The Future of Nuclear Power after Fukushima

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TECHNOLOGY • RESOURCES • SUSTAINABILITY

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
Jacopo Buongiorno, Massachusetts Institute of Technology
Hisashi Ninokata, Tokyo Institute of Technology
Mike Ryan, M.T. Ryan and Associates LLC
Craig D. Sawyer, Retired Senior Engineer
Amir Shahkarami, Exelon Nuclear
Akira Tokuhiro, University of Idaho

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 the 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

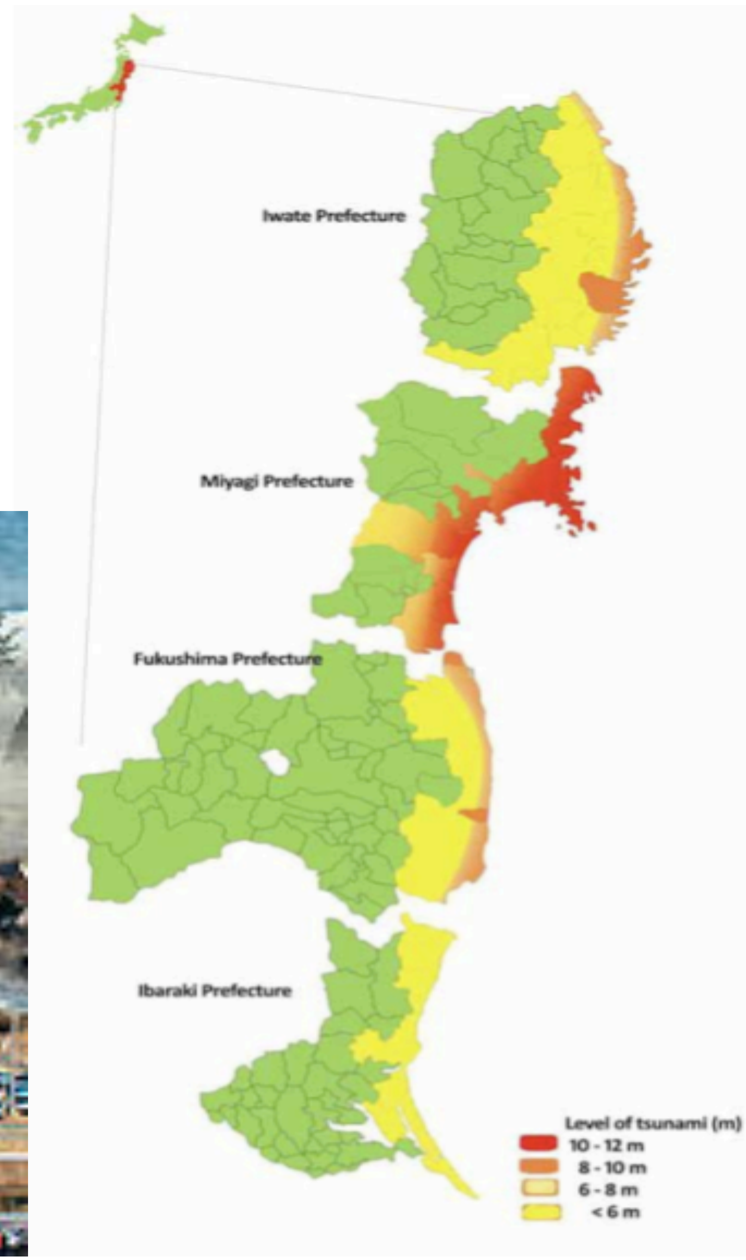
- The Fukushima nuclear facilities were damaged in a magnitude 9 earthquake on March 11 (2.46pm JST), centered offshore of Sendai region (Tokyo 250km SW).
  - Plant designed for magnitude 8.2 earthquake. A magnitude ~9 quake is much greater in size.
- Serious secondary effects followed including a significantly 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 ‘unforseen’

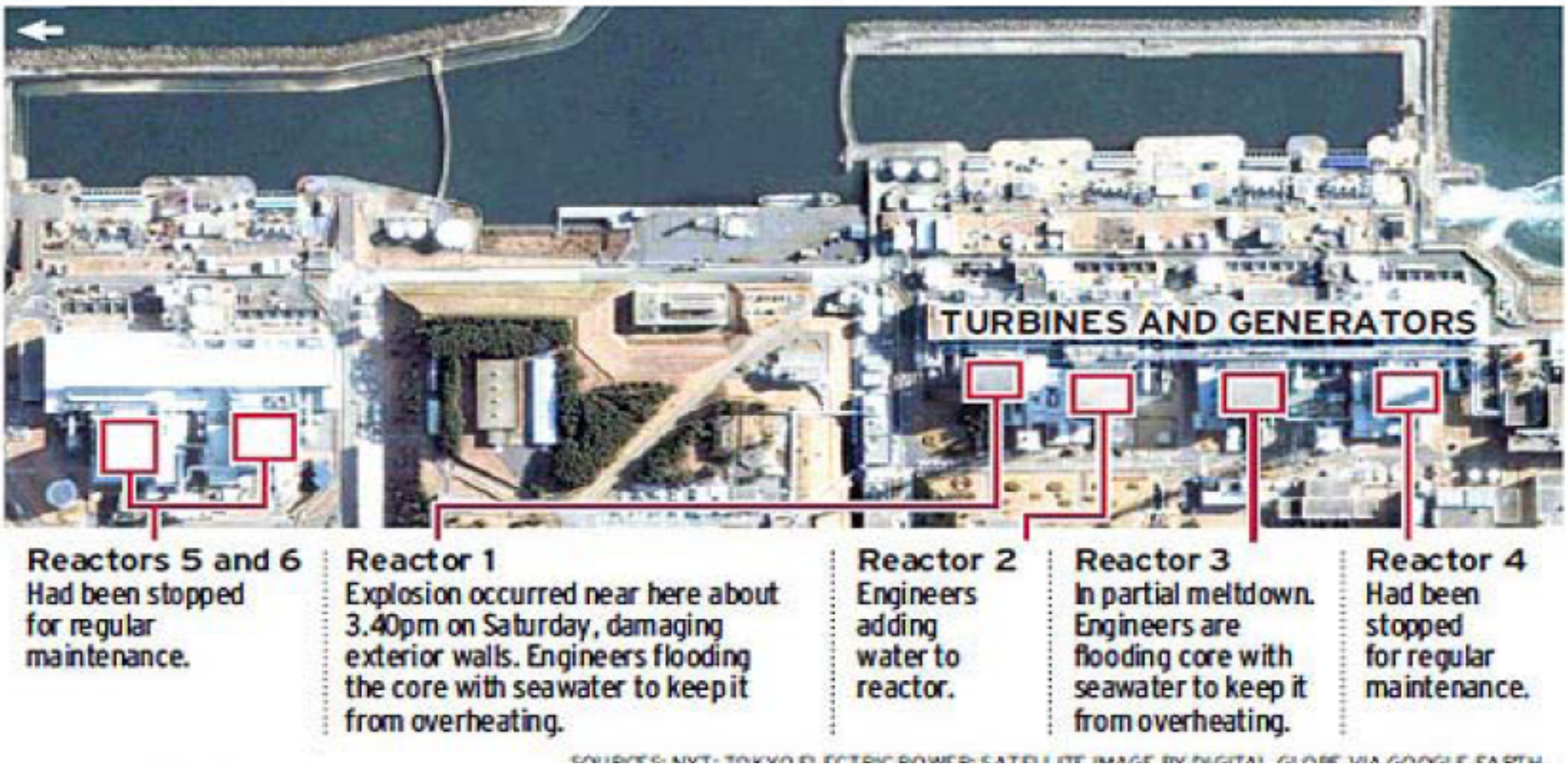
Japanese officials knew of past tsunami’s that were above the March event - 869AD - Prob ~10^{-3} (unacceptable event in the US)

Japanese Regulatory restructured



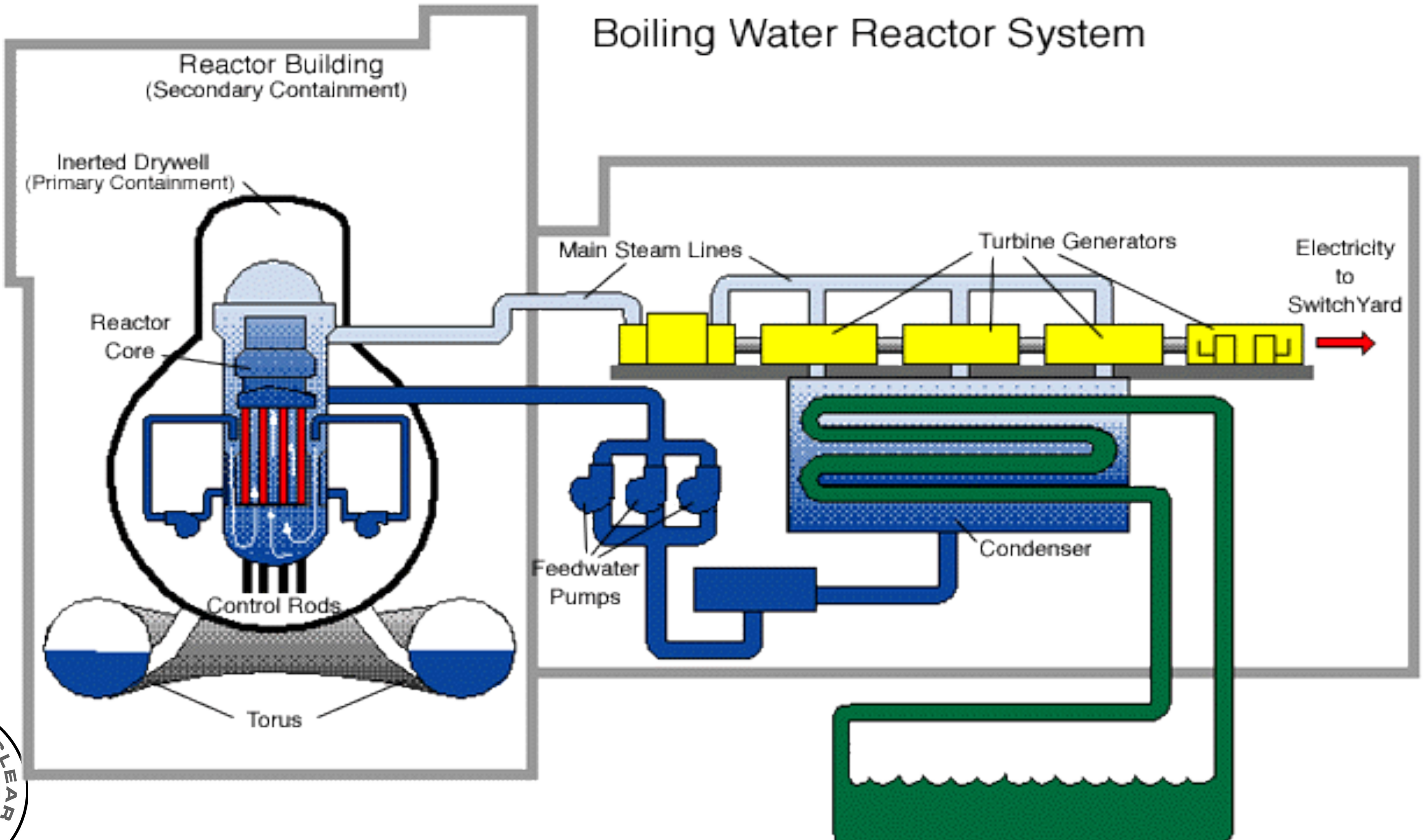
Six BWR units at the Fukushima Nuclear Station:

