Nuclear Power & Lessons from the Fukushima Power Plant Accident

Hugh Outhred
STTNAS Seminar
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h.outhred@unsw.edu.au
hugh_outhred@ipenconsulting.com
www.ipenconsulting.com

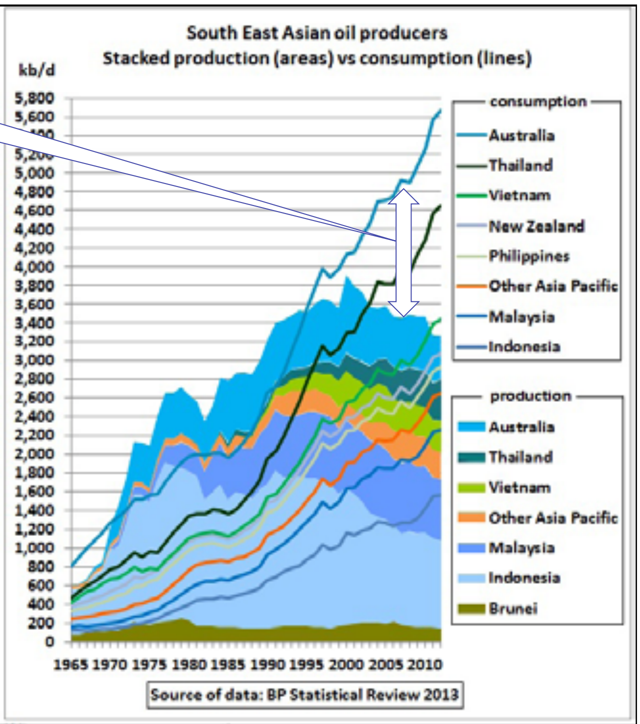
Outline

- Why consider nuclear?
  - Oil consumption exceeding production in Southeast Asia
  - Climate change emission constraints
- Uranium fuel cycle & its implications
- Evolution of nuclear power
- The Fukushima Accident & its consequences
- Lessons from Fukushima

The gap between SE Asia oil consumption & production will continue to grow

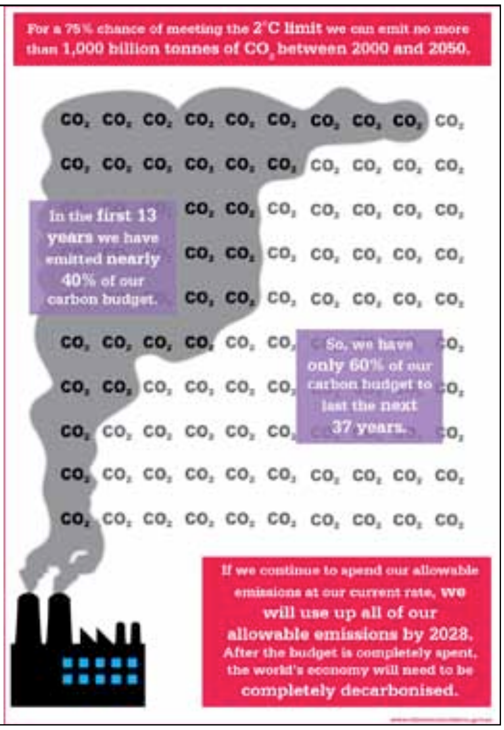
Cumulative Oil production & Consumption in South-East Asia

(Mushalik, June 2013)

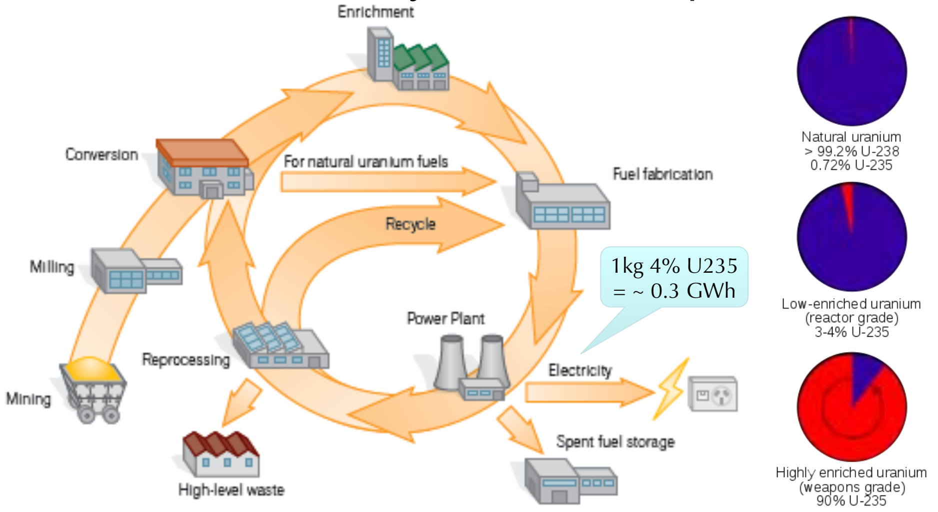


40% of "safe" 2000-2050 CO_2 emission budget already "spent" in 25% of time

(Australian Climate Commission, June 2013)

