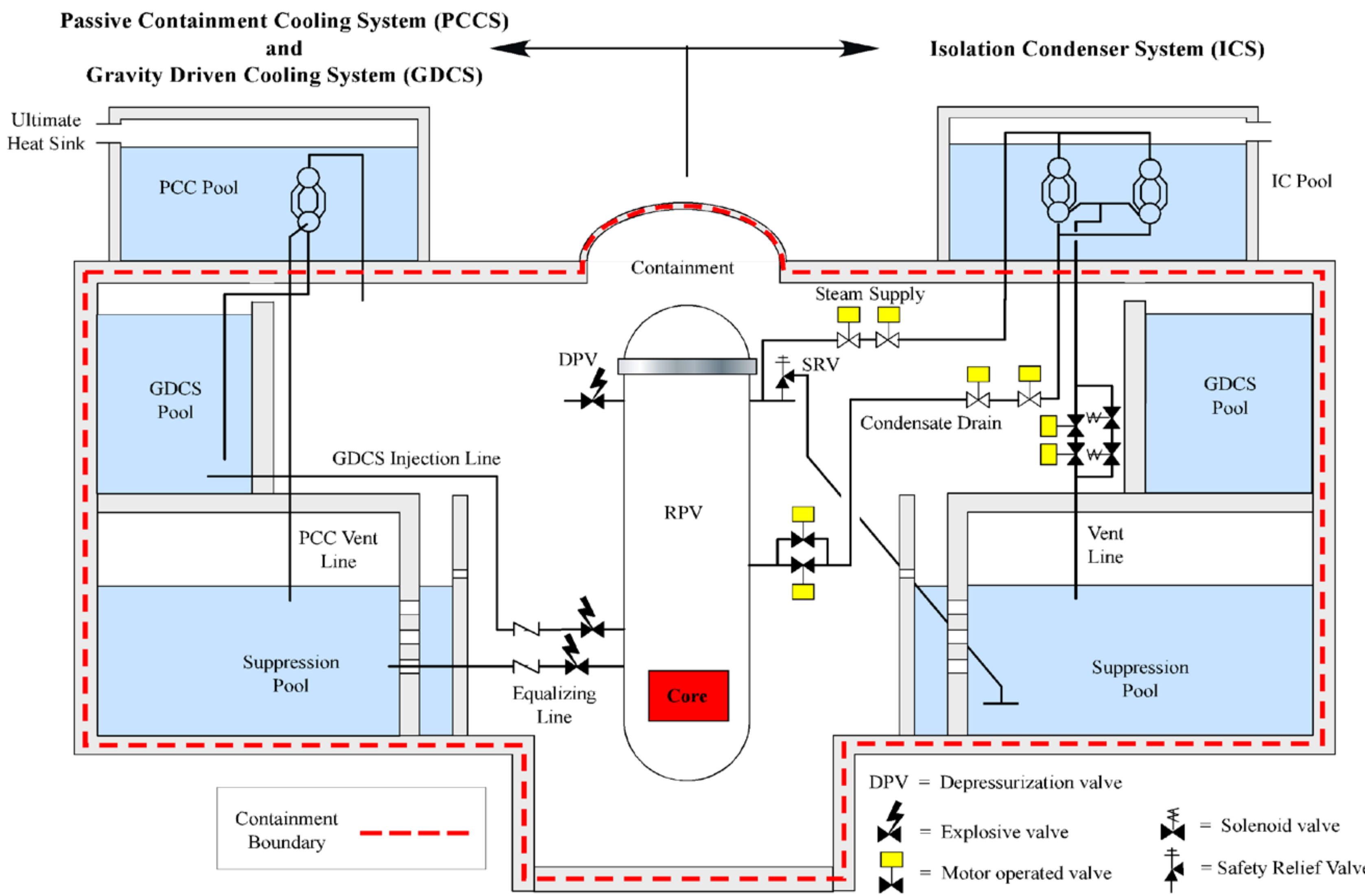
Westinghouse AP1000 Reactor



Advanced LWR: EPR



General Electric – Hitachi ESBWR Plant

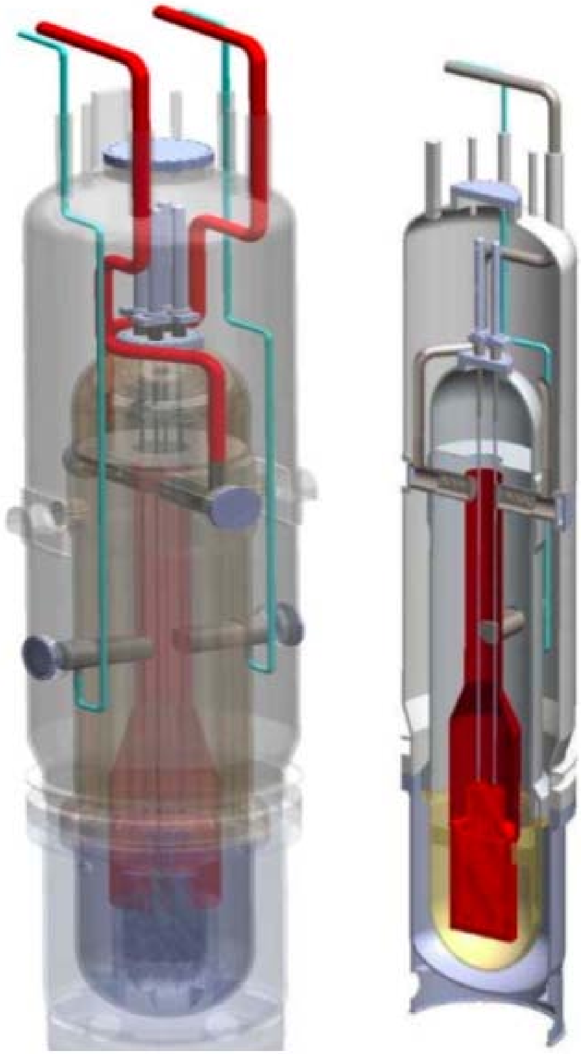


Summary Table of Modular Reactor Concepts

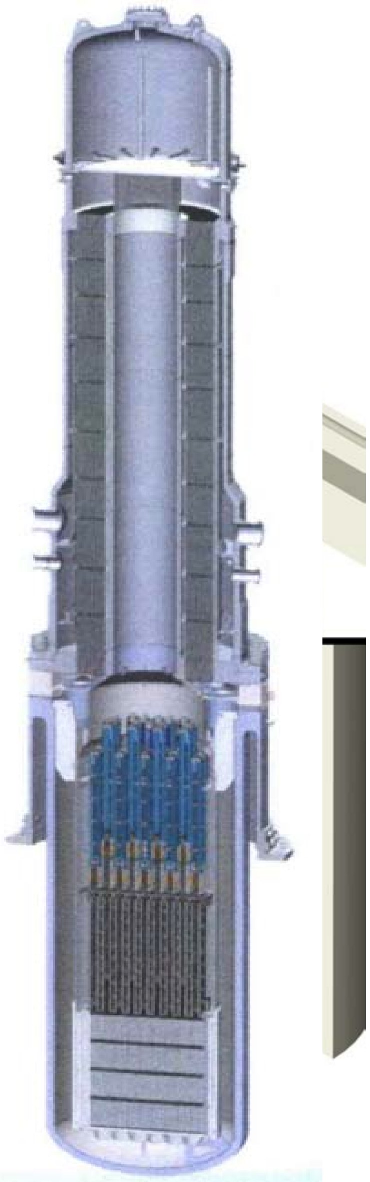
Name/ TYPE	(MWe)	Vendor	Design Feature
PWR (IRIS)	<200	Westinghouse - Toshiba	Integral SG; refuel 5 yrs
NuScale / PWR	45	NuScale Power, Inc.	Modular; integral SGs; refuel 5 yrs; store SF
m-Power / LWR	125	Babcock & Wilcox	Modular, integral SGs; refuel 5 yrs; store SF
NGNP / Gas (Next Generation N-Plant)	200	DOE Design Competition GA, AREVA, West.	Modular; demo hi-temp hydrogen production
PRISM / Liquid Metal (Power Rx Inherently Safe Module)	<200	General Electric - Hitachi	Modular; integral SGs; pool type; U-Pu-Zr fuel
4S / Liquid Metal (Super safe, small & simple)	10-50	Toshiba - Westinghouse	Remote locations; 30 yr refuel; U-Zr fuel
Hyperion	25	Hyperion Power Generation (LANL concept)	Modular; U-hydride fuel; K-heat pipes PCS
Traveling-Wave / LMR	> 200	TerraPower, LLC	Pool-type LMR;U-238 or DU =>breed/burn