- 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)

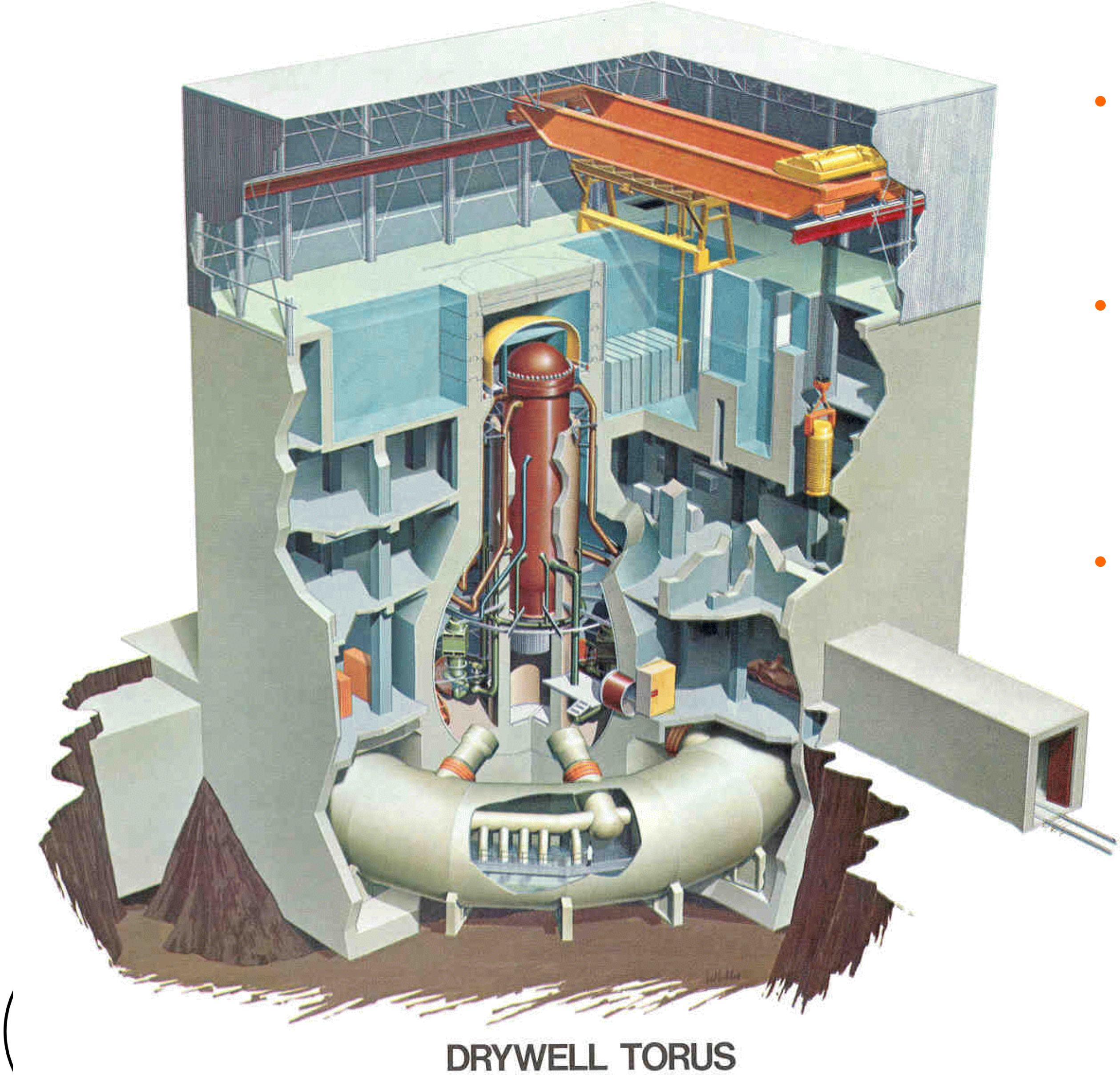


Overview of Boiling Water Reactor

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



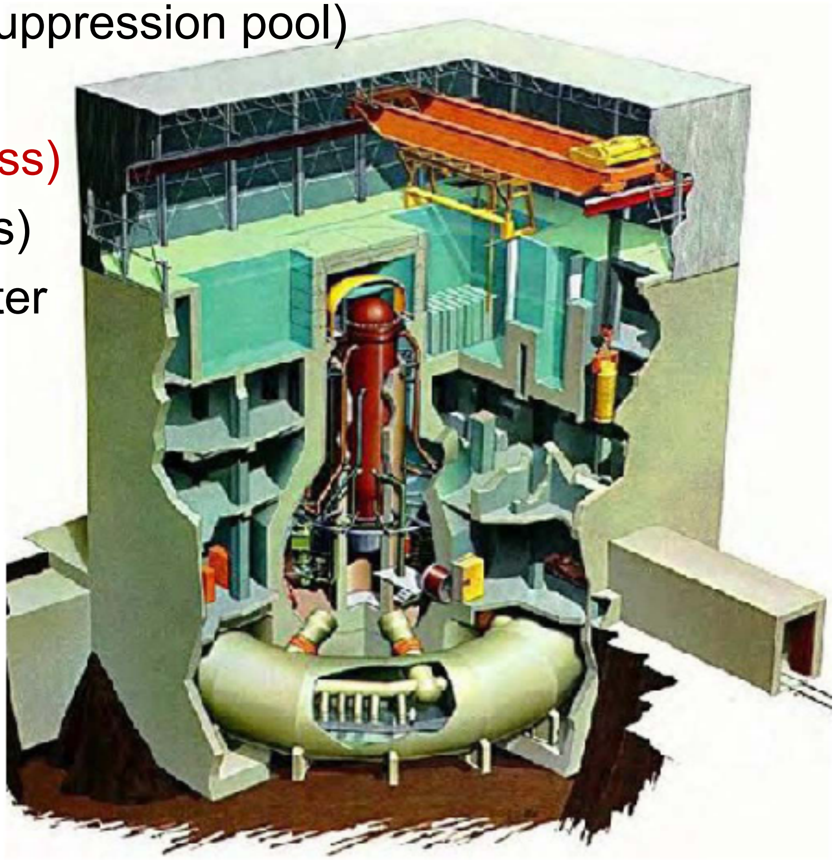
Mark 1 Containment and Reactor Building



- 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).