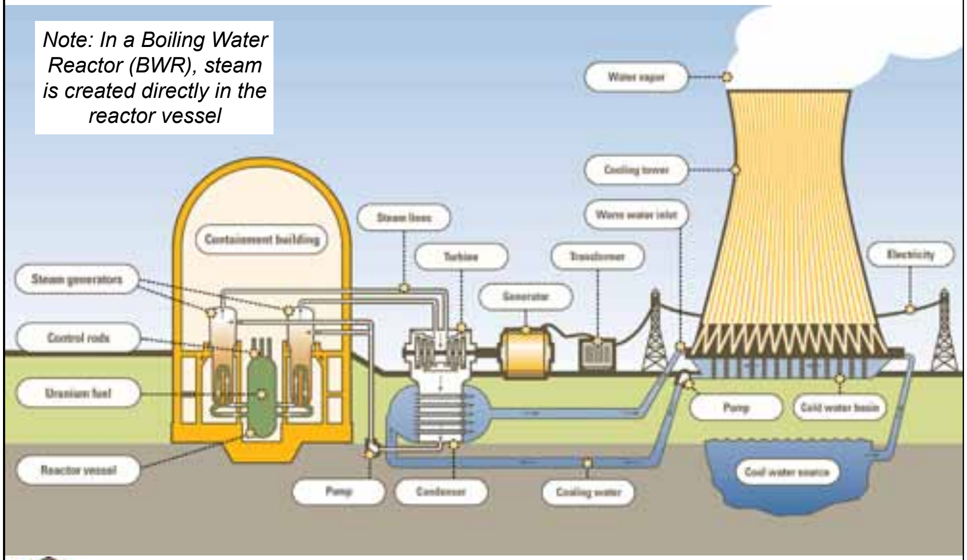


Uranium fuel cycle & nuclear power

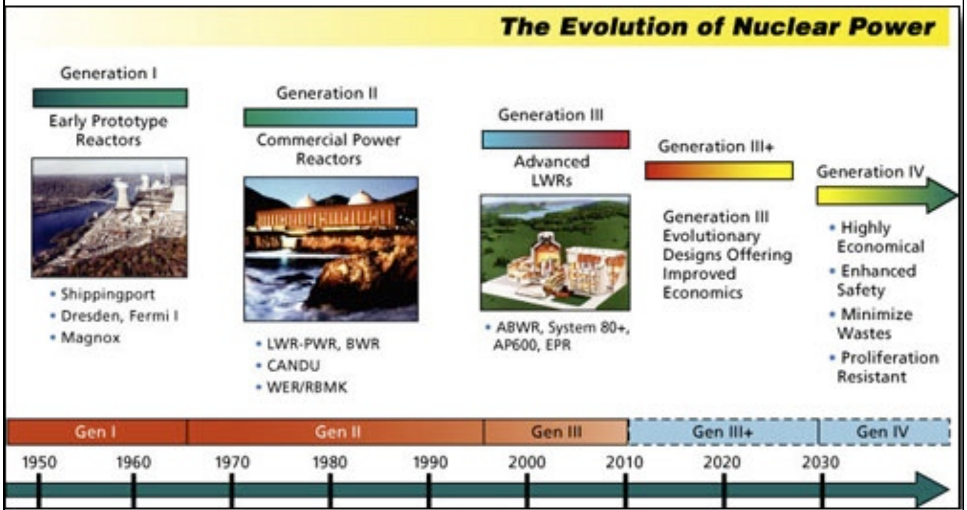


Key issues that need to be solved:
- Improve reliability, safety & cost of nuclear power station designs
- Reduce risks of terrorism & nuclear weapon proliferation
- Construct safe, long term, nuclear waste storage facilities