Modular Advanced Reactor Designs

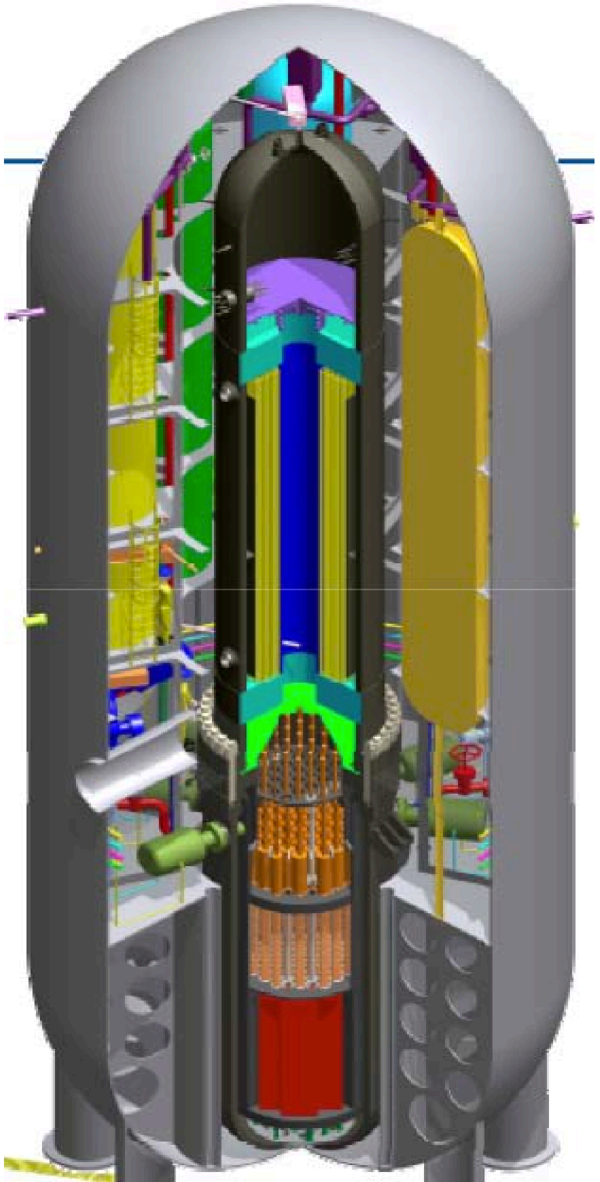
NuScale PWR



mPower-PWR



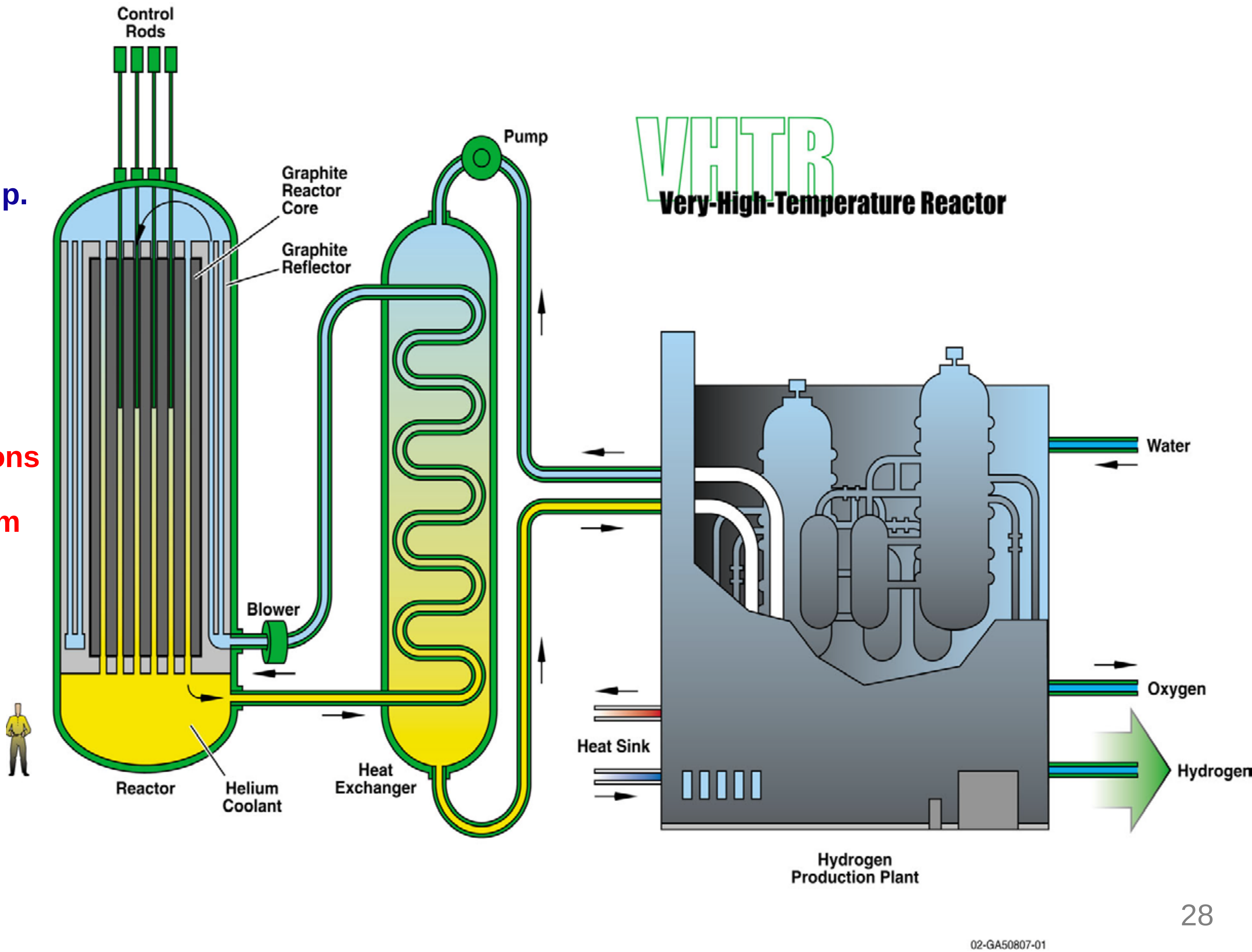
Westinghouse PWR



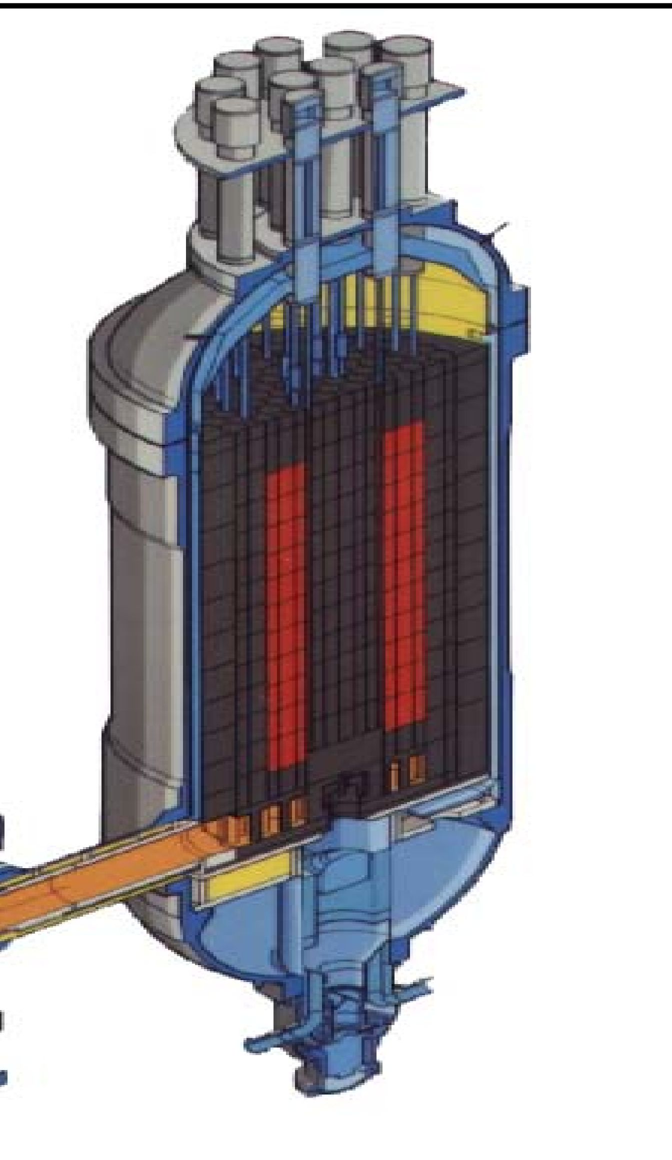
Hi-Temperature Gas-cooled Reactor (VHTR)

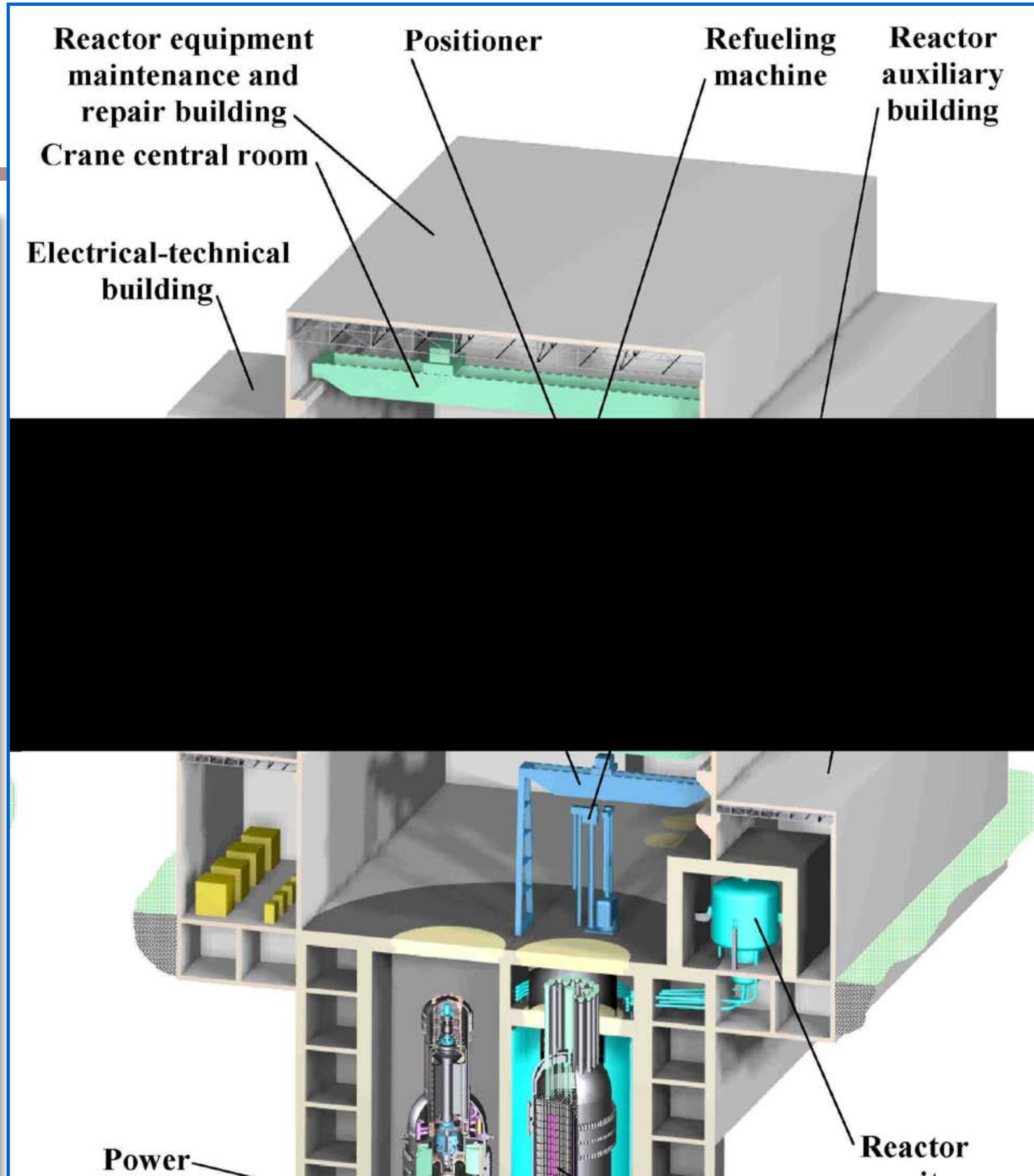
- Characteristics
  - Helium coolant
  - 1000°C outlet temp.
  - 200 - 600 MWth