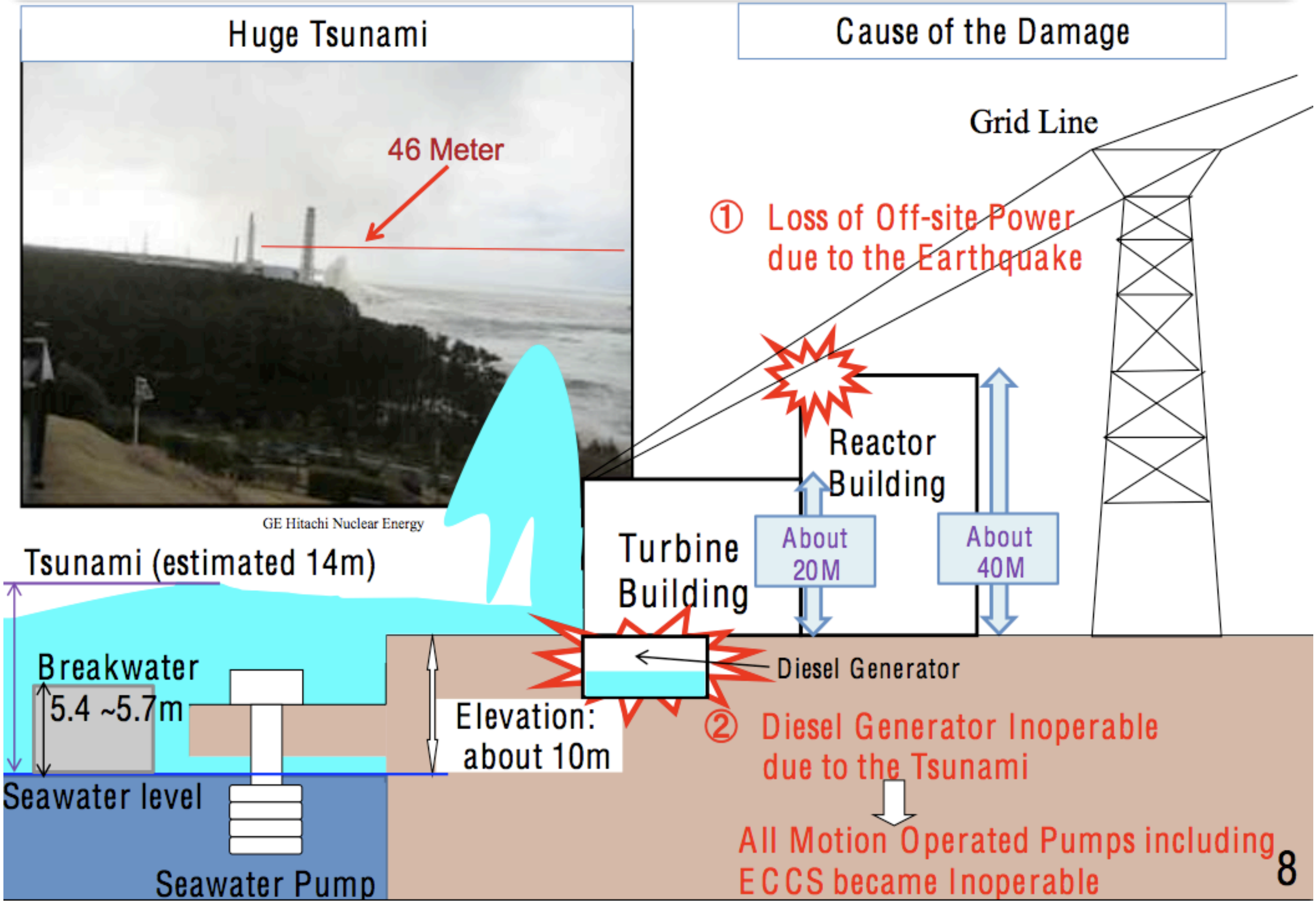
Mark 1 Containment and Reactor Building

- 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

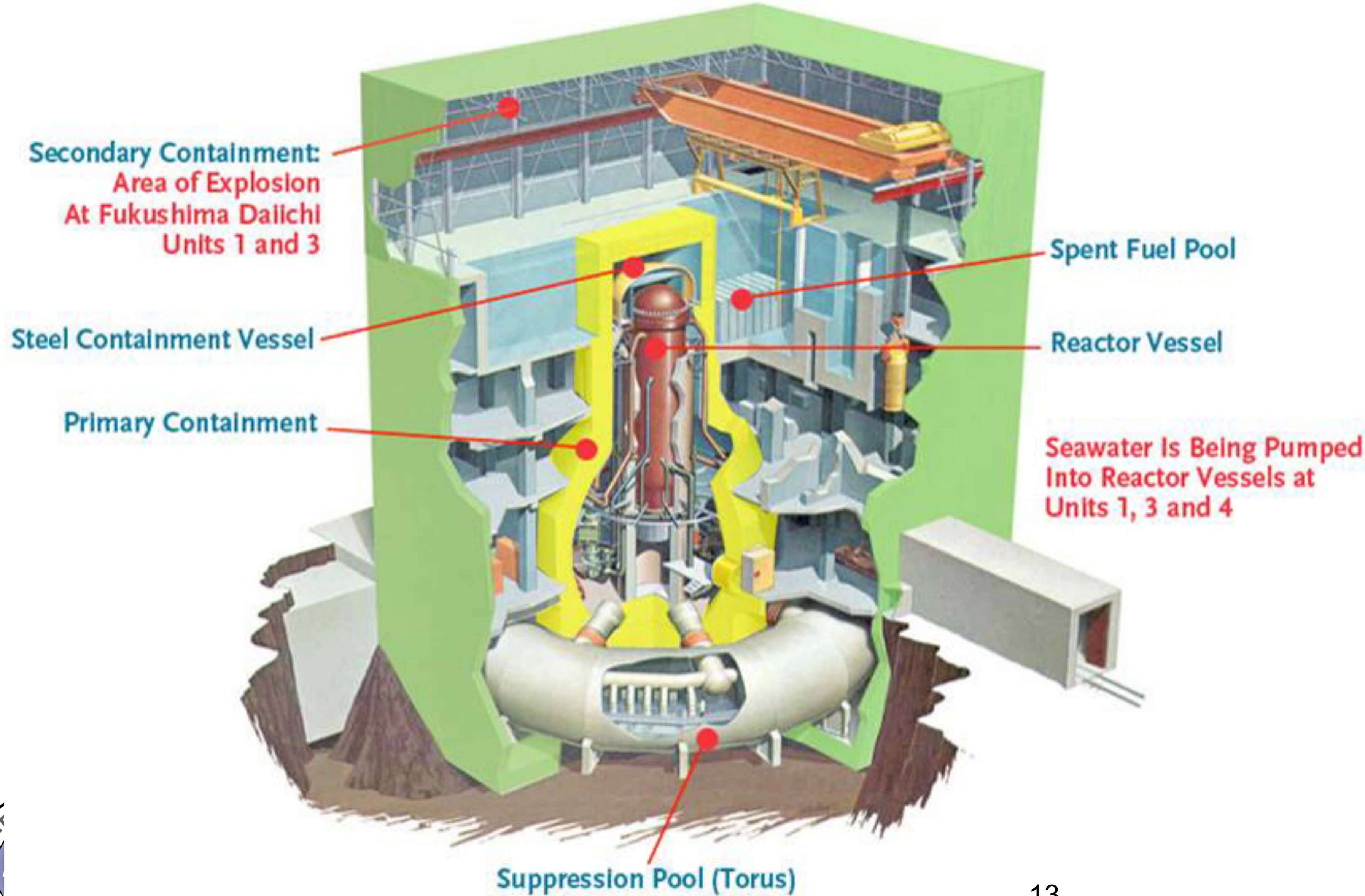
Fukushima Accident Initiation



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

Gas Sampling in the Drywell

Nuclides	Concentration of sample (Bq/cm3) Unit 1 (Sampled on Mar. 8, 2012) Gas vial container	Detection limits of Unit 1 (Bq/cm3)	Concentration of sample (Bq/cm3) Unit 2 (Sampled on Mar. 7, 2012) Gas vial container	Detection limits of Unit 3 (Bq/cm3)	Concentration of sample (Bq/cm3) Unit 3 (Sampled on Mar. 1, 2012) Gas vial container	Detection limits of Unit 3 (Bq/cm3)
I-131	N.D.	1.3×10^{-1}	N.D.	1.2×10^{-1}	N.D.	1.3×10^{-1}
Cs-134	3.5×10^{-1}	3.0×10^{-1}	5.9×10^{-1}	3.0×10^{-1}	4.0×10^{-1}	3.2×10^{-1}
Cs-137	5.5×10^{-1}	3.6×10^{-1}	8.1×10^{-1}	3.6×10^{-1}	7.2×10^{-1}	3.8×10^{-1}
Kr-85		2.5×10^{-1}	N.D.	2.5×10^{-1}	N.D.	2.5×10^{-1}
Xe-131m		2.9×10^{0}	N.D.	3.0×10^{0}	N.D.	3.3×10^{0}
Xe-133		2.4×10^{-1}	N.D.	2.7×10^{-1}	N.D.	2.2×10^{-1}
Xe-135		1.1×10^{-1}	N.D.	1.0×10^{-1}	N.D.	1.0×10^{-1}

N.D. : not detected

(Source: TEPCO)

Water Sampling in the Drywell / Wetwell

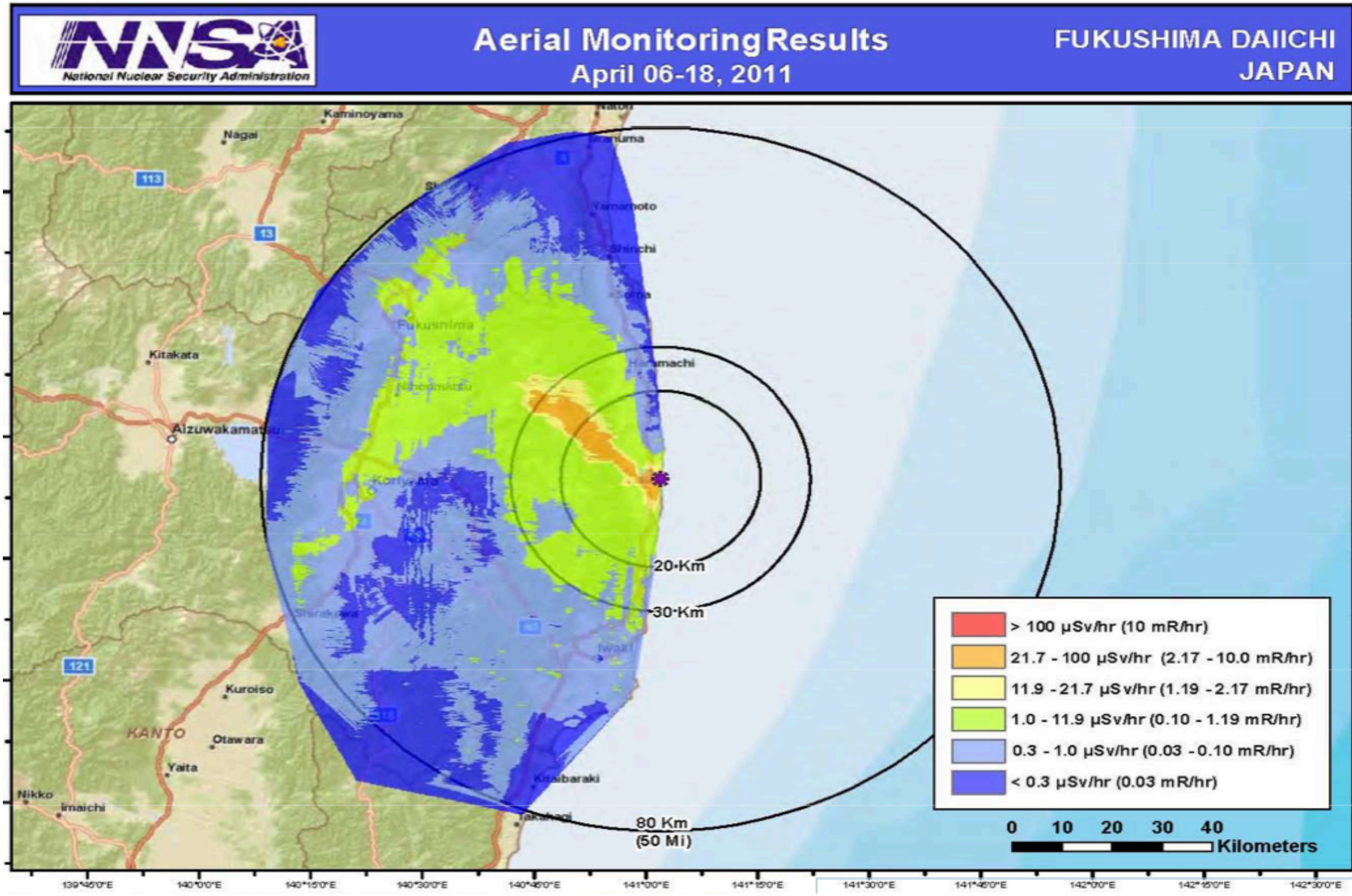
nuclide	Density of sample (Bq/cm3)							
	Unit 1		Unit 2		Unit 3		Unit 4	
	Sampled on Mar. 27, 2011	Sampled on Jan. 20, 2012	Sampled on Mar. 24, 2011	Sampled on Jan. 12, 2012	Sampled on Mar. 24, 2011	Sampled on Feb. 12, 2012	Sampled on Mar. 24, 2011	Sampled on Feb. 12, 2012
I-131	3.0E+04	ND	2.0E+06	ND	1.2E+06	ND	3.6E+02	ND
Cs-134	1.2E+05	2.2E+04	2.6E+06	2.2E+05	1.8E+05	8.5E+04	3.1E+01	2.1E+04
Cs-137	1.6E+05	3.0E+04	2.8E+06	3.0E+05	1.8E+05	1.1E+05	3.2E+01	2.8E+04
Y-91		ND		ND		ND		ND
Mo-99		ND		ND		ND		ND
Tc-99m		ND		ND		ND		ND
Te-129m		ND		ND		ND		ND
Te-132		ND		ND		ND		ND
I-132		ND		ND		ND		ND
Cs-136		ND		ND		ND		ND
Ba-140	<560	ND	2.4E+05	ND		ND		ND
La-140	<300	ND	2.2E+05	ND		ND		ND

* In the case the measurement is under the detection threshold, "ND" is marked.