Pressurised Water Reactor (PWR) power station

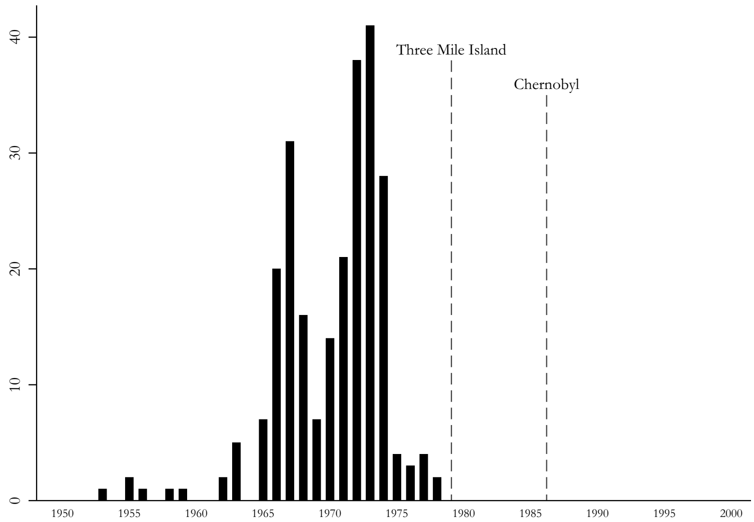


Nuclear power station design evolution



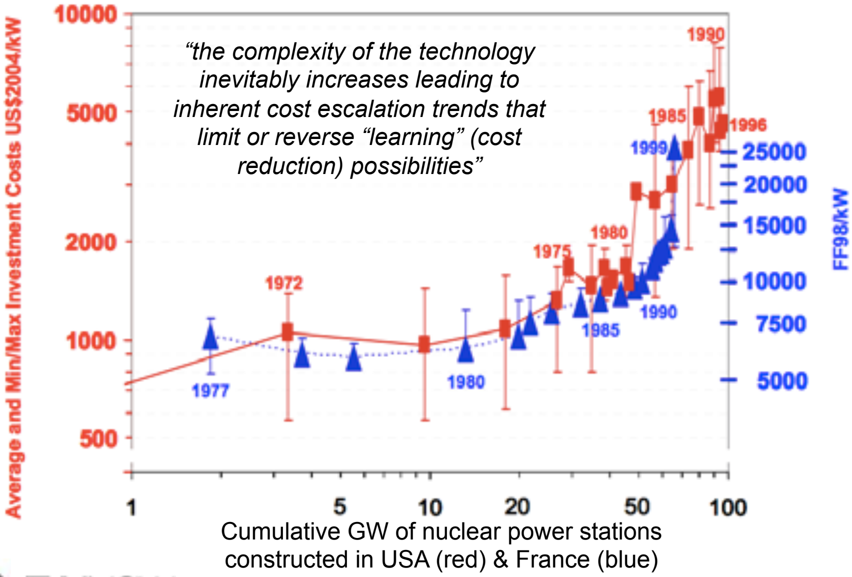
Annual orders for nuclear reactors in USA, 1950-2000

(Davis, Prospects for US nuclear power after Fukushima, EI@Haas, Aug 2011)



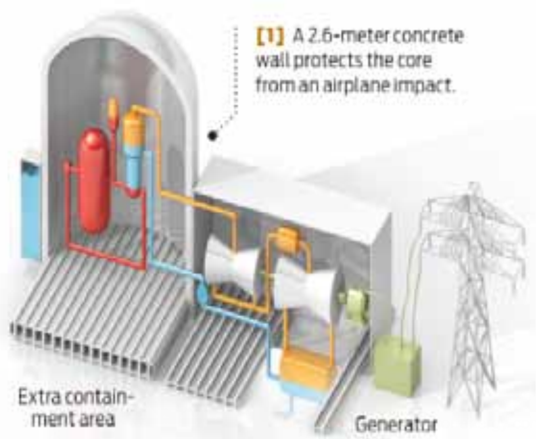
Nuclear power “negative learning curve”

http://www.iiasa.ac.at/web/home/research/researchPrograms/TransitionstoNewTechnologies/06_Grubler_French_Nuclear_WEB.pdf

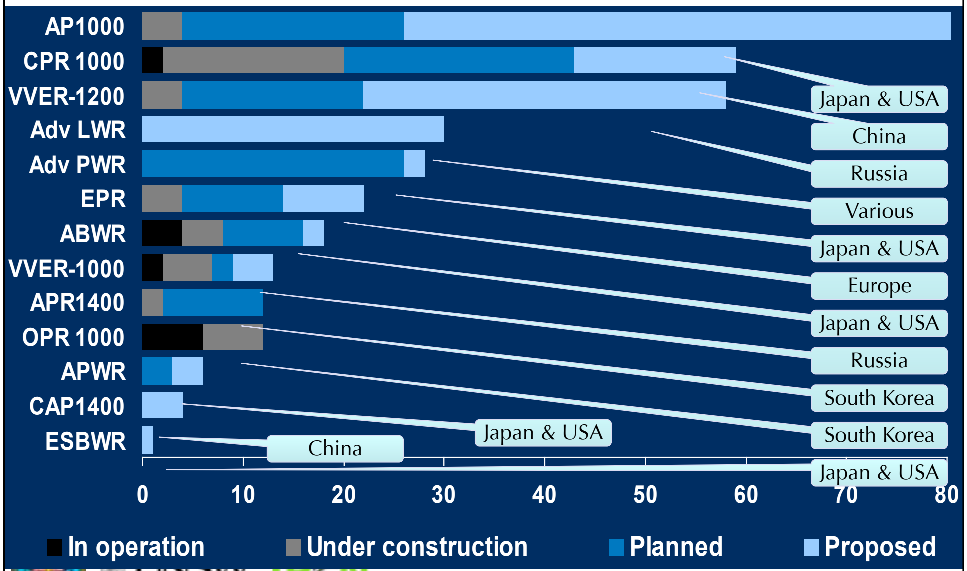


Nuclear reactor designs:

Right: Westinghouse AP1000 (III+)
Below: European EPR (III)
(IEEE Spectrum, Aug 2010)



Current status of generation II+ to III+ nuclear reactors
(Kee, NERA, June 2013)