- Key Benefits
  - High thermal efficiency
  - Process heat for various applications with novel power conversion system

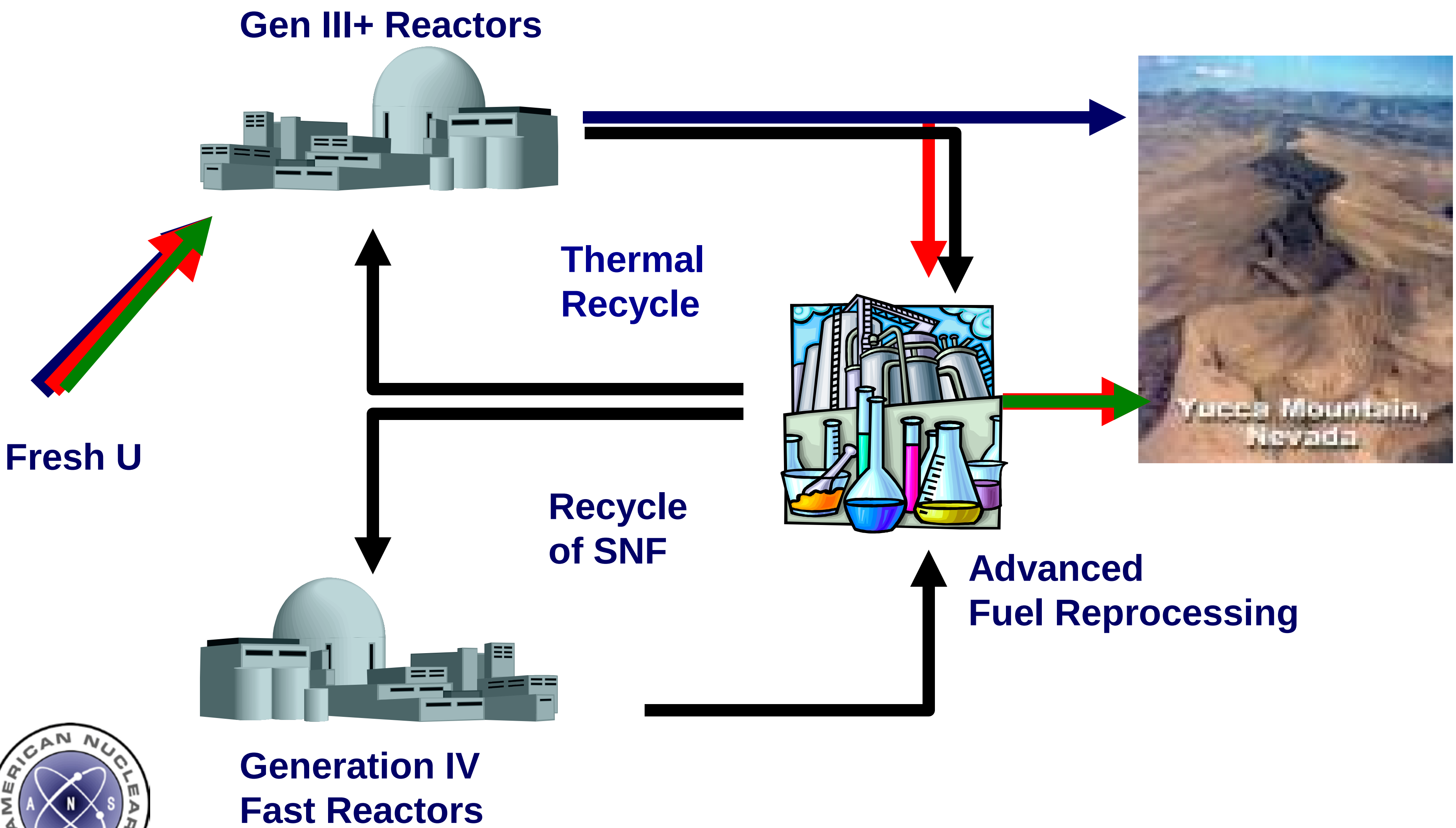


Gas-Cooled Reactor

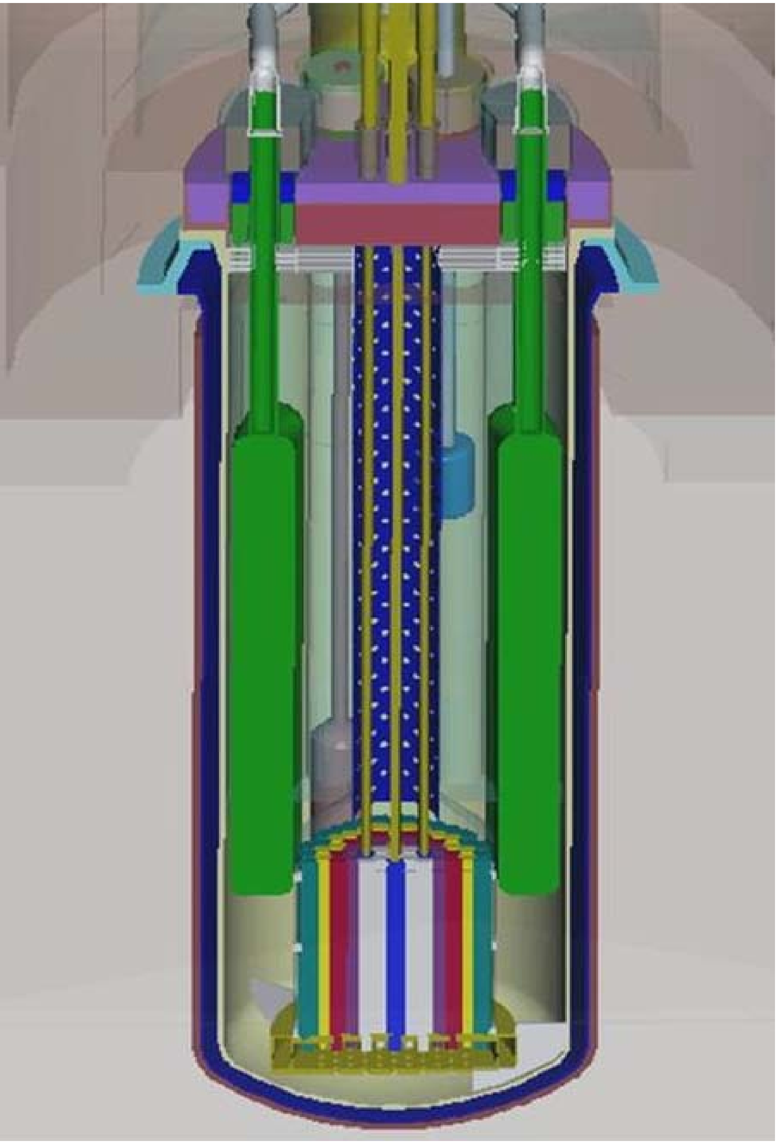




Advanced fuel cycles with Fast Reactor



GENIV: Sodium-cooled Fast Burner



- Basic viability of sodium-cooled fast reactor technology has been demonstrated
- Low pressure primary coolant (T_{max}= 550C)
- Pool configuration
  - Pumps and heat exchangers contained
- Heat exchanged to secondary coolant for energy conversion system
  - Rankine steam (SC) or SC-CO_2 Brayton
- High power density core
  - 250 kW/l (vs. 75 kW/l for LWR)
  - Higher fuel enrichment (~20% fissile)
- Passive decay heat removal
  - Either from pool heat exchangers or air cooling of reactor vessel
- Passive safety behavior to transients

Societal Energy Policy Questions

- What is the level of residual risk from energy technologies that the public is willing to accept
  - Nuclear power: public health risk vs. environmental impact
  - Coal: free-release of emissions that are not monetized
  - Natural gas: short-term panacea that is highly volatile
  - Oil: highly volatile => can biomass add a buffer
  - Opportunity cost of renewables is hidden in REP
  - Electricity transmission & storage is a major issue
  - Current recession has taken energy landscape back to the late 20^{th} century by demand and business practices
  - There is no unifying plan or even a discussion of a plan

ANS Public Outreach

- Imagine a world where people have “perfect information” about the risks and benefits of nuclear technology…
  - How would we use nuclear technology differently? (electricity, transport, process heat, irradiation, medical isotopes)
  - Would our industry be more competitive globally? How many jobs could we create? Would we be safer, more prosperous?

- The Nuclear “Conundrum”
  - Despite resilient public support in the wake of Fukushima, there remains an unease about all things nuclear.
  - Nuclear/radiation pushes many of our “fear buttons”
    - can’t be detected by senses or cause ‘immediate’ death
    - is “man made” and controlled by large entities
  - These fears may not be rational => human systems need to consider
  - Nuclear technology costs more and is utilized less than it might, while often externalities of “conventional” technologies are ‘overlooked’

ANS Public Outreach

- How do we move forward? Improve “nuclear literacy”
  - –ANS will focus on 4 key groups: school-age children; the general public; the media, and policymakers
  - –Public relations will not do this => rather, sustained education on the facts

- Why should ANS be a leader in this education effort?
  - –Credibility: The general public has trust in honest discussion of scientists and engineers, but is quite savvy and quick to disregard “industry messaging”
  - –Human Element: With nearly 11,000 members, ANS has strength in numbers to engage in “broad” outreach.

Backup Slides

Accident Description at Fukushima Dai-ichi site

- What happened to the spent fuel pools in each unit?

  From what is known spent fuel pools were not damaged

- Why did other plants survive the earthquake and tsunami?