(Source: TEPCO)

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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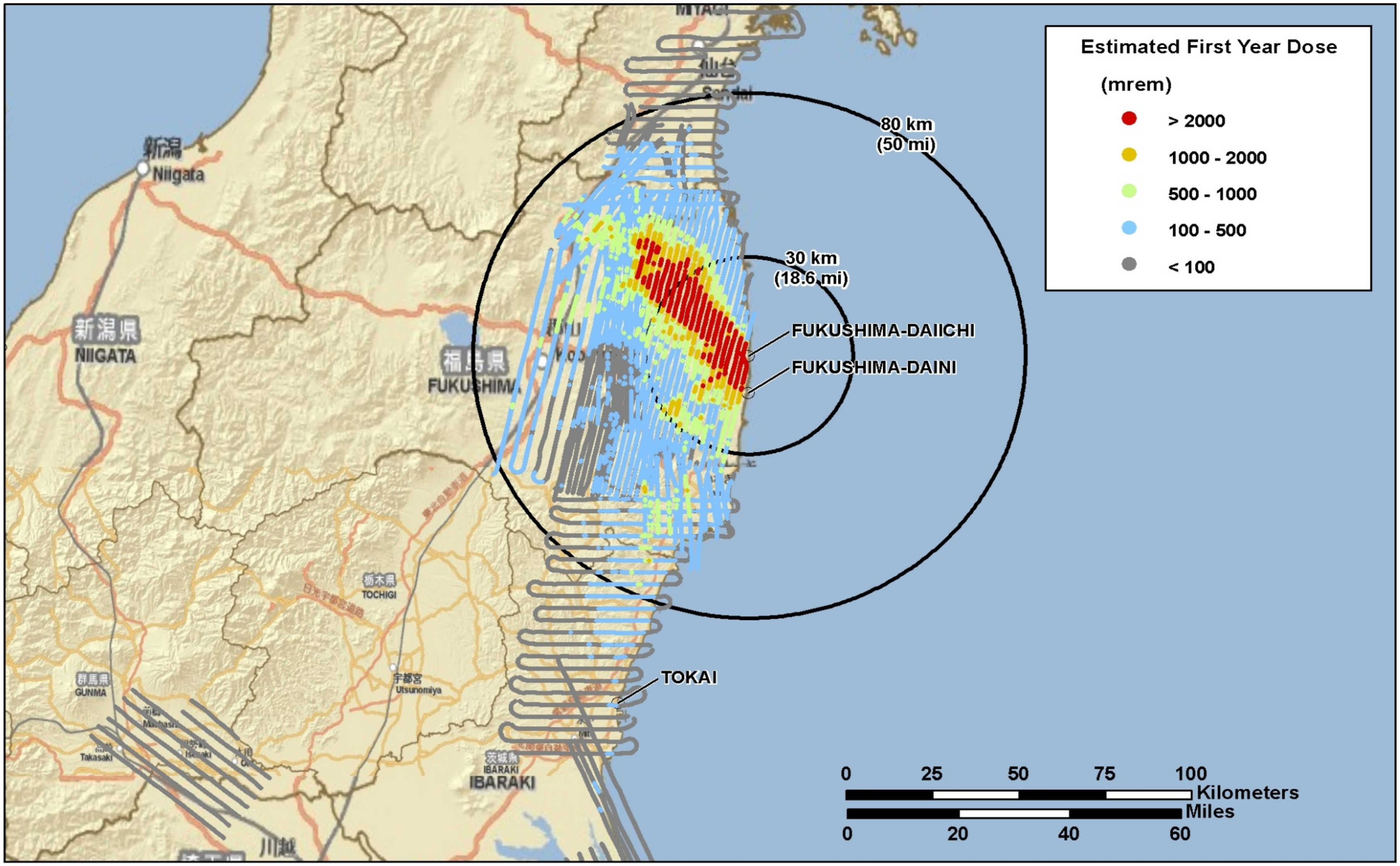
NNSA National Nuclear Security Administration

First-Year Dose Estimate

Dose Commencing March 16, 2011 for 365 Days

FUKUSHIMA DAIICHI JAPAN



Map created on 04092011 1300 JST

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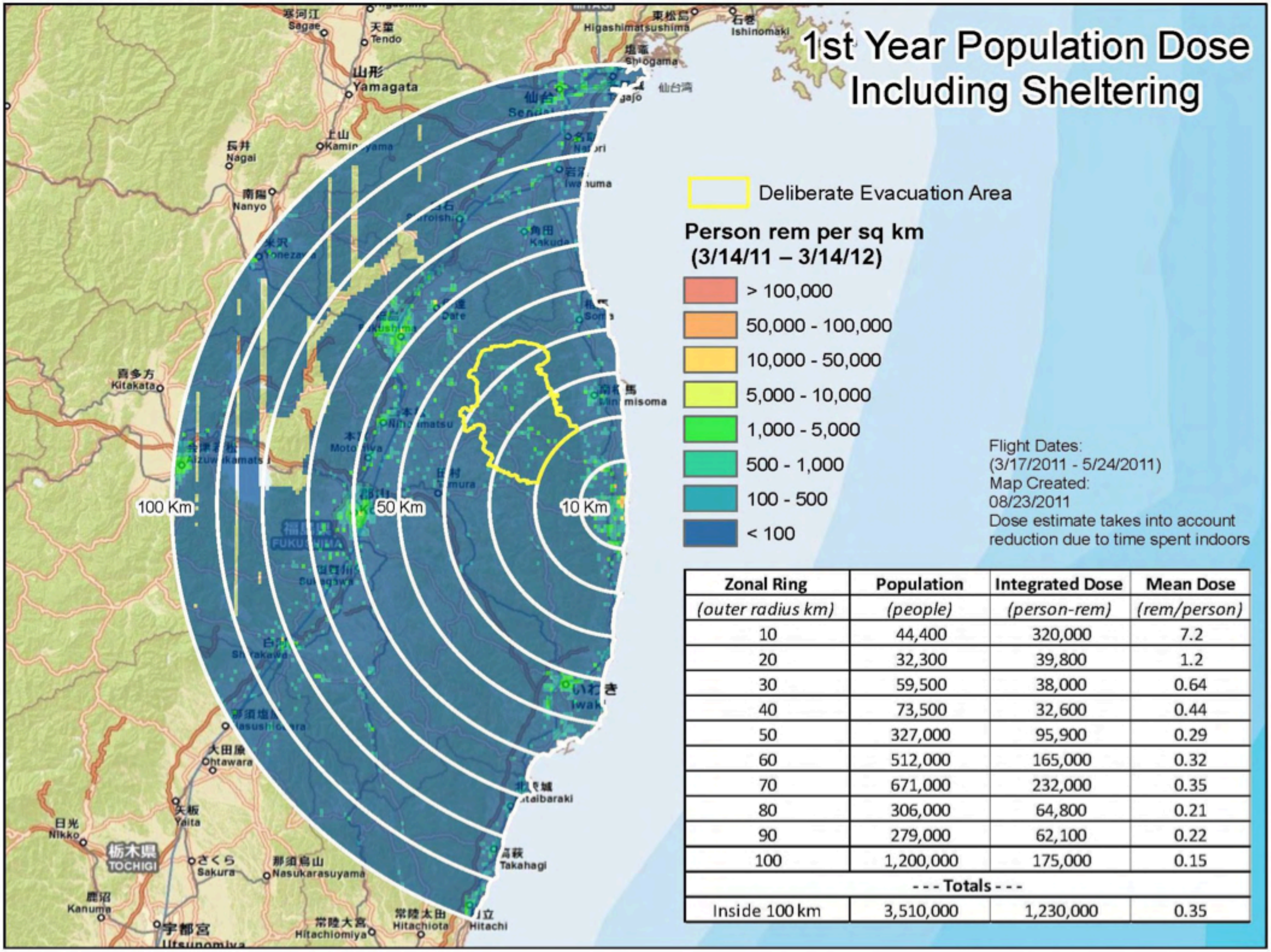
Nuclear Incident Team DOE NIT

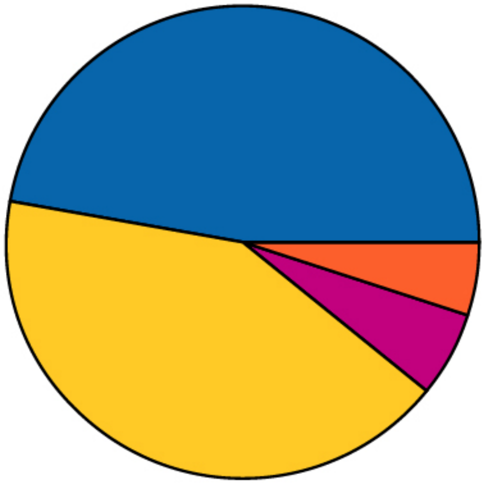


Zonal Ring	Population	Integrated Dose	Mean Dose
(outer radius km)	*(people)*	*(person-rem)*	*(rem/person)*
10	44,400	320,000	7.2
20	32,300	39,800	1.2
30	59,500	38,000	0.64
40	73,500	32,600	0.44
50	327,000	95,900	0.29
60	512,000	165,000	0.32
70	671,000	232,000	0.35
80	306,000	64,800	0.21
90	279,000	62,100	0.22
100	1,200,000	175,000	0.15
--- Totals ---			
Inside 100 km	3,510,000	1,230,000	0.35