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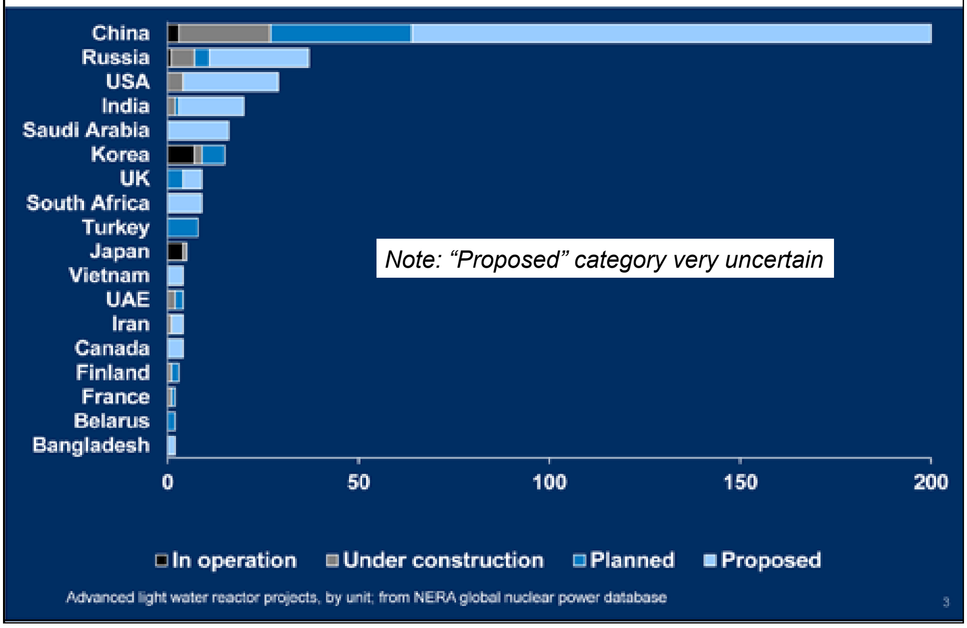
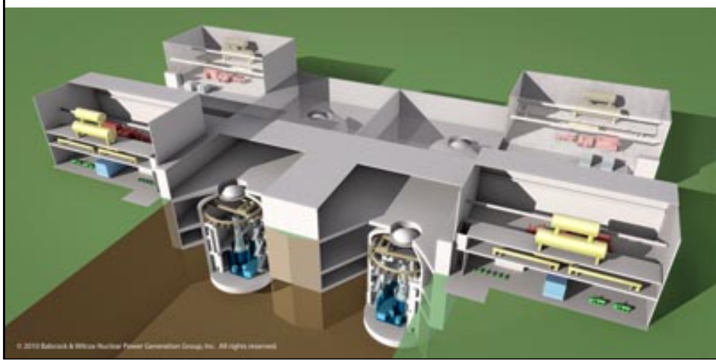
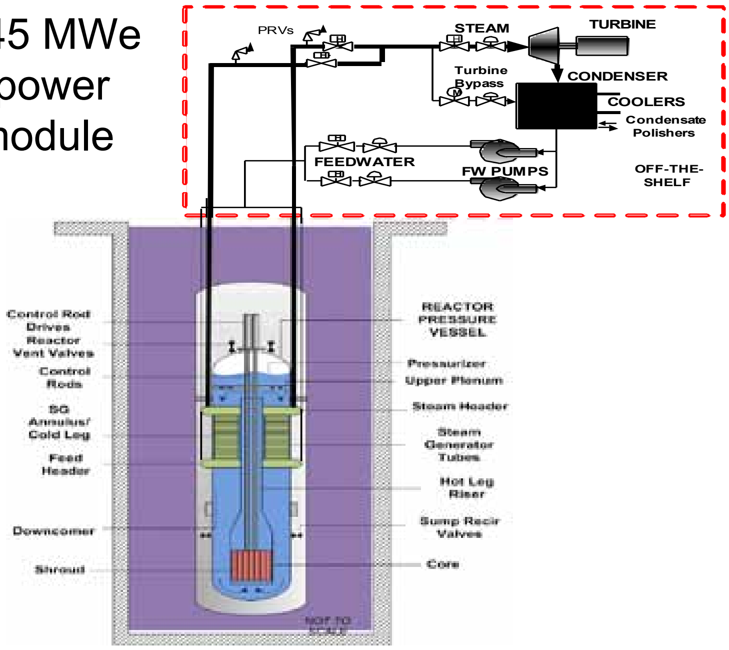


Generation III+ Modular: mPower 125MWe underground modular design (refueling after 4.5 yr

(www.babcock.com/products/modular_nuclear/)

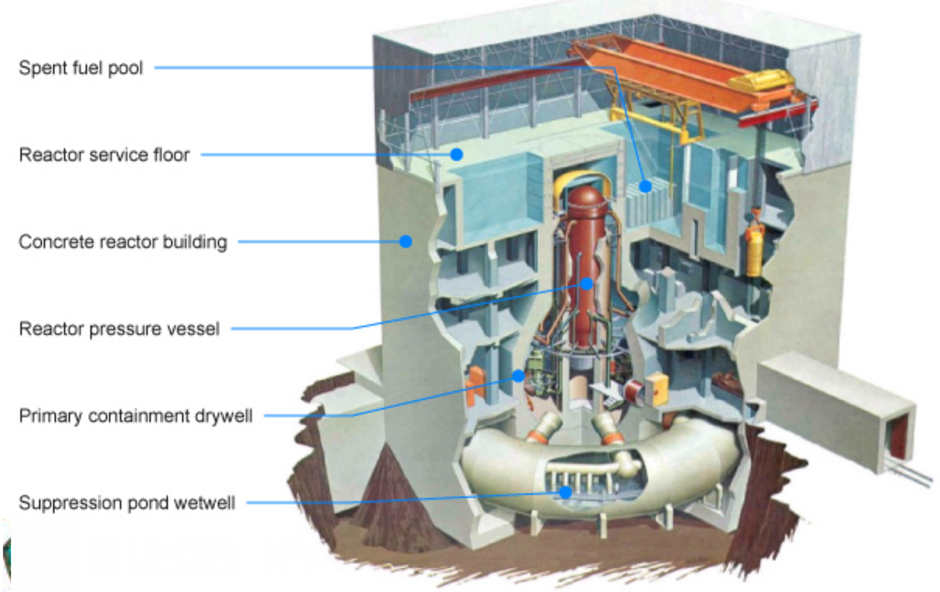


NuScale 45 MWe nuclear power station module



Fukushima reactors, 460, 784 & 1100 MWe

(1960's Generation II GE Boiling Water Reactor design)
http://world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Fukushima-Accident-2011/#.UbfgTRZOnfg