  Dai-ni plants were in a bay which mitigated the tsunami effects

- What was the command and control structure in Japan as compared to the U.S.? In the U.S. the plant manager on-duty has complete authority during any site emergency

- What were the emergency procedures for the Japanese plants and U.S. differences? As we know the procedures were generally similar for the Japanese plants

Three Mile Island Unit 2 History

- Reactor scram: 04:00 3/28/79
- Core melt and relocation: ~05:00 – 07:30 3/28/79
- Hydrogen deflagration: 13:00 3/28/79
- Recirculation cooling: Late 3/28/79
- Phased water processing: 1979-1993
- Containment venting 43Kci Kr-85: July 1980
- Containment entry: July 1980
- Reactor head removed and core melt found: July 1984
- Start defuel: October 1985
- Shipping spent fuel: 1988-1990
- Finish defuel: January 1990
- Evaporate ~2.8 M gallons processed water: 1991-1993
- Cost: ~$2 billion

Nuclear Safety Regulation System in Japan

Licensee

Application for Establishment Permit

Application →

Regulatory Bodies

Nuclear and Industry Safety Agency (**NISA**) for NPPs

↑ *Technical supports*

Japan Nuclear Energy Safety Organization (**JNES**)

Ministry of Education, Culture, Sports and Science and Technology (**MEXT**) for RRs

Inquiry →

← *Report*

Cabinet Office
Nuclear Safety Commission **(NSC)**

- Secondary Review: "Double check"
- Supervise and audit the regulatory bodies
- Receive and respond to reports on accidents and problems

NISA :

- Issue license for NPPs and related facilities
- Approve construction and suitability of safety program and pre-service inspection
- Conduct periodic inspections of facilities, suitability of safety inspection, emergency preparedness

MEXT :

- The same function as NISA for test and research reactor facilities

JNES :

- Inspection and cross-check analysis, etc. for NPPs
- Investigations and tests to be reflected onto the safety regulations

Subsequent Regulation

(NISA/JNES and MEXT)

Construction phase
Approve design, ---
Operation Phase
Periodic inspections etc
Others
Periodic inspections etc

Periodic Report →

← *Supervise & Audit*

(NSC)
Review subsequent regulation

Major Design Parameters for Fukushima Dai-ichi Units 1-4

	Unit 1	Unit 2	Unit 3	Unit 4
Commercial operation	1971	1974	1976	1978
Reactor design	BWR-3	BWR-4	BWR-4	BWR-4
Rated power (MWe)	460	784	784	784
Thermal power (MWt)	1,380	2,381	2,381	2,381
Isolation cooling system	IC	RCIC	RCIC	RCIC
ECCS configuration	HPCI (1) ADS CS (4)	HPCI (1) ADS CS (2) LPCI (2)	HPCI (1) ADS CS (2) LPCI (2)	HPCI (1) ADS CS (2) LPCI (2)
Primary containment vessel	Mark-I	Mark-I	Mark-I	Mark-I
Operation status at the earthquake occurred	In service ↓ Shutdown	In service ↓ Shutdown	In service ↓ Shutdown	Outage

ECCS: Emergency core cooling system, HPCI: High pressure core injection system, ADS: Automatic depressurization system, CS: Core spray system, LPCI: Low pressure core injection system, IC: Isolation condenser, RCIC: Reactor core isolation cooling system

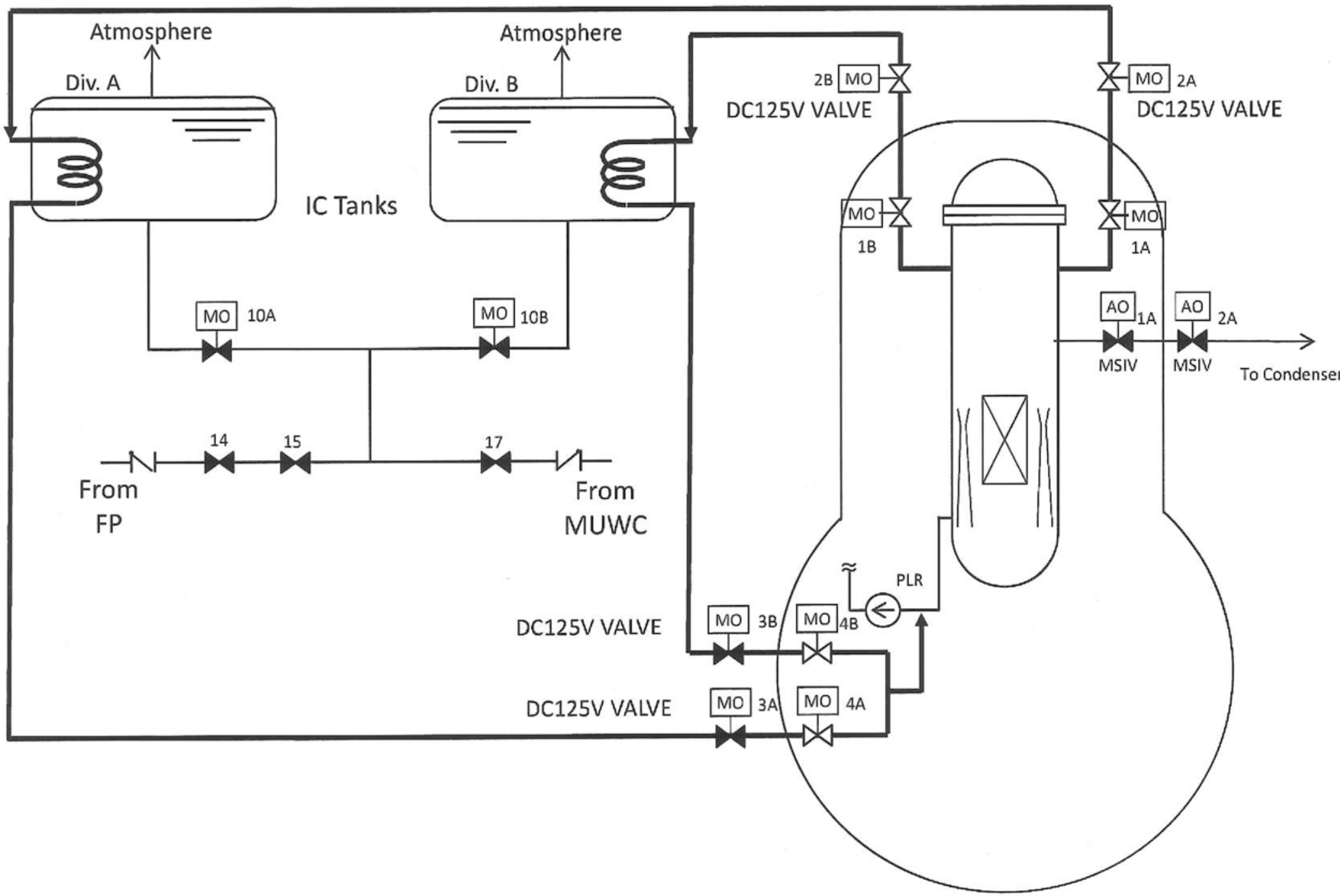
Important Systems Coping with SBO

	Unit 1	Unit 2, 3	Remarks
Number of EDG	2	2	• 1 DG was added to Unit 2, 4, and 6 in 1990s as part of SAMG implementation
DC battery capacity	10 hrs	8 hrs	• Based on SBO coping evaluation (using different system, U1: IC, U2/3: RCIC/HPCI) • Compliant with NSCs regulatory requirement for short term SBO (Guide 27: see below)
Non-AC dependent systems	IC, HPCI	RCIC, HPCI	• Only DC battery power needed to operate
Containment venting	HVS installed	HVS installed	• In 1990s, hardened venting systems were installed in each unit

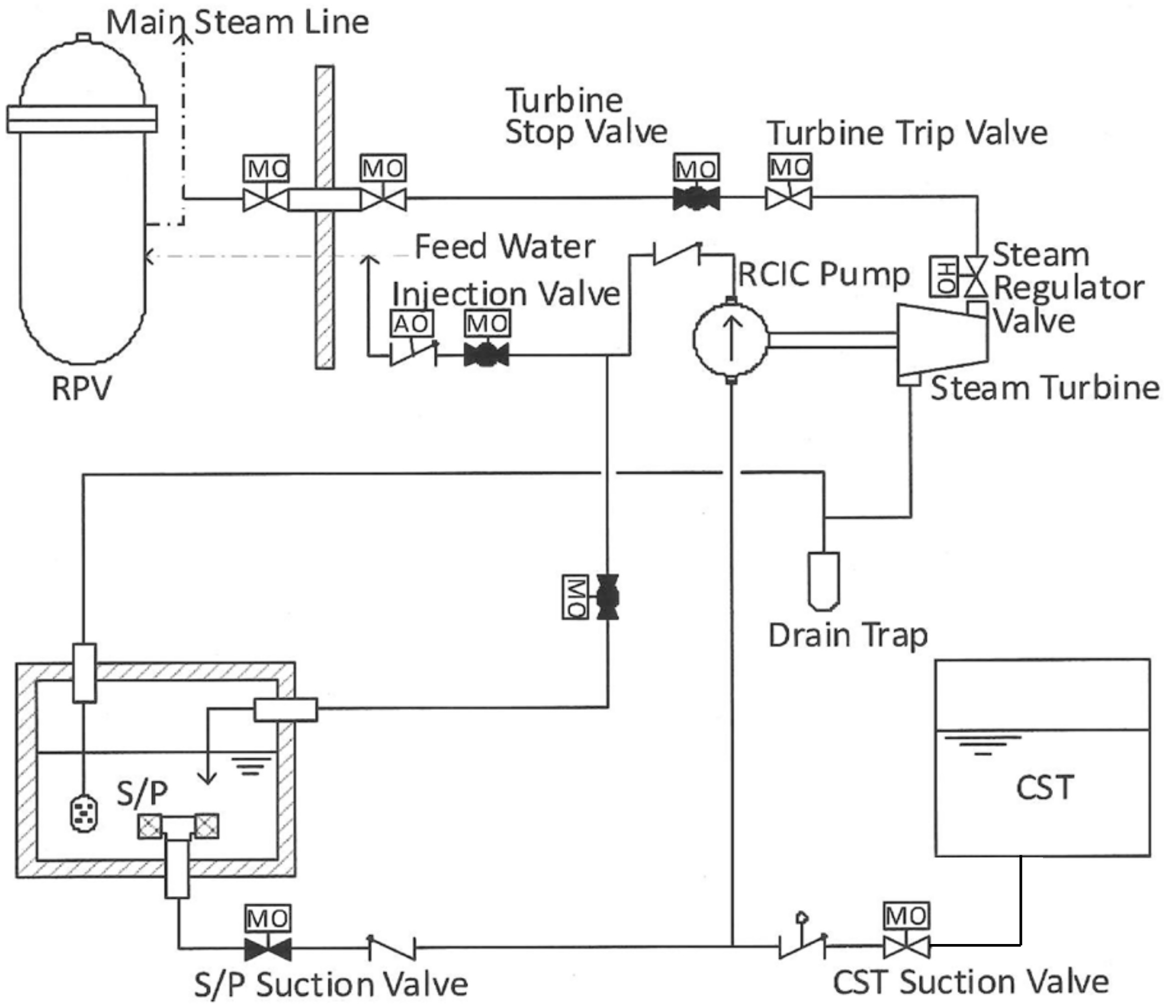
NSC Safety Design Guide 27: Design considerations against loss of power . . . shall be designed that safe shutdown and proper cooling of the reactor after shut-down can be ensured in case of a short term total AC power loss.
Commentary to Guide 27: no particular considerations are necessary against a long-term total AC power loss because of repair of transmission line or emergency power system can be expected in such a case.