Safety-Related Issues

- Safety approach should evolve to risk-informed regulation
- Command/control of an accident should reside with plant manager on-site 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 with 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 pump systems
  - Logistically position fuel, generators and pumps to move onto plant site

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

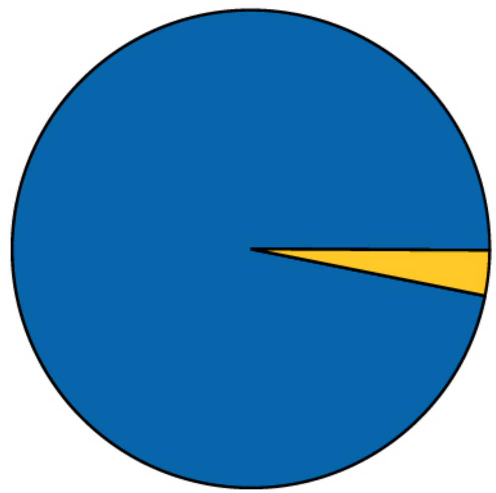


PEACH BOTTOM

- STATION BLACKOUT, 47%
- ATWS, 42%
- LOCA, 6%
- TRANSIENTS, 5%

GRAND GULF

- STATION BLACKOUT, 97%
- ATWS, 3%



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
- Emergency Planning decisions in Japan were puzzling
- 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 construction continues (slower)
- Other international plans have not been altered
- IAEA is strongly focused on international safety standards and improving safety review

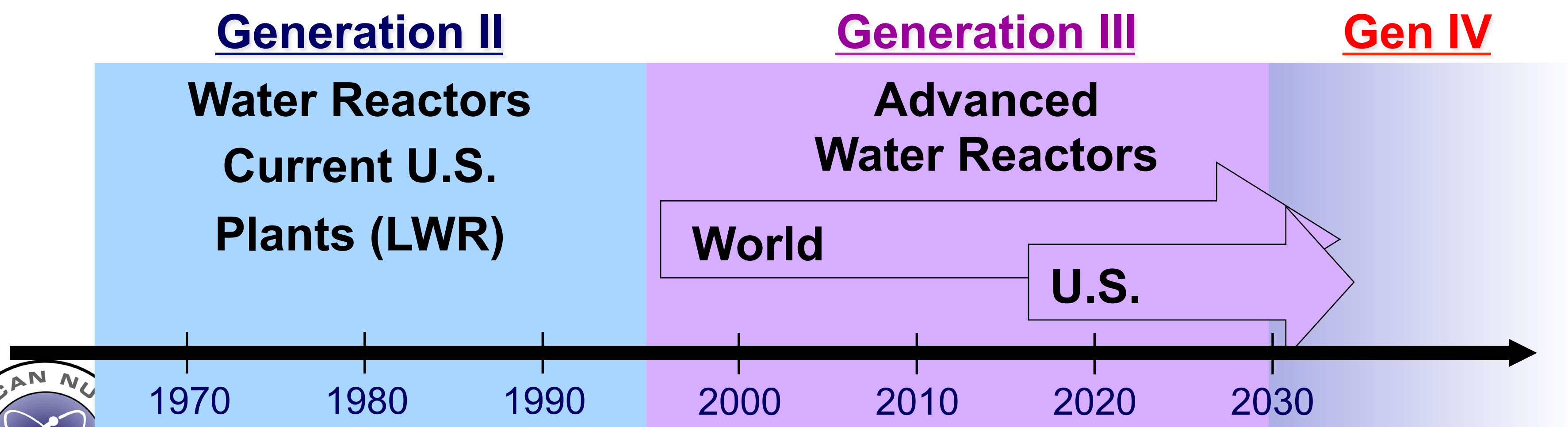
Status of Nuclear Power

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)

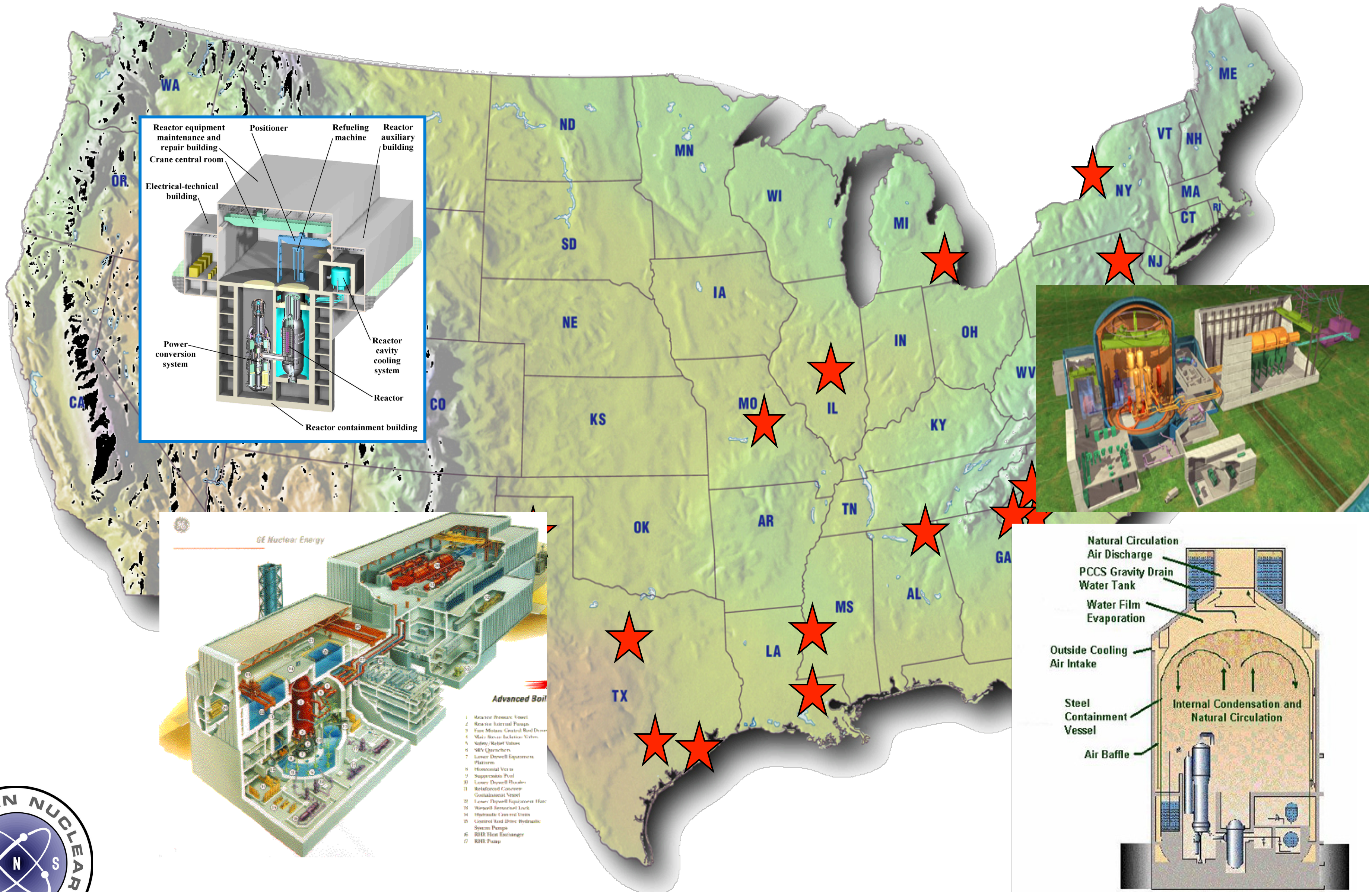
Generation III+: Design changes for improved safety and lower cost
US: 30 proposed, 24 applications received and 4-6 proceeding [1]
World: 12 operating, 63 under construction, >100 planned [2]