Fukushima Daiichi reactor design parameters

(Fukushima Daiichi Accident – Technical Causal Factor analysis, EPRI, March 2012, Table 1)
(http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001024946)

1960's design, Total rated power output = 4700 MWe

Unit	Startup	MWe Output	Reactor Type, Containment	High Pressure Cooling*
1	1971	460	BWR-3, Mark I	IC, HPCI
2	1974	784	BWR-4, Mark I	RCIC, HPCI
3	1976	784	BWR-4, Mark I	RCIC, HPCI
4	1978	784	BWR-4, Mark I	RCIC, HPCI
5	1978	784	BWR-4, Mark I	RCIC, HPCI
6	1979	1100	BWR-5, Mark II	RCIC, HPCS

* IC: Isolation Condenser; RCIC: Reactor Core Isolation Cooling; HPCI: High Pressure Coolant Injection; HPCS: High Pressure Core Spray

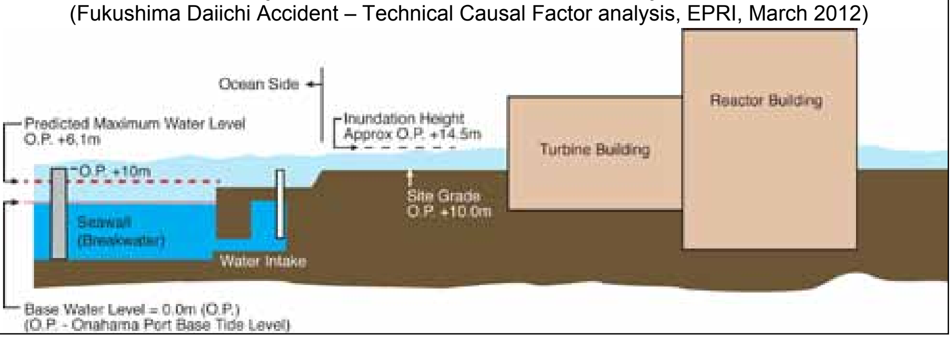
Japan Nuclear Regulator had granted Unit 1 a 10 year life extension in Feb 2011

Fukushima Daiichi prior to accident

(Fukushima Daiichi Accidentt – Technical Causal Factor analysis, EPRI, March 2012)
(http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001024946)

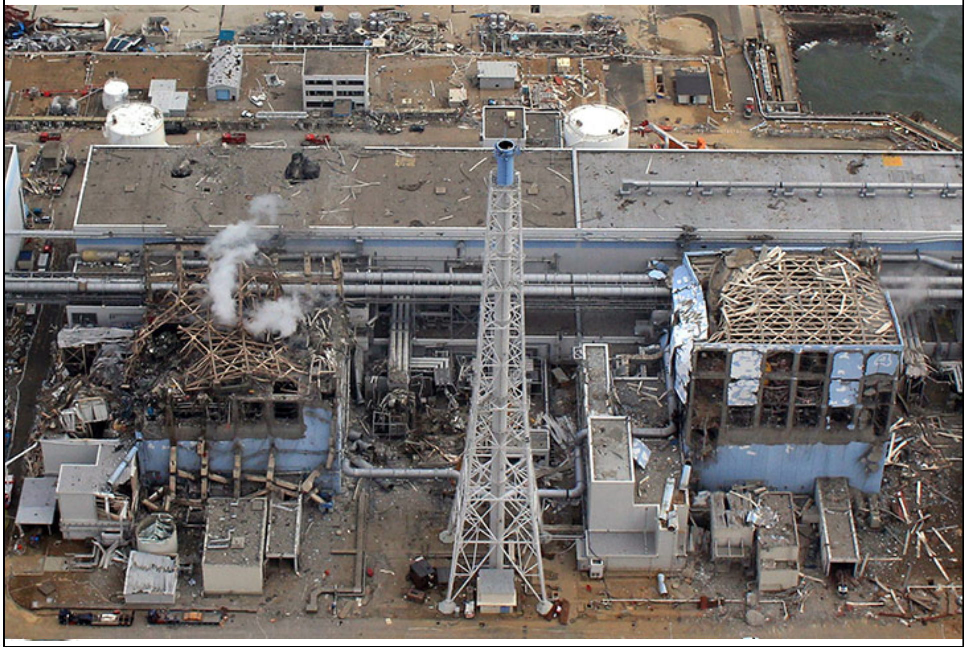
Tsunami impact on Fukushima Daiichi power station

(Fukushima Daiichi Accident – Technical Causal Factor analysis, EPRI, March 2012)