HPCI: High pressure core injection system
RCIC: Reactor core isolation cooling system
IC: Isolation condenser
HVS: Hardened venting system

Schematic of Isolation Condenser (Unit 1)



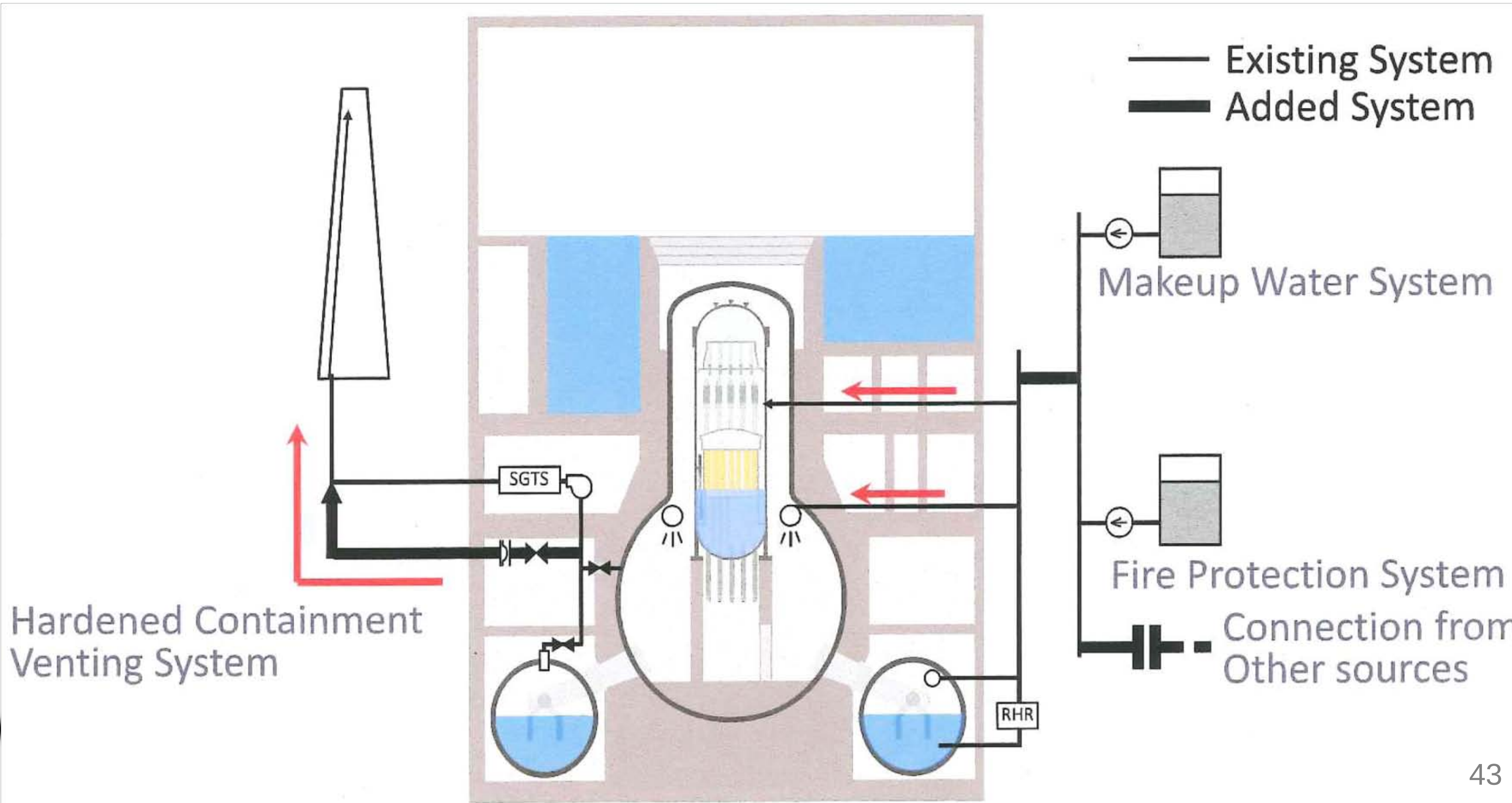
Schematic of RCIC (Units 2 and 3)*



*HPCI (high pressure core injection system) was also available as AC independent system

SA Countermeasures in Fukushima

- Alternative water injection system did provide water into either RPV (or PVC) by using existing systems (RHR/LPCI, MUWC, FP) from several water sources
- Hardened containment venting system from either from wetwell or drywell



Browns Ferry Primary Containment

Fukushima Daiichi Unit 1

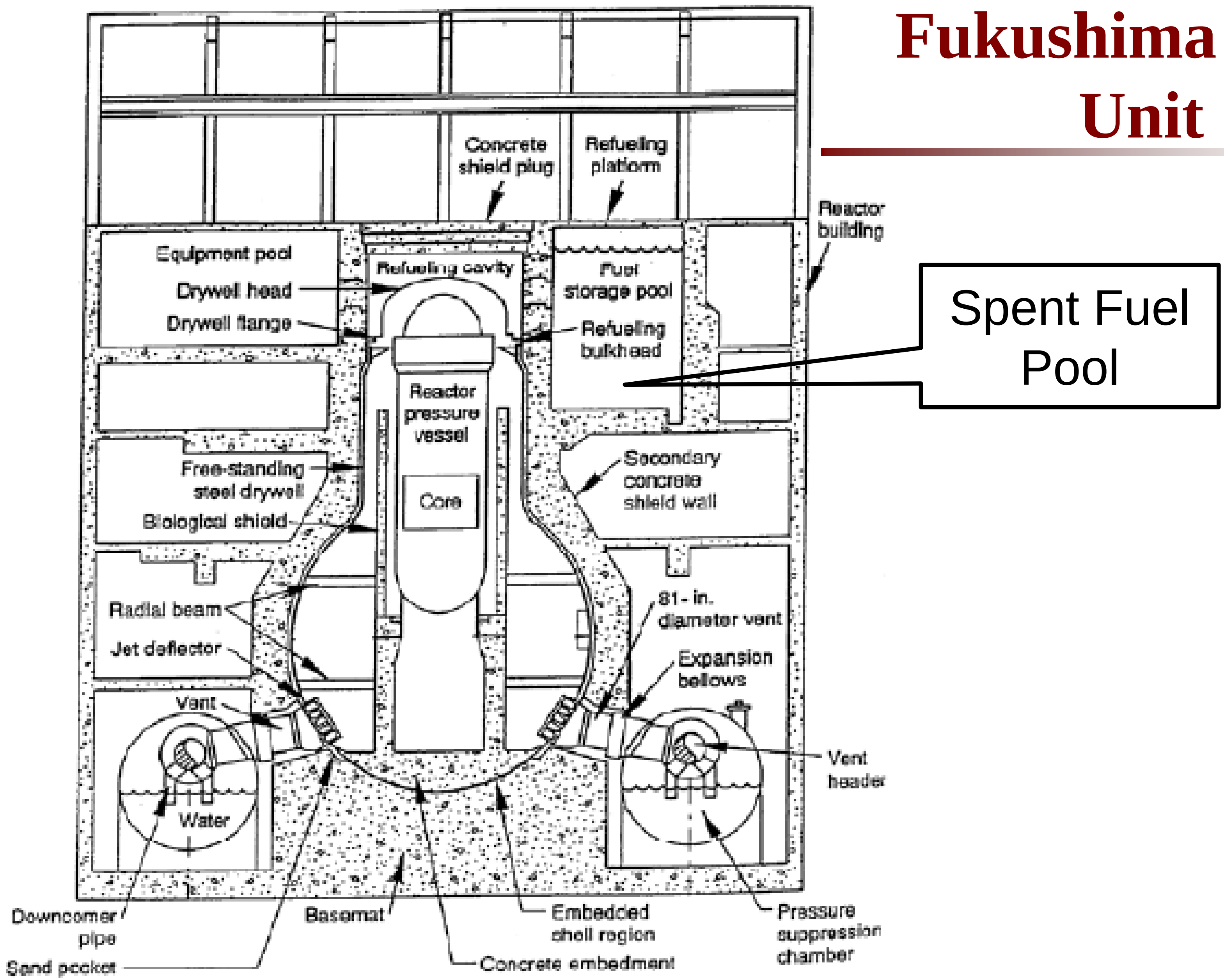
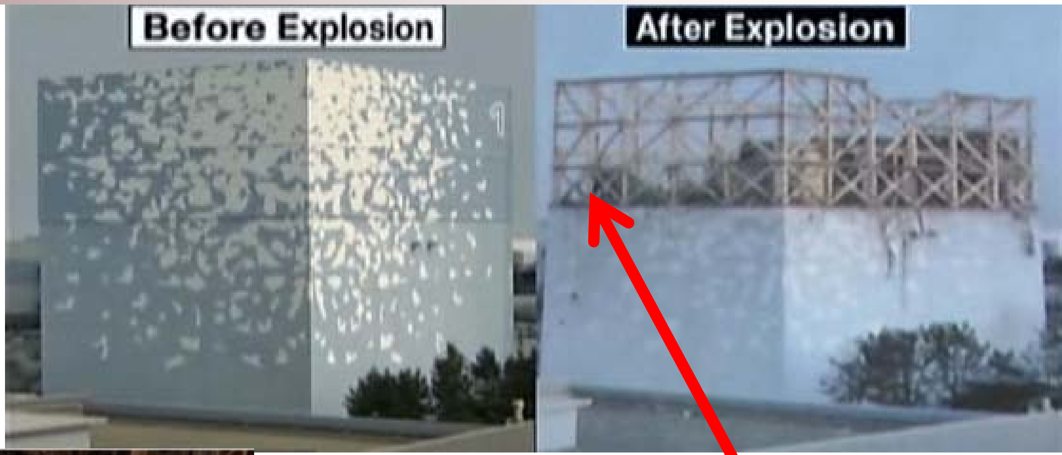