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

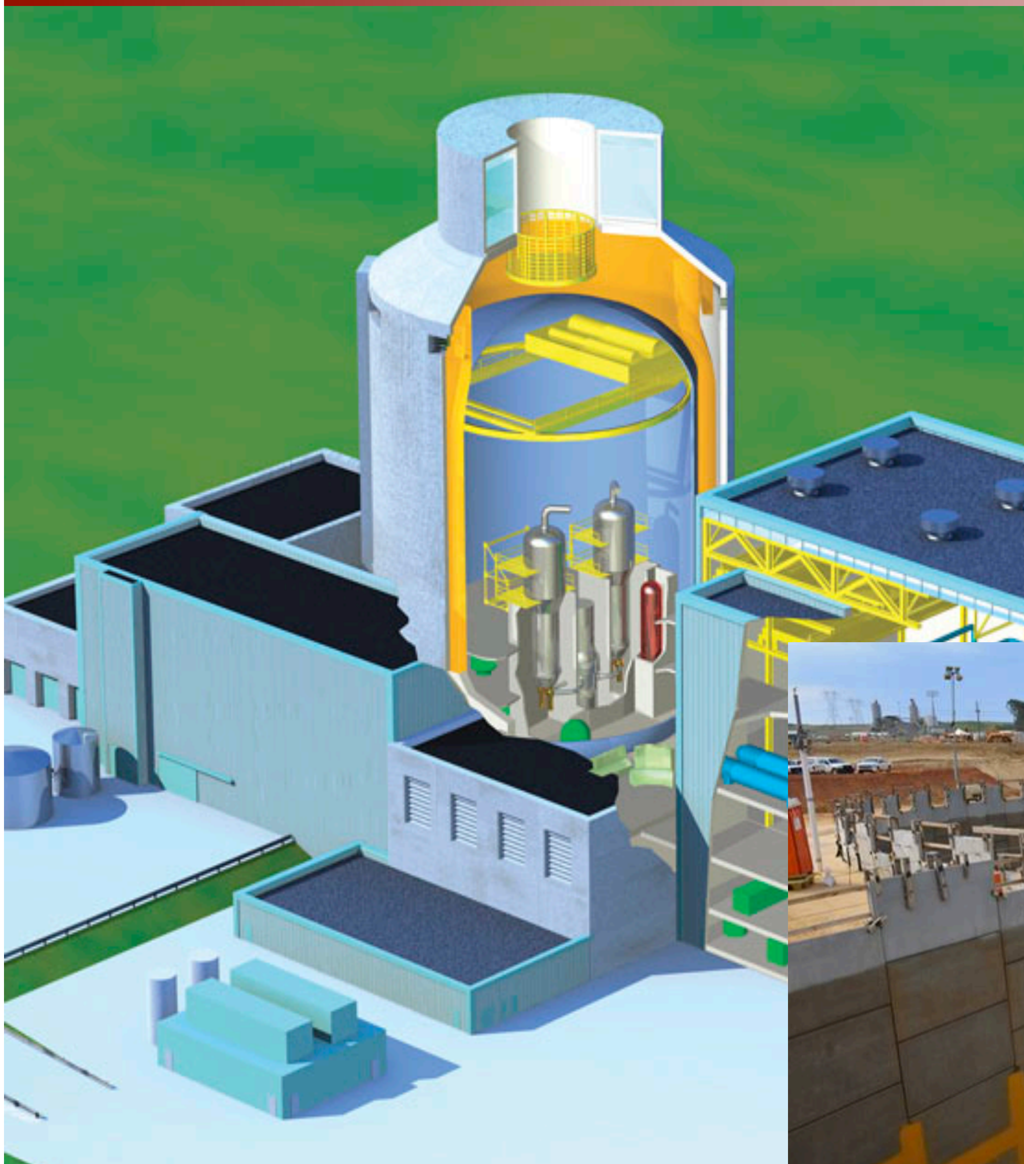


[1] NRC: 2011 [2] IAEA: 2011

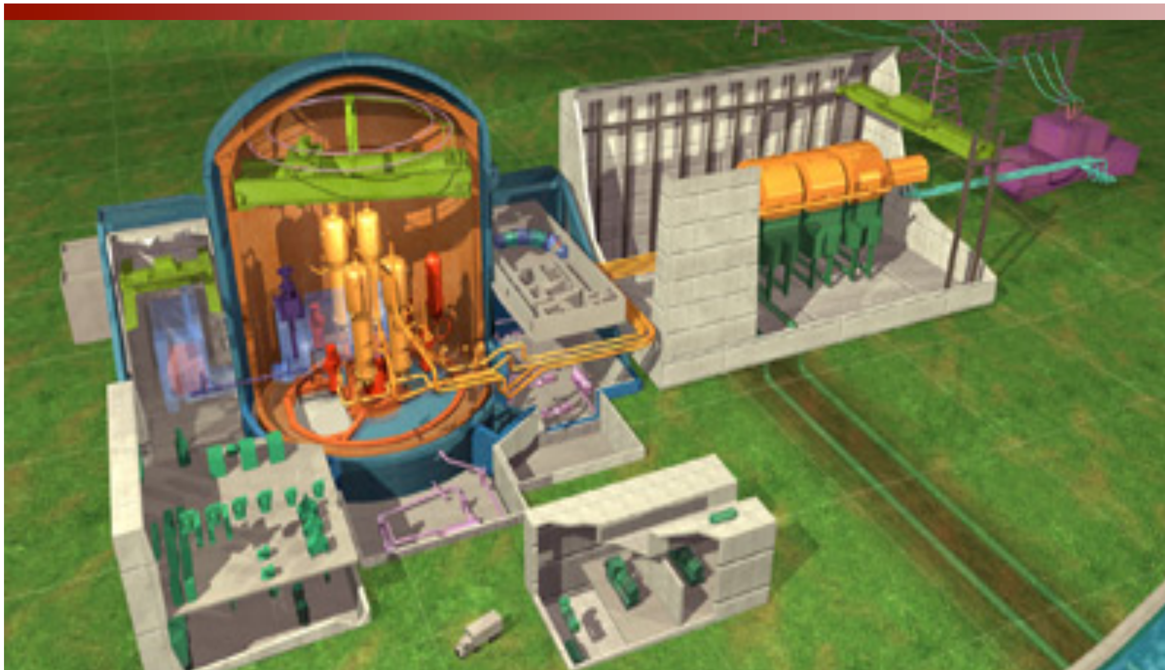
Locations for Advanced Nuclear Plants



Westinghouse AP1000 Reactor

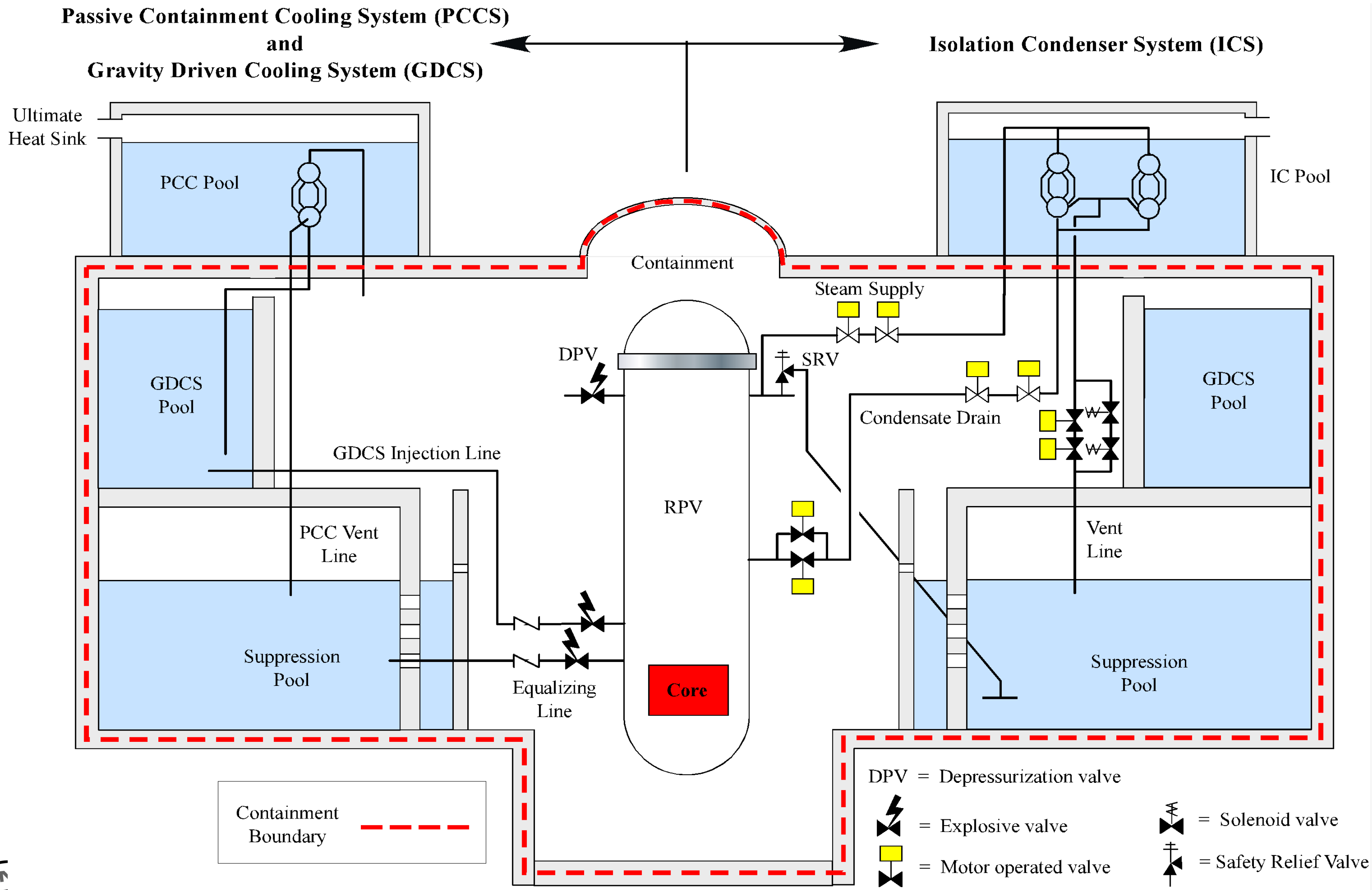


Advanced LWR: EPR



the

General Electric – Hitachi ESBWR Plant

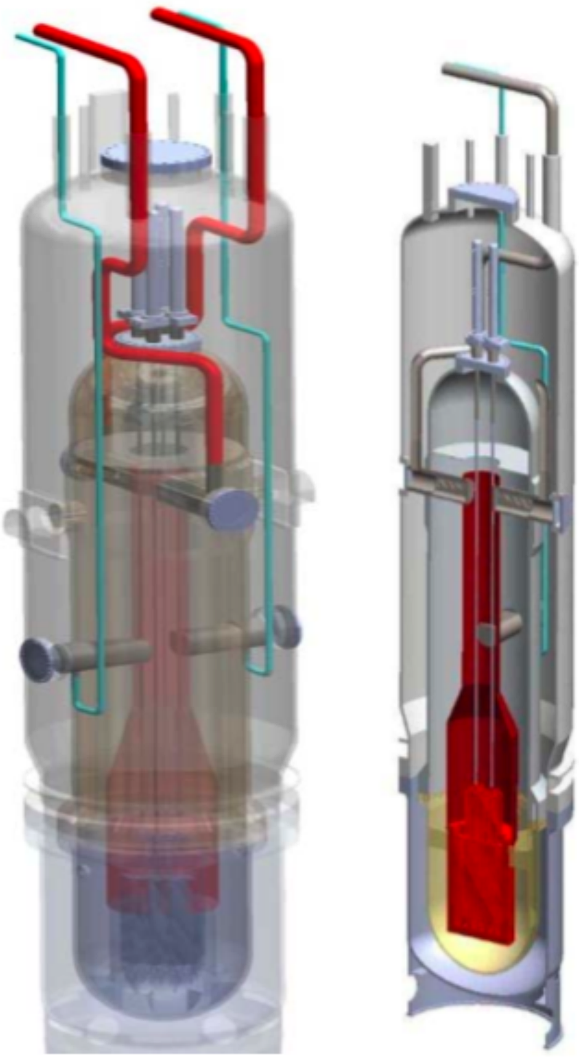


Summary Table of Modular Reactor Concepts

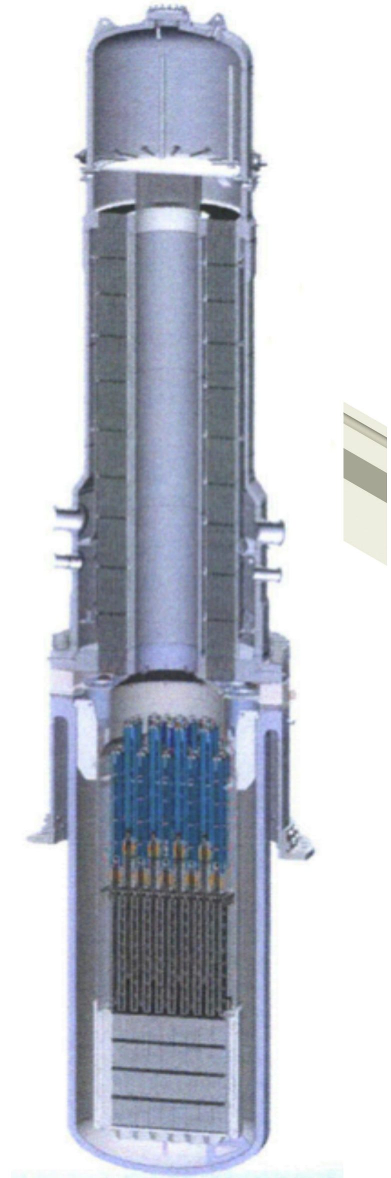
Name/ TYPE	(MWe)	Vendor	Design Feature
PWR (IRIS)	<200	Westinghouse - Toshiba	Integral SG; refuel 5 yrs
NuScale / PWR	45	NuScale Power, Inc.	Modular; integral SGs; refuel 5 yrs; store SF
m-Power / LWR	125	Babcock & Wilcox	Modular, integral SGs; refuel 5 yrs; store SF
NGNP / Gas (Next Generation N-Plant)	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