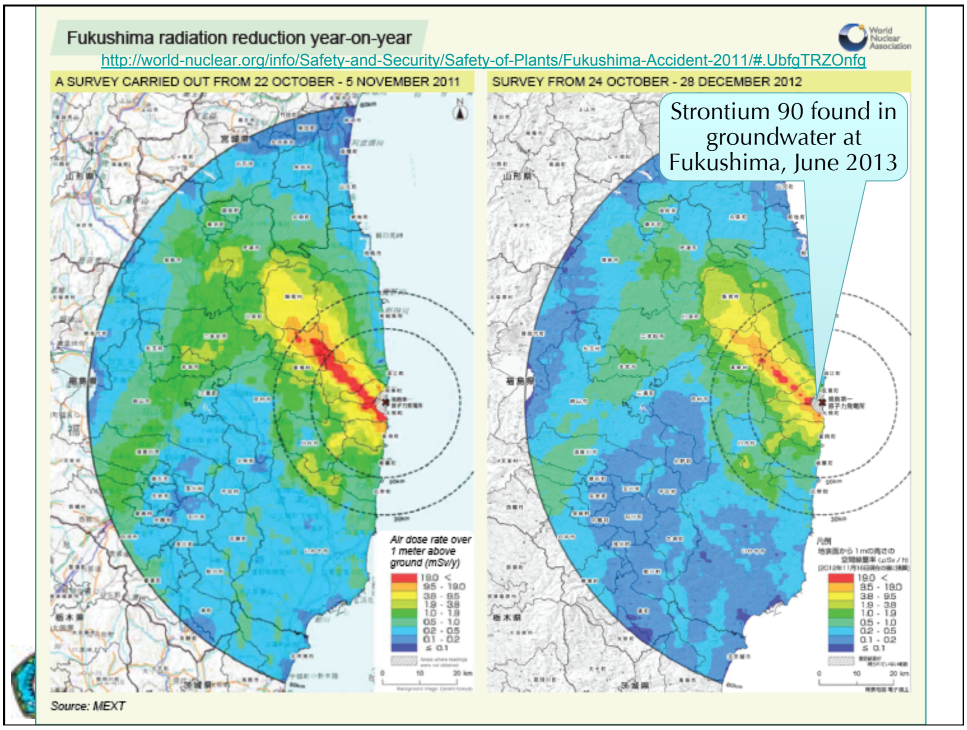
Fukushima Daiichi Reactors 1-4 after accident

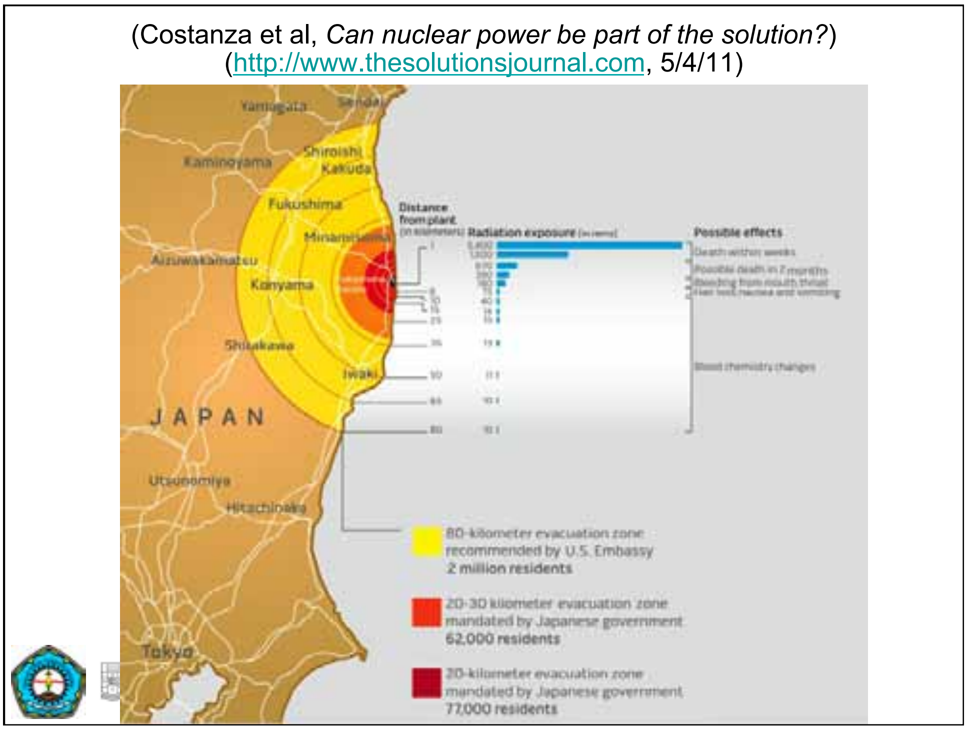
Fukushima Daiichi Units 3 & 4 after accident



http://world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Fukushima-Accident-2011/#.UbfgTRZOnfg

- Following a major earthquake, a 15-metre tsunami disabled the power supply and cooling of three Fukushima Daiichi reactors, causing a nuclear accident on 11 March 2011.
- All three cores largely melted in the first three days.
- The accident was rated 7 on the INES scale, due to high radioactive releases in the first few days. Four reactors are written off - 2719 MWe net.
- After two weeks the three reactors (units 1-3) were stable with water addition but no proper heat sink for removal of decay heat from fuel. By July they were being cooled with recycled water from the new treatment plant. Reactor temperatures had fallen to below 80oC at the end of October, and official 'cold shutdown condition' was announced in mid December.
- Apart from cooling, the basic ongoing task was to prevent release of radioactive materials, particularly in contaminated water leaked from the three units.
- There have been no deaths or cases of radiation sickness from the nuclear accident, but over 100,000 people had to be evacuated from their homes to ensure this. Government nervousness delays their return.