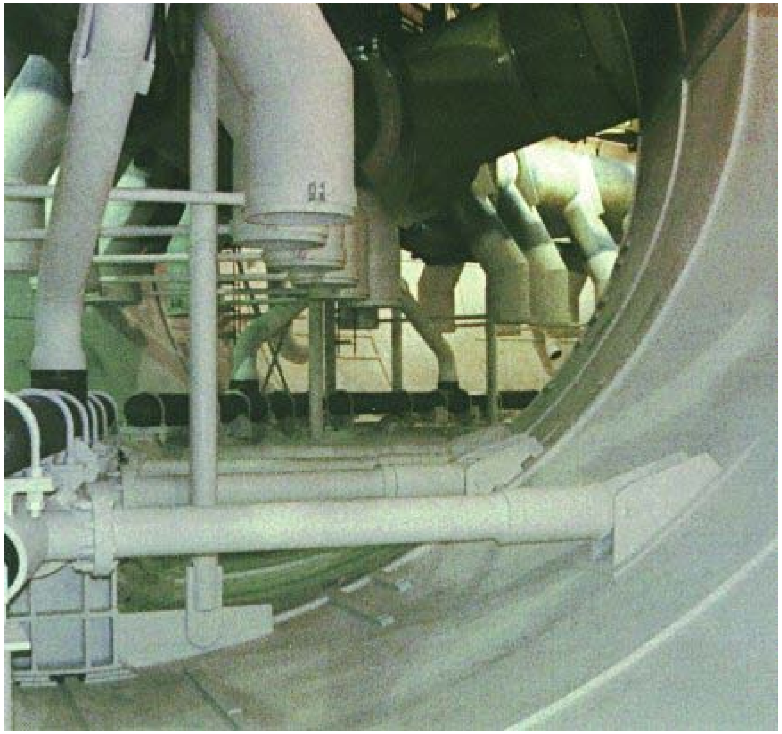
Figure 20. Mark I General Electric,GE BWR Containment.

Hydrogen Explosion in all the Units



Reactor Building

Refuel Floor



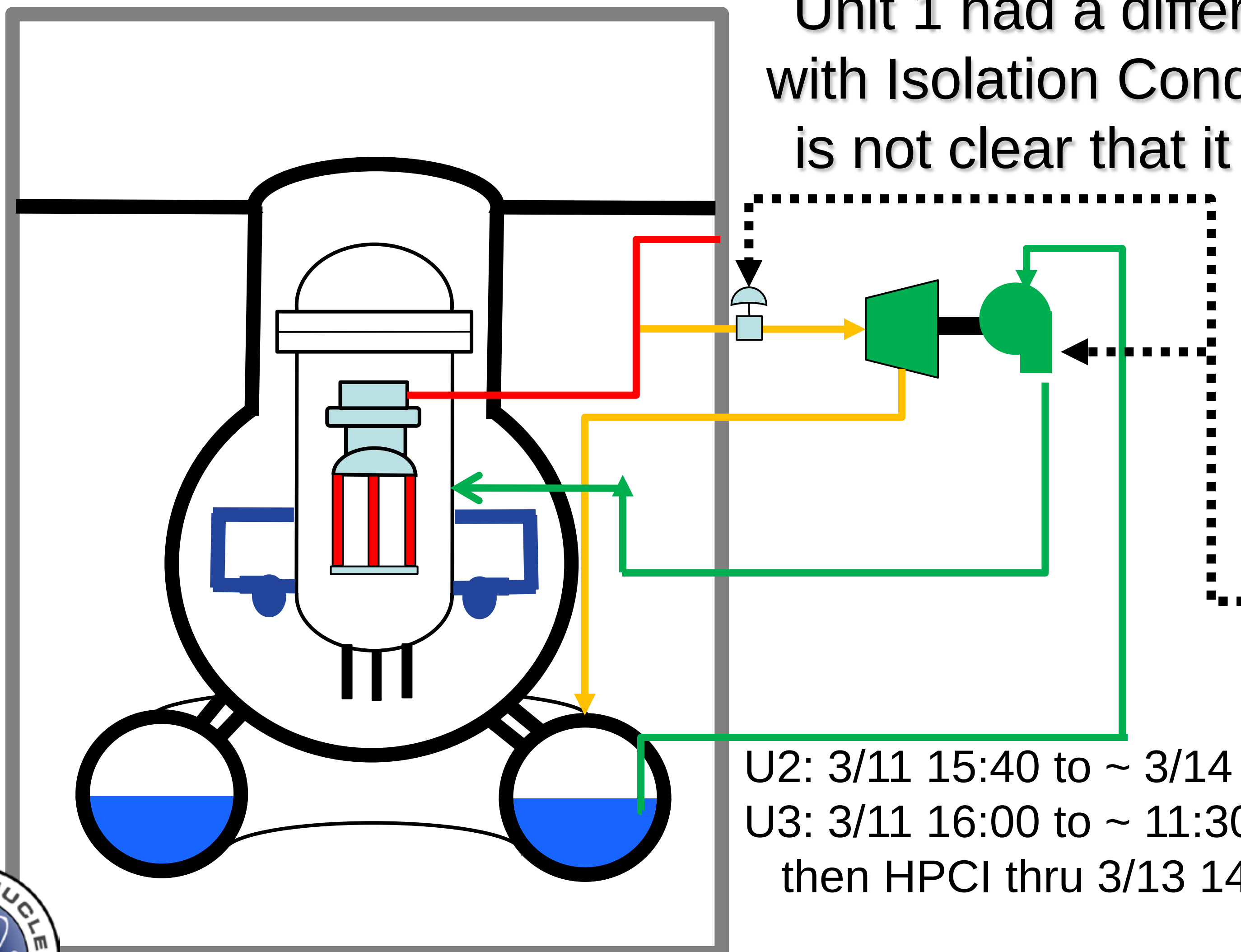
Hydrogen Explosion in all the Units

Hydrogen Explosion

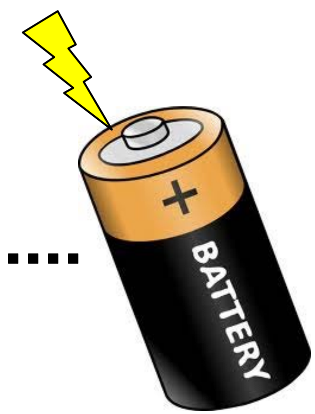
- Unit 1: March 12 15:36 (Reactor Building)
- Unit 2: March 15, 6:00 (Torus?)
- Unit 3: March 14,11:01 (Reactor Building)
- Unit 4: March 15, 6:00 (Reactor Building)

Unit 2 & 3 Battery Power Controlled Steam-Driven Reactor Core Isolation Cooling (RCIC) System

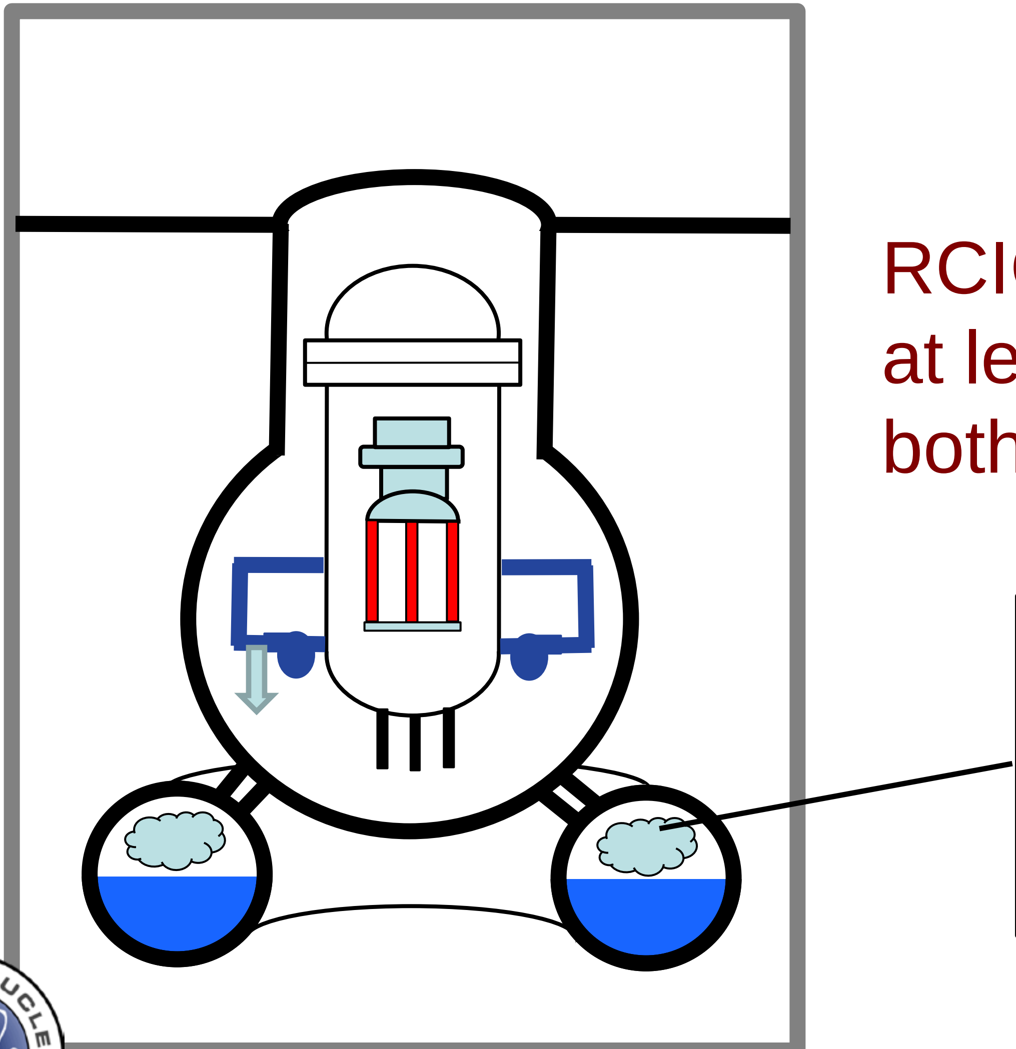
Unit 1 had a different design with Isolation Condenser but it is not clear that it functioned



U2: 3/11 15:40 to ~ 3/14 13:25 JST
U3: 3/11 16:00 to ~ 11:30JST
then HPCI thru 3/13 14:42 JST



