Power from Nuclear Fission

Strategic Issues

The Diablo Canyon NPPT produces CO_2-free electricity at half the state's (CA) average cost (2¢/kwh)

Strategic Issues of Nuclear Technology, Real and Perceived

Issues for any production technology:
Sustainability, reliability, safety, eco-foot print, cost, scalability
Specific issue for nuclear power: proliferation safety