Fukushima radiation reduction year-on-year
World Nuclear Association
http://world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Fukushima-Accident-2011/#.UbfqTRZOnfq
A SURVEY CARRIED OUT FROM 22 OCTOBER - 5 NOVEMBER 2011
SURVEY FROM 24 OCTOBER - 28 DECEMBER 2012
Strontium 90 found in groundwater at Fukushima, June 2013
Air dose rate over 1 meter above ground (mSv/y)
190 <
95 - 190
38 - 95
19 - 38
10 - 19
0.5 - 1.0
0.2 - 0.5
0.1 - 0.2
≤ 0.1
Source: MEXT


(Costanza et al, *Can nuclear power be part of the solution?*)
(http://www.thesolutionsjournal.com, 5/4/11)
Yamagata
Sendai
Shiroishi
Kakuda
Kaminoyama
Fukushima
Minamisoma
Aizuwakamatsu
Koriyama
Shirakawa
Iwaki
JAPAN
Utsunomiya
Hitachinaka
Tokyo
Distance from plant
Radiation exposure
Possible effects
80-kilometer evacuation zone recommended by U.S. Embassy 2 million residents
20-30 kilometer evacuation zone mandated by Japanese government 62,000 residents
20-kilometer evacuation zone mandated by Japanese government 77,000 residents

The earthquake & tsunami of 11/3/11

(Fukushima Daiichi Accident – Technical Causal Factor analysis, EPRI, March 2012)

- 9.0 magnitude earthquake at 14:46 JST
- First tsunami at 15.27 JST, height 14-15 m compared to design basis of 6.1 m
- In 2006, TEPCO evaluated the probability of occurrence of a credible tsunami. The study estimated the probability of the coast near the Fukushima Daiichi plant experiencing a tsunami greater than 6m to be less than 10^{-2} in the following 50-year period.

Fukushima accident: Event timeline following the earthquake at 14:46 JST on 11/3/11

(Fukushima Daiichi Accident – Technical Causal Factor analysis, EPRI, March 2012)

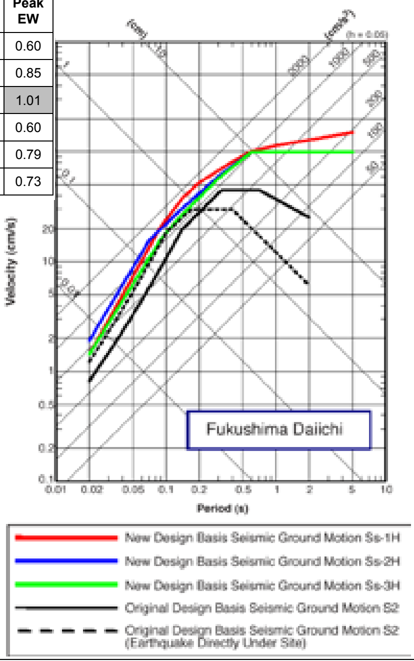
Event	Unit 1	Unit 2	Unit 3
Loss of AC power	51 min	54 min	52 min
Loss of cooling	1 hour	70 hours	36 hours
Water level down to top of fuel	3 hours	74 hours	42 hours
Core damage starts	4 hours	77 hours	44 hours
Reactor pressure vessel damage	11 hours	Uncertain	Uncertain
Fire pumps with fresh water	15 hours		43 hours
Hydrogen explosion	25 hours	87 hours	68 hours
Fire pumps with sea water	28 hours	77 hours	46 hours
Off-site electricity supply restored	11-15 days	11-15 days	11-15 days
Fresh water cooling restored	14-15 days	14-15 days	14-15 days

	Measured (g)				Max Design Basis (g)				Ratio of Measured to Design Basis			
Unit	NS	EW	VERT	Peak EW	NS	EW	VERT	Peak EW	NS	EW	VERT	Peak EW
1	0.47	0.46	0.26	0.91	0.50	0.50	0.42	1.51	0.94	0.91	0.63	0.60
2	0.35	0.56	0.31	1.23	0.45	0.45	0.43	1.45	0.79	1.26	0.72	0.85
3	0.33	0.52	0.24	1.50	0.46	0.45	0.44	1.49	0.72	1.15	0.54	1.01
4	0.29	0.33	0.20	0.87	0.46	0.45	0.43	1.46	0.63	0.72	0.47	0.60
5	0.32	0.56	0.26	1.17	0.46	0.46	0.44	1.49	0.69	1.21	0.60	0.79
6	0.30	0.45	0.25	1.03	0.45	0.46	0.42	1.40	0.67	0.99	0.59	0.73

Table above: Measured acceleration compared to Fukushima design basis

Graph right: Fukushima original design basis (black) compared to 2006 Japanese Regulatory Guide for reviewing design adequacy

(Technical Causal Factor analysis, EPRI, March 2012)



Extracts from *Fukushima Accident 2011*, World Nuclear Association

(http://world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Fukushima-Accident-2011/#.UbfgTRZOnfg 6/6/13)

- The recorded seismic data for both plants - some 180 km from the epicentre - shows that 550 Gal (0.56 g) was the maximum ground acceleration for [Fukushima] Daiichi, and 254 Gal was maximum for [Fukushima] Daini.
- Daiichi units 2, 3 and 5 exceeded their maximum response acceleration design basis in E-W direction by about 20%. The recording was over 130-150 seconds. (All nuclear plants in Japan are built on rock - ground acceleration was around 2000 Gal a few kilometres north, on sediments).
- Possible seismic damage to Daiichi condensers from the earthquake is now being investigated (June 2013)

Conclusions, Fukushima Daiichi Accident – Technical Causal Factor analysis (EPRI, March 2012)

- The technical analysis traced the cause for the eventual loss of all practical cooling paths for the reactors to the tsunami's flooding of the plant protection. Specifically, the analysis identified the significant difference between the design basis tsunami height and the actual tsunami height, as well as the limitations of beyond-design-basis tsunami protection or mitigation that could address the effects of the actual event.
- From a causal analysis perspective, these were caused by a methodology that specified that the rupture of combinations of geological fault segments in the vicinity of the plant need not be considered in establishing the design basis tsunami height. The tsunami that occurred was caused by a combined rupture of multiple fault segments.