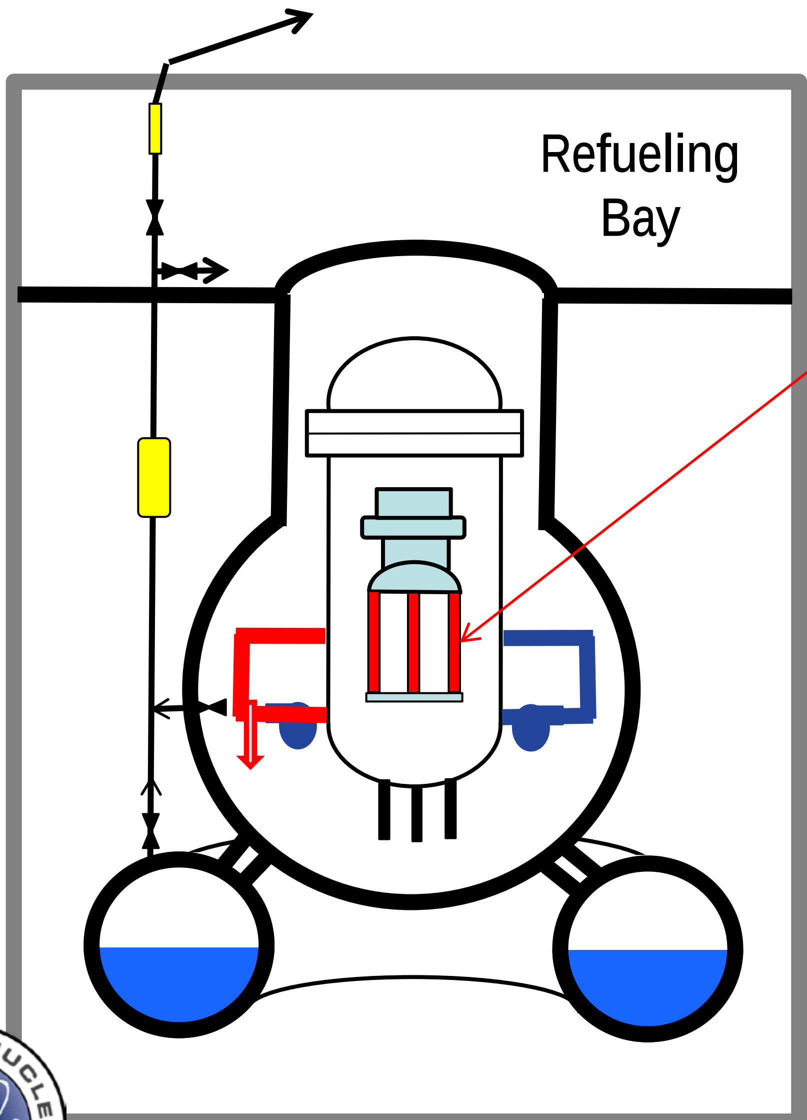
Unit 2 & 3 Battery Power Controlled Steam-Driven Reactor Core Isolation Cooling (RCIC) System



RCIC was operated for at least another day on both units

Suppression pool (wet well) becomes saturated and cooling degraded

Venting Primary Containment



Reactor core uncovered, overheated, oxidized and released steam and H_2 to the containment (DW, WW)

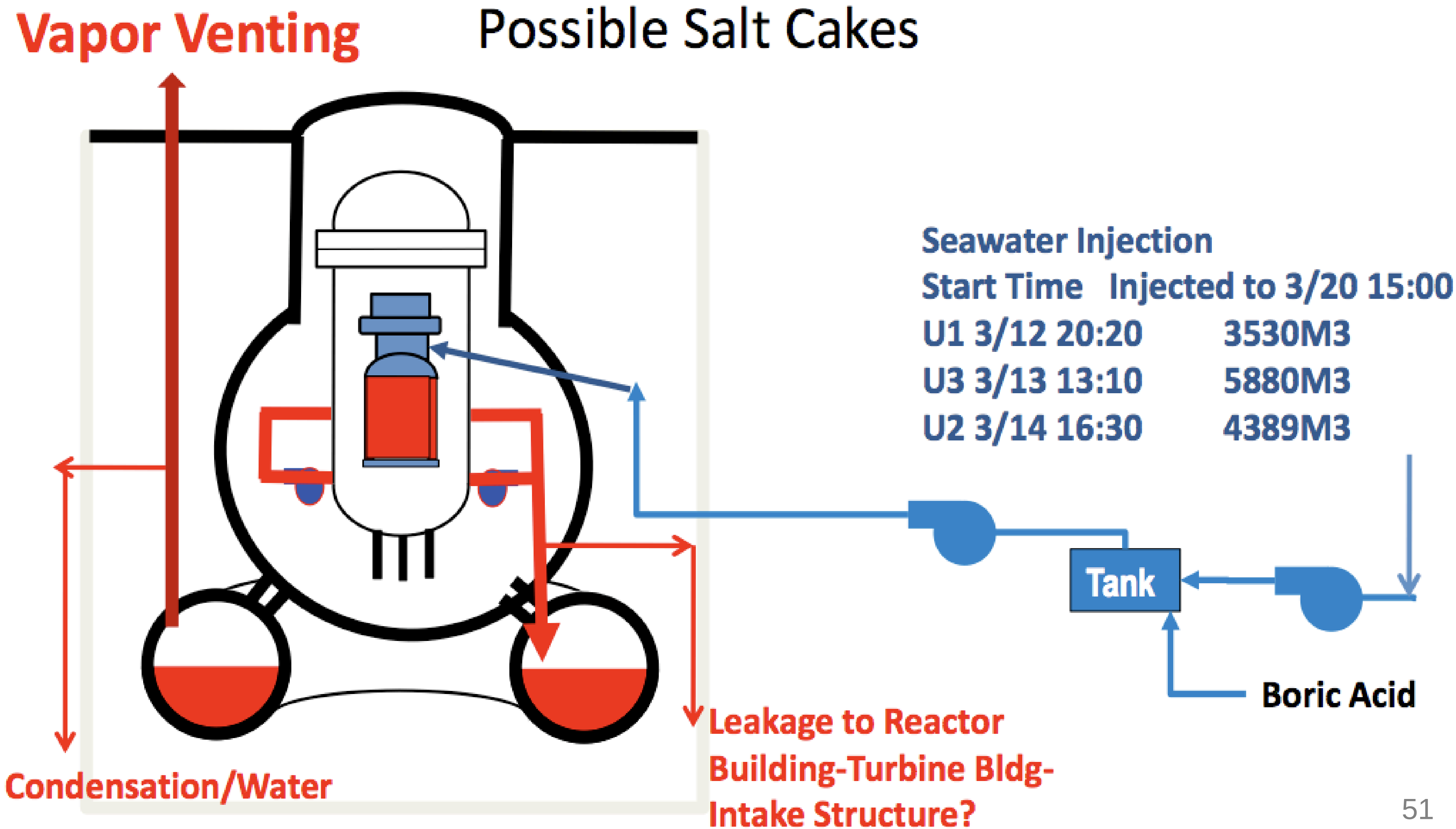
Primary Containment
Pressures were above 100psi

3/12 ~ 14:30 U1 attempted
3/13 ~ U2 is not clear
3/13 ~ 09:40 U3

Bleed & Feed Cooling Established

Seawater Injection Started Using Fire Engine Pump

Shift to Fresh Water Injection ~3/26-Present:To Dissolve Possible Salt Cakes



Predicted BWR Severe Accident Response Is Different from that Expected of a PWR in Several Aspects

- More zirconium metal
- Isolated reactor vessel
- Reduction in power factor in the outer core region
- Consider effects of safety relief valve actuations
- Progressive relocation of core structures
- Importance of core plate boundary
- Steel structures in vessel
- Large amount of water in vessel lower plenum

Fukushima Lessons-Learned

Issues That Require More Physical Insight:

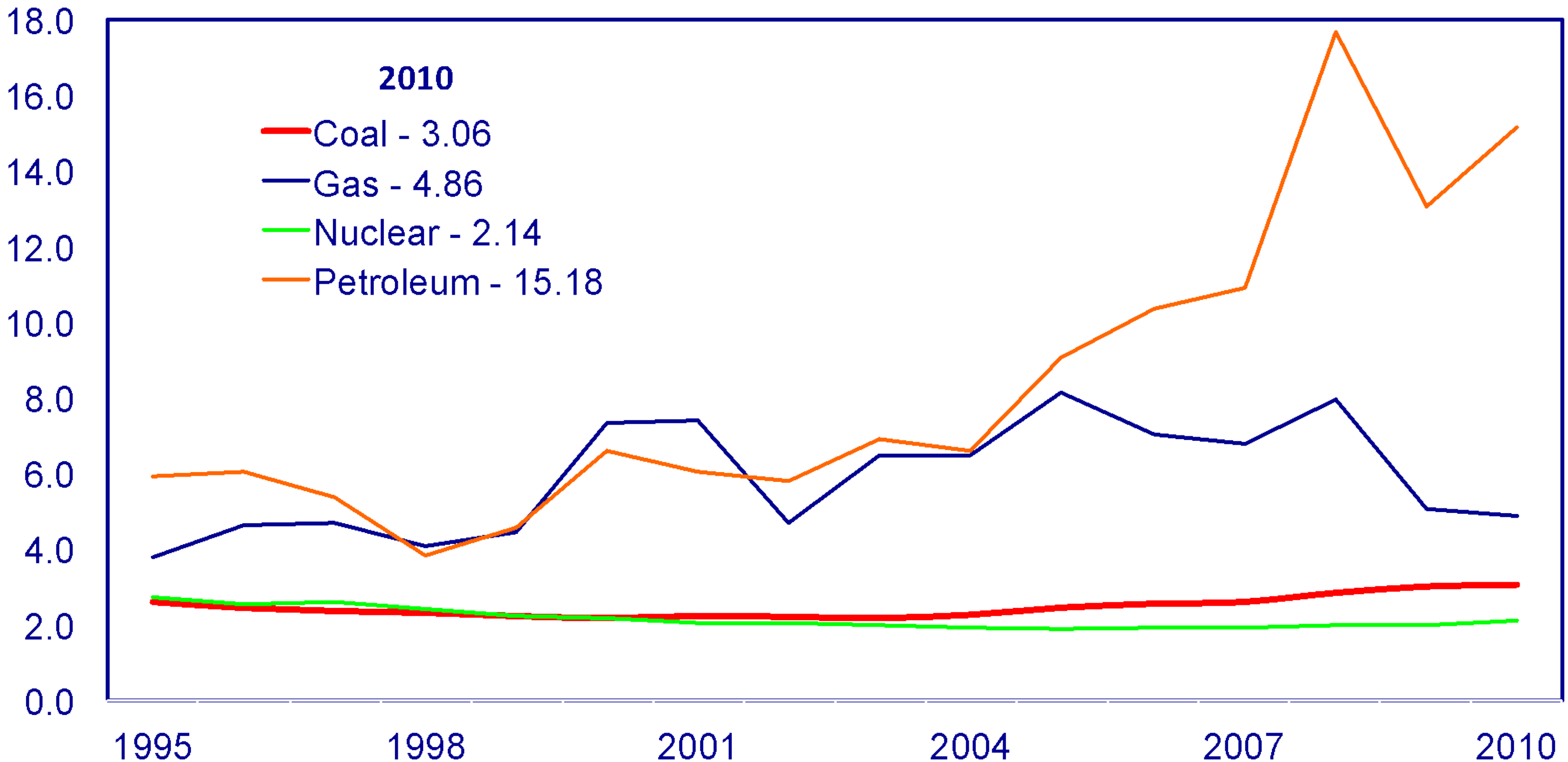
- •Hydrogen transport and mixing in reactor containment compartments as well as H2 mixing/recombination
- •Effect of ‘raw’ water addition and salt accumulation to in-vessel cooling, accident progression, source term
- •In-vessel retention in BWR core geometries
- •Ex-vessel coolability in containment reactor cavity
- •Innovative passive long-term decay heat removal
- •Instrumentation for better TH understanding

Accident Description at Fukushima Daiichi

- Discuss accident sequence for Units at Fukushima Daiichi?
- What happened to the spent fuel pools in each unit?
- Why did other plants survive the earthquake and tsunami?
- What was the command and control structure in Japan as compared to the U.S.?
- What were the emergency procedures for the Japanese plants and how are they different within U.S.?

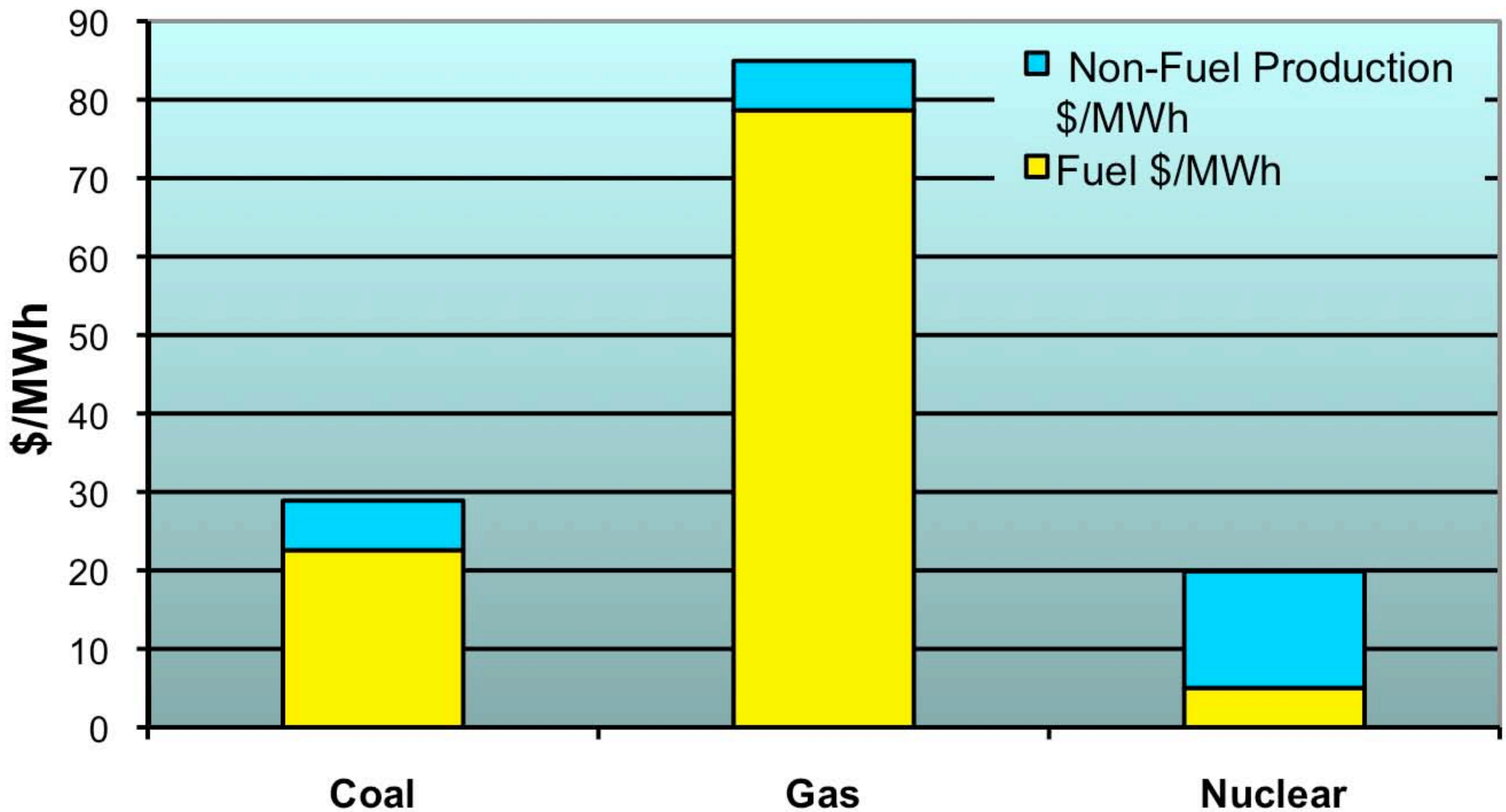
U.S. Electricity Production Costs

1995-2010, ***In 2010 cents per kilowatt-hour***



Production Costs = Operations and Maintenance Costs + Fuel Costs. Production costs do not include indirect costs and are based on FERC Form 1 filings submitted by regulated utilities. Production costs are modeled for utilities that are not regulated. Updated: 5/11

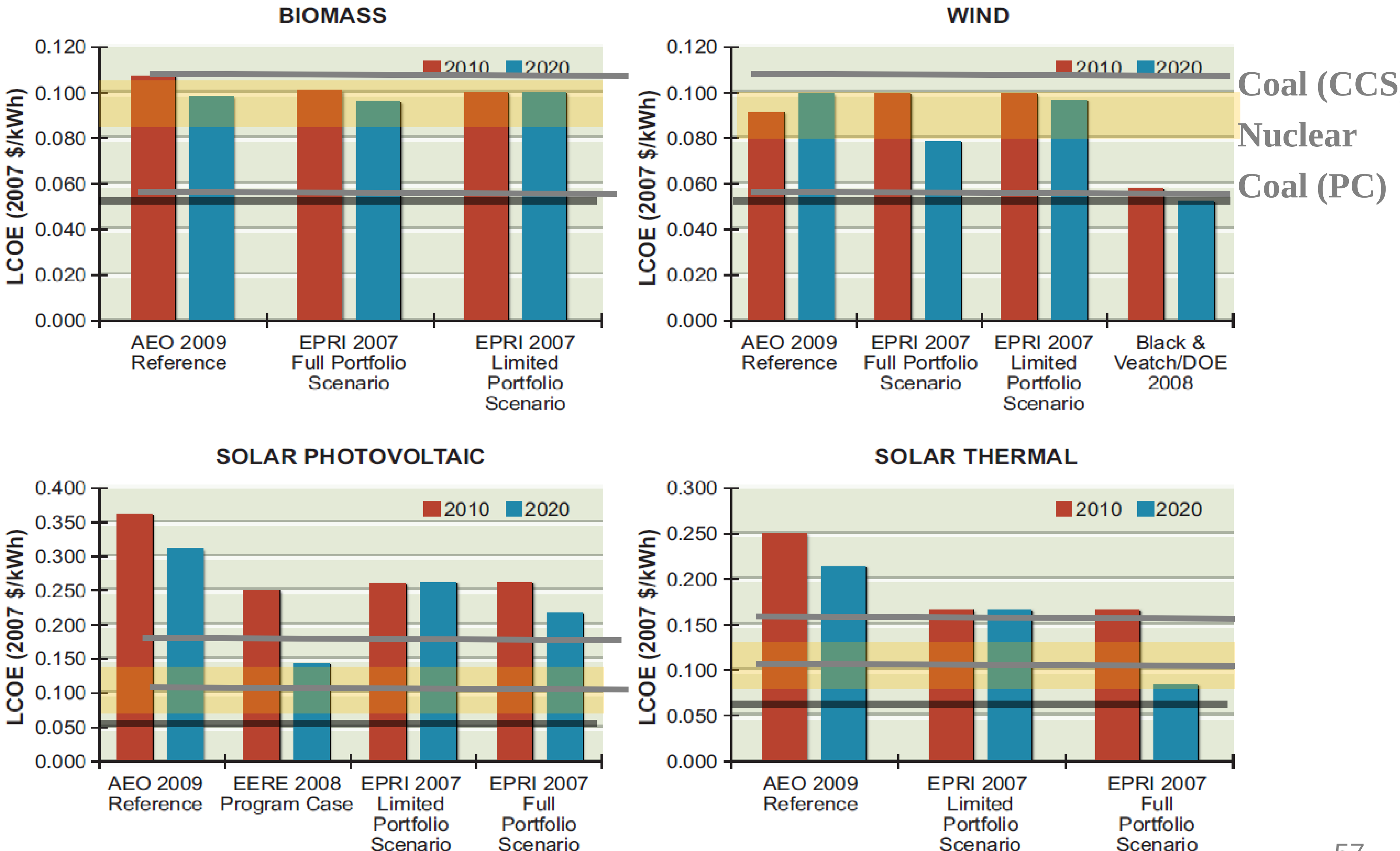
Nuclear is the Most Economical Option



2009 Production Costs

Levelized Cost of Electricity (¢/kWhr)

*** 2010: J. Davidson, Univ. Minn.**



1000 Mwe-yr Power Plant Emissions

	COAL	GAS	NUCLEAR
Sulfur-oxide	~ 1000 mt		
Nitrous-oxide	~ 5000 mt	400 mt	
Particulates	~ 1400 mt		
Ash (solids)	~ 1 million mt		
CO_2	> 7 million mt	3.5mill. mt	
Trace elements	> 0.1mt**		< 1 kg
Spent Fuel			20-30 mt
Fission Products			~1 mt

** Volatilized heavy metals: e.g., Mercury, Lead, Cadmium, Arsenic

Life-cycle Emissions