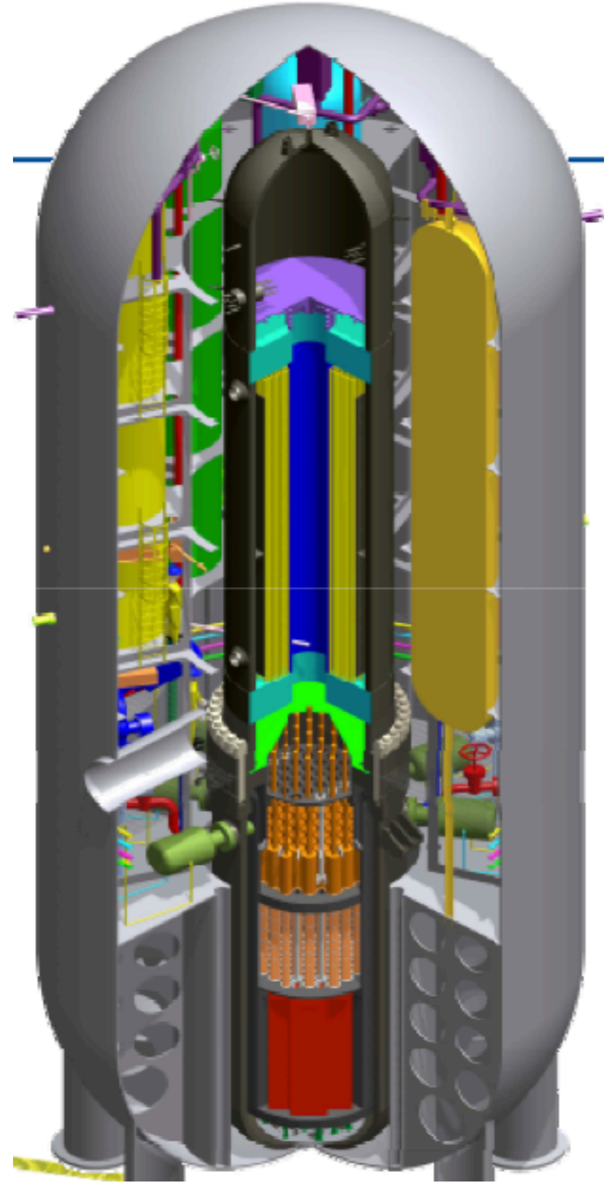
NuScale PWR



mPower-PWR

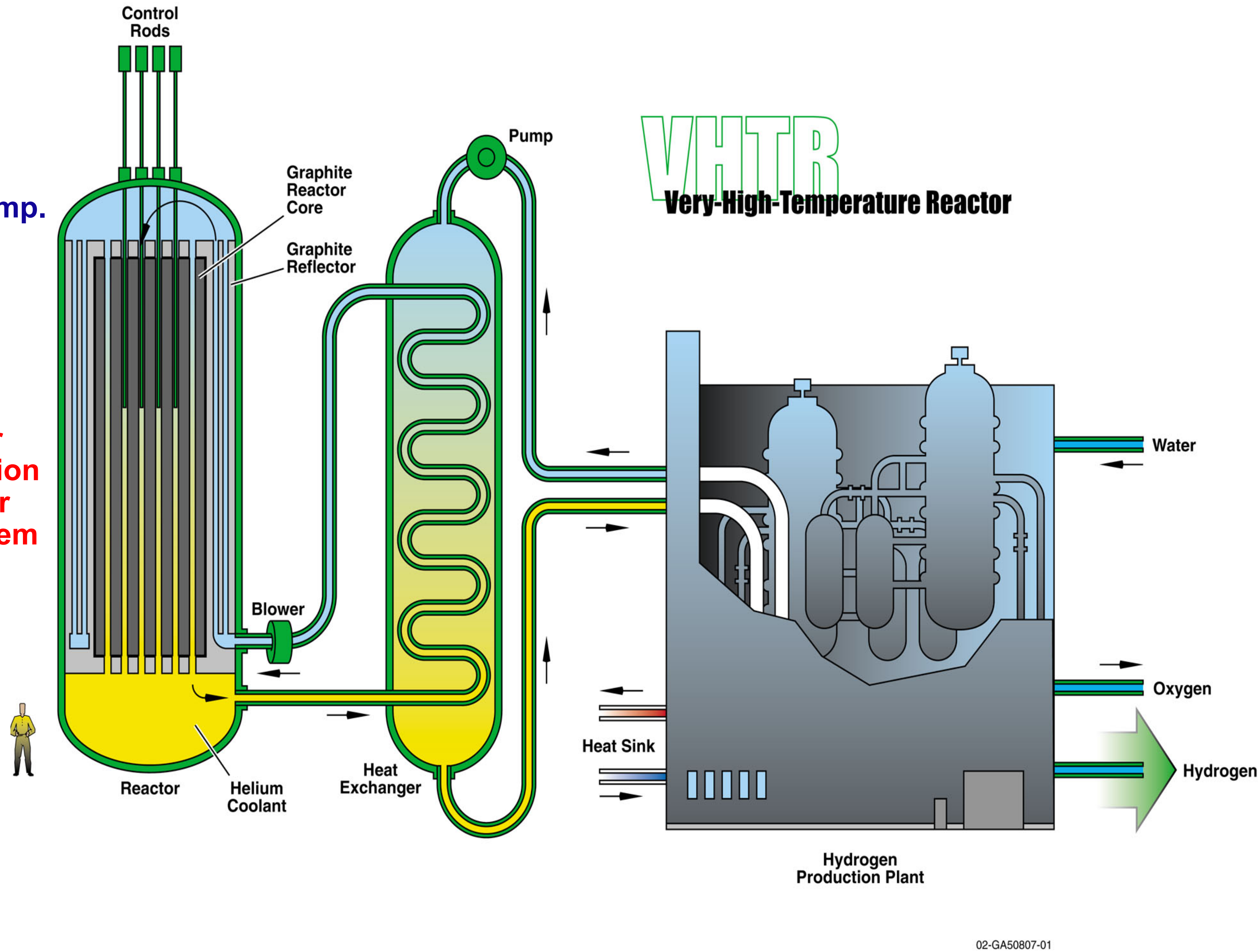


Westinghouse PWR

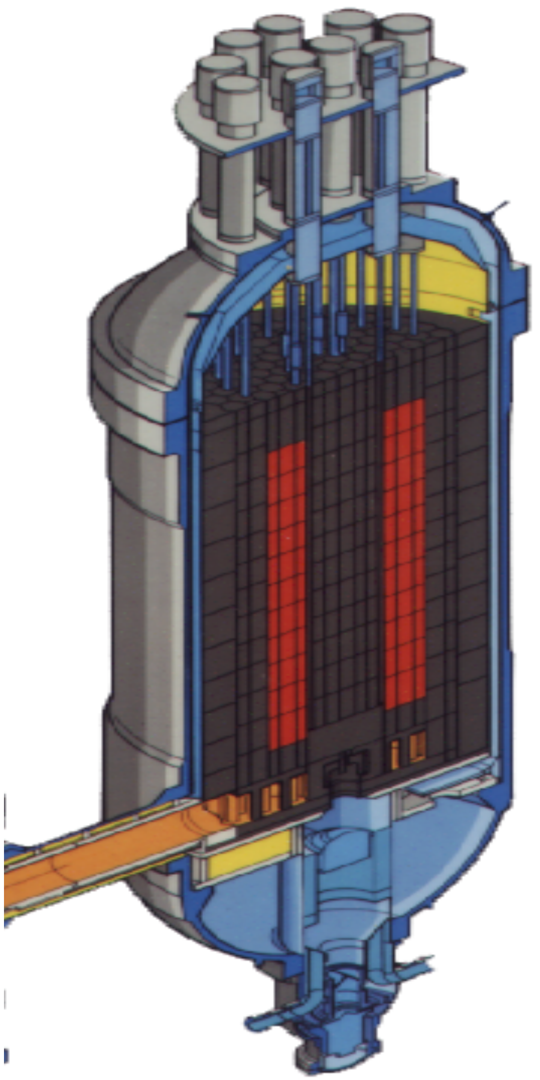


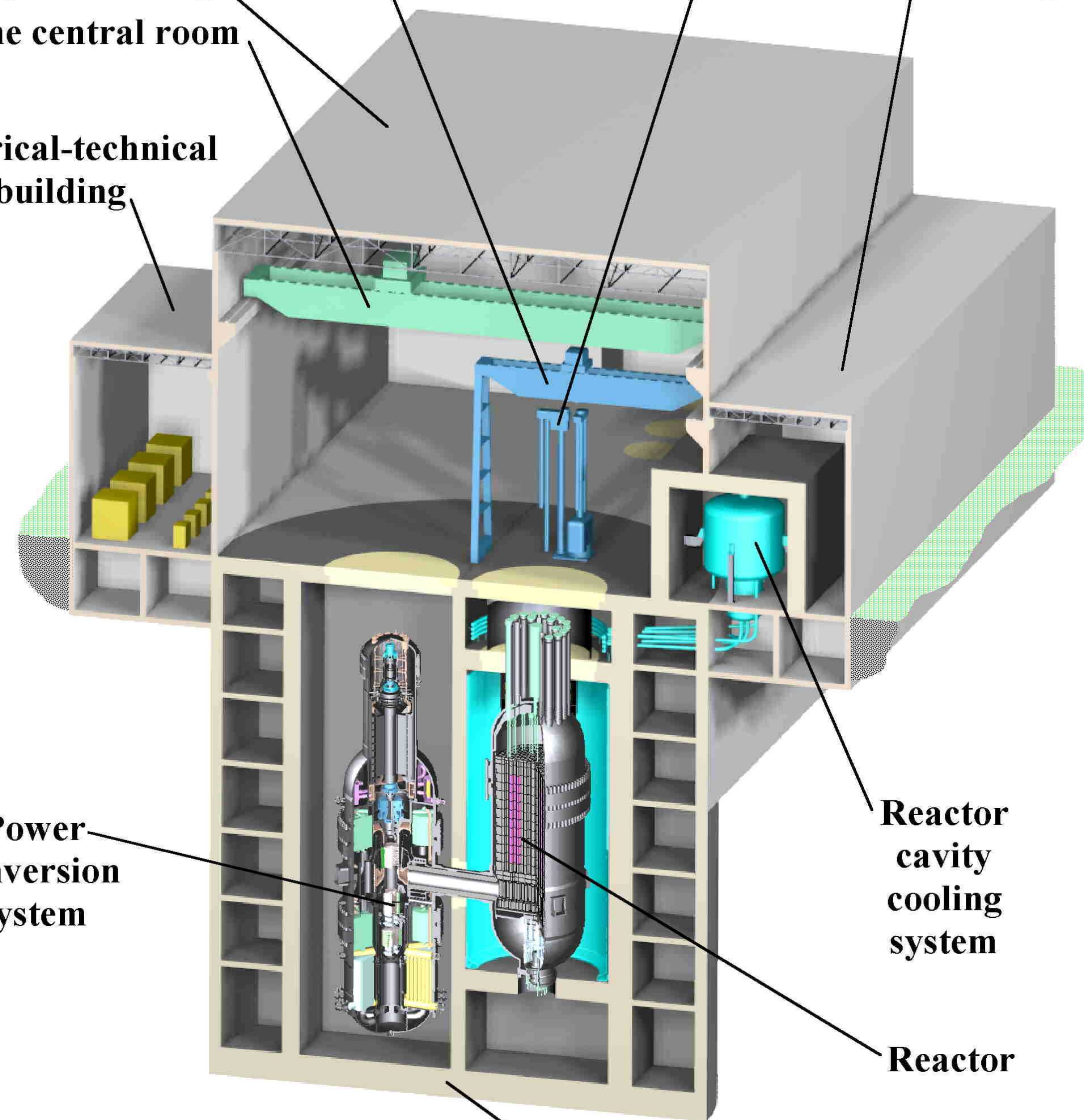
Hi-Temperature Gas-cooled Reactor (VHTR)

- Characteristics
  - Helium coolant
  - 1000°C outlet temp.
  - 200 - 600 MWth
- Key Benefit
  - High thermal efficiency
  - Process heat for various application with novel power conversion system

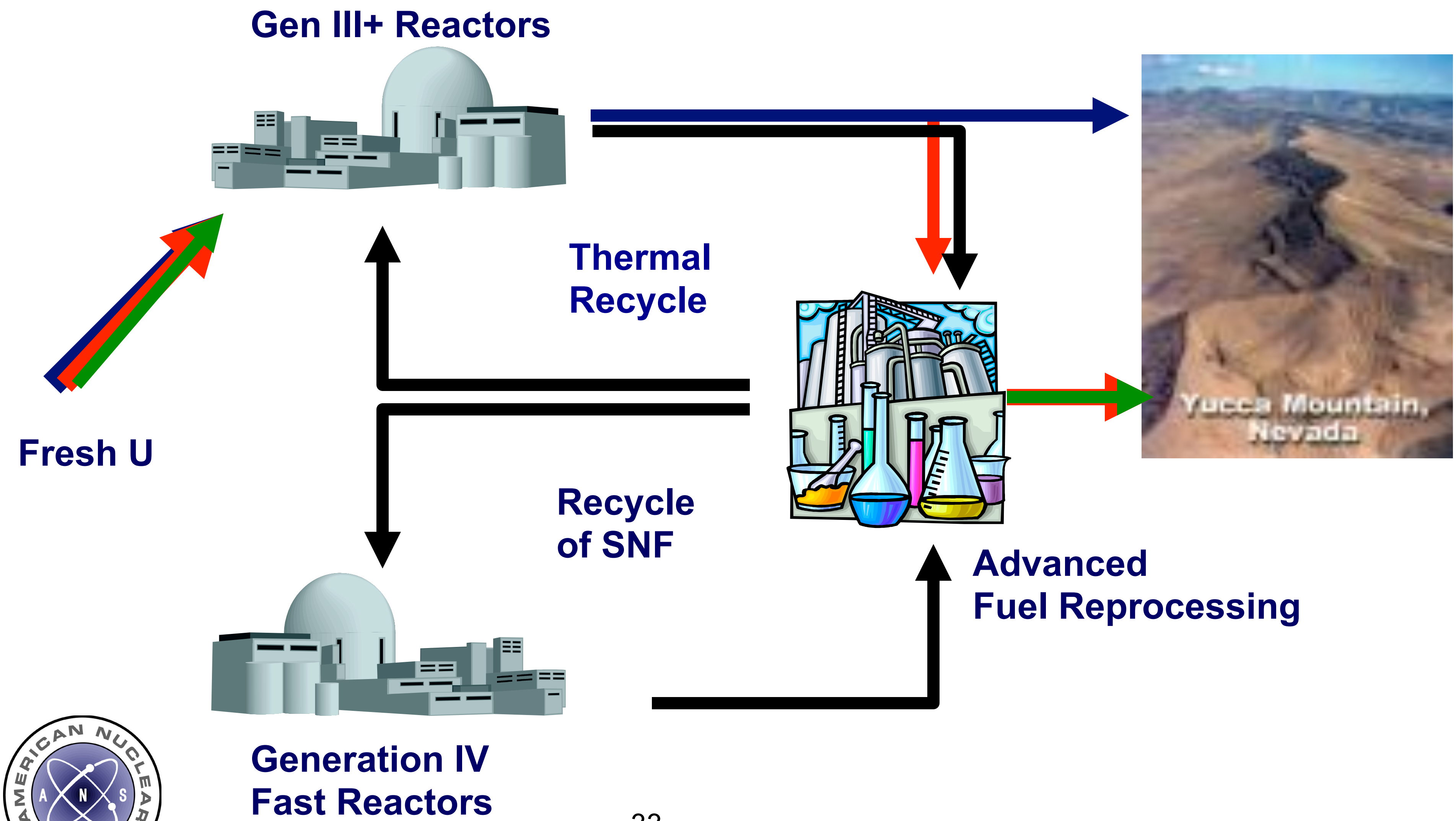


GAS-COOLED REACTOR

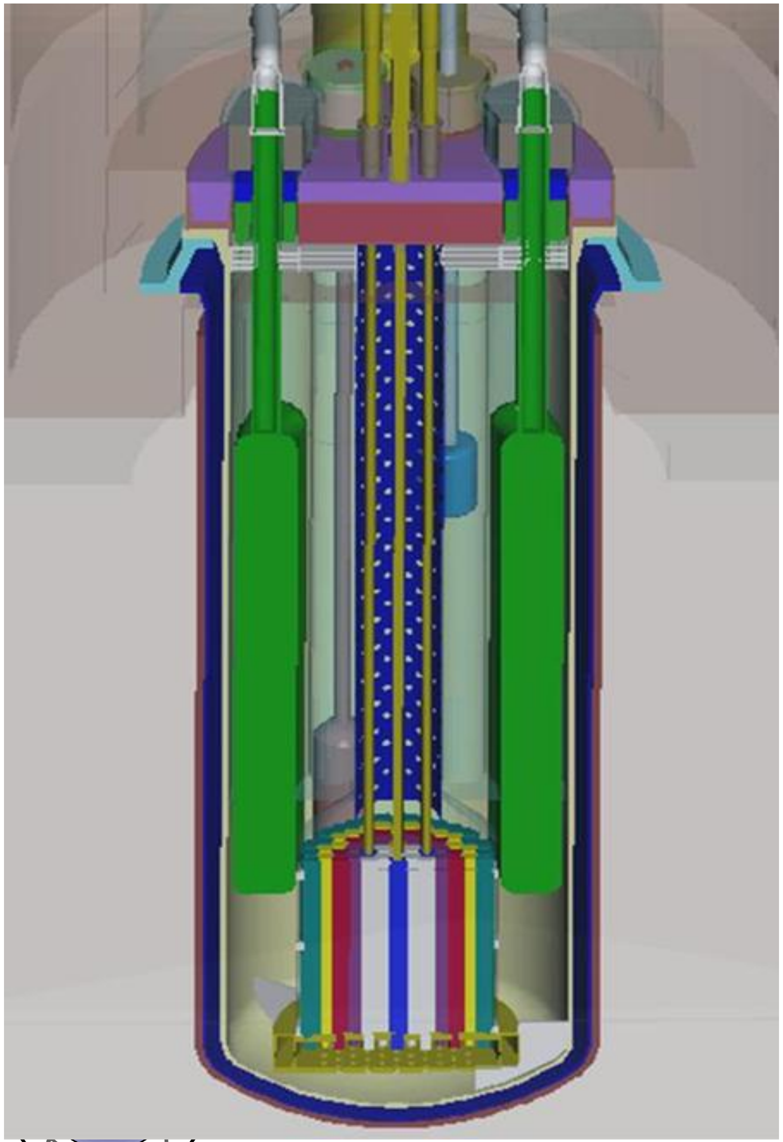




Advanced fuel cycles with Fast Reactor



GENIV: Sodium-cooled Fast Burner



- Basic viability of sodium-cooled fast reactor technology been demonstrated
- Low pressure primary coolant
- Pool configuration
  - Pumps and heat exchangers contained
- Heat exchanged to secondary coolant for energy conversion system
  - Rankine steam (SC) or $SC\text{-}CO_2$ Brayton
- High power density core
  - 250 kW/liter (vs. 50-100 kW/l for LWR)
- 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 has been volatile
  - Oil: highly volatile, but can biomass buffer this?
  - Opportunity cost of renewables is hidden in REP
  - Electricity transmission & storage is a major issue
  - Current recession has taken back energy landscape to late 20th century by demand and business practices
  - There is no unifying plan or even a discussion of a plan

ANS Public Outreach

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

- Why should the 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.

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