Extracts from *Fukushima Accident 2011*, World Nuclear Association

(http://world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Fukushima-Accident-2011/#.UbfqTRZOnfg 6/6/13)

- The tsunami countermeasures taken when Fukushima Daiichi was designed and sited in the 1960s were considered acceptable in relation to the scientific knowledge then, with low recorded run-up heights for that particular coastline.
- But through to the 2011 disaster, new scientific knowledge emerged about the likelihood of a large earthquake and resulting major tsunami.
- However, this did not lead to any major action by either the plant operator, Tepco, or government regulators, notably the Nuclear & Industrial Safety Agency (NISA).
- The tsunami countermeasures could also have been reviewed in accordance with IAEA guidelines which required taking into account high tsunami levels, but NISA continued to allow the Fukushima plant to operate without sufficient countermeasures, despite clear warnings.

Conclusions of the Japanese Nuclear Accident Independent Investigation Commission (July 2012)

(http://world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Fukushima-Accident-2011/#.UbfgTRZOnfg 6/6/13)

- The commission's report concluded that the accident was a "manmade disaster," the result of "collusion between the government, the regulators and Tokyo Electric Power Co."
- Tepco had been aware since 2006 that Fukushuima Daiichi could face a station blackout if flooded, as well as the potential loss of ultimate heat sink in the event of a major tsunami
- The "root causes were the organizational and regulatory systems that supported faulty rationales for decisions and actions."
- "The consequences of negligence at Fukushima stand out as catastrophic, but the mindset that supported it can be found across Japan"

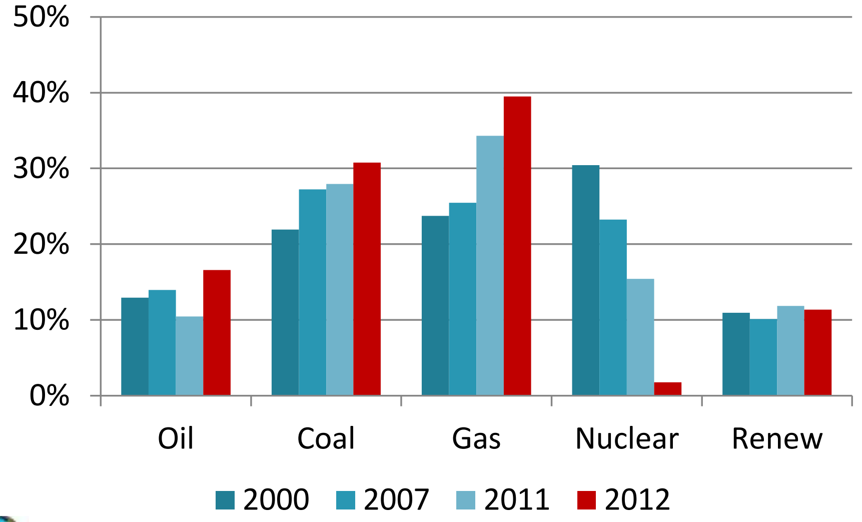
Main outcomes of Fukushima accident to date

- Permanent loss of 4700 MW nuclear power:
  - Replaced so far by increased coal & gas generation
  - Long-term radiation containment & decommissioning
- Large, on-going cost to Tokyo Electric Power & Japan
- Societal impact in Japan:
  - "Families are suffering and people have been uprooted and are concerned about their livelihoods and futures, the health of their children... it is these issues that will be the long-lasting fallout of the accident."

    (UN Scientific Committee on the Effects of Atomic Radiation, May 2013)
- Impacts on global nuclear industry:
  - Worldwide review of nuclear power plant design & nuclear industry regulation that will further increase costs
  - Public relations disaster

Japanese electricity generation shares by fuel type

(Enerdata, *Gobal Energy Balance 2012,* 30 May 2013)



Lessons from Fukushima

- Electricity supply systems are becoming more complex over time:
  - Fossil fuel constraints & climate change forcing transition to more difficult energy conversion chains
  - Unintended consequences hard to predict & avoid
- Thus, important to:
  - Explore ways to reduce design complexity:
    - E.g. modular nuclear reactors
  - Rigorously identify & investigate potential failure modes, particularly low-probability, high-impact events:
    - Eg. Complex earthquakes involving multiple faults that have severe, irreversible consequences
  - Avoid cultural blind spots indecision-making

Hugh Outhred Bsc, BE (Hons 1), PhD

Hugh Outhred is a Senior Visiting Fellow at the University of New South Wales, *Guru Besar Luar Biasa* at STTNAS Jogjakarta, Indonesia and a Director of Ipen Pty Ltd, which provides advisory and educational services on energy, society and the environment.

Hugh retired in 2007 after a 35-year career at UNSW, most recently as Presiding Director, Centre for Energy and Environmental Markets and Head, Electrical Energy Research Group, School of Electrical Engineering and Telecommunications.

During his career, Hugh has been a Fulbright Senior Fellow at the University of California Berkeley, a Lead Author for the IPCC Special Report on Renewable Energy Sources & Climate Change Mitigation, a Board Member of the Australian Cooperative Research Centre for Renewable Energy, an Associate Director of UNSW's Centre for Photovoltaic Devices and Systems, a Member of CSIRO's Energy Flagship Advisory Committee, a Member of the National Electricity Tribunal and a Member of the New South Wales Licence Compliance Advisory Board.

h.outhred@unsw.edu.au;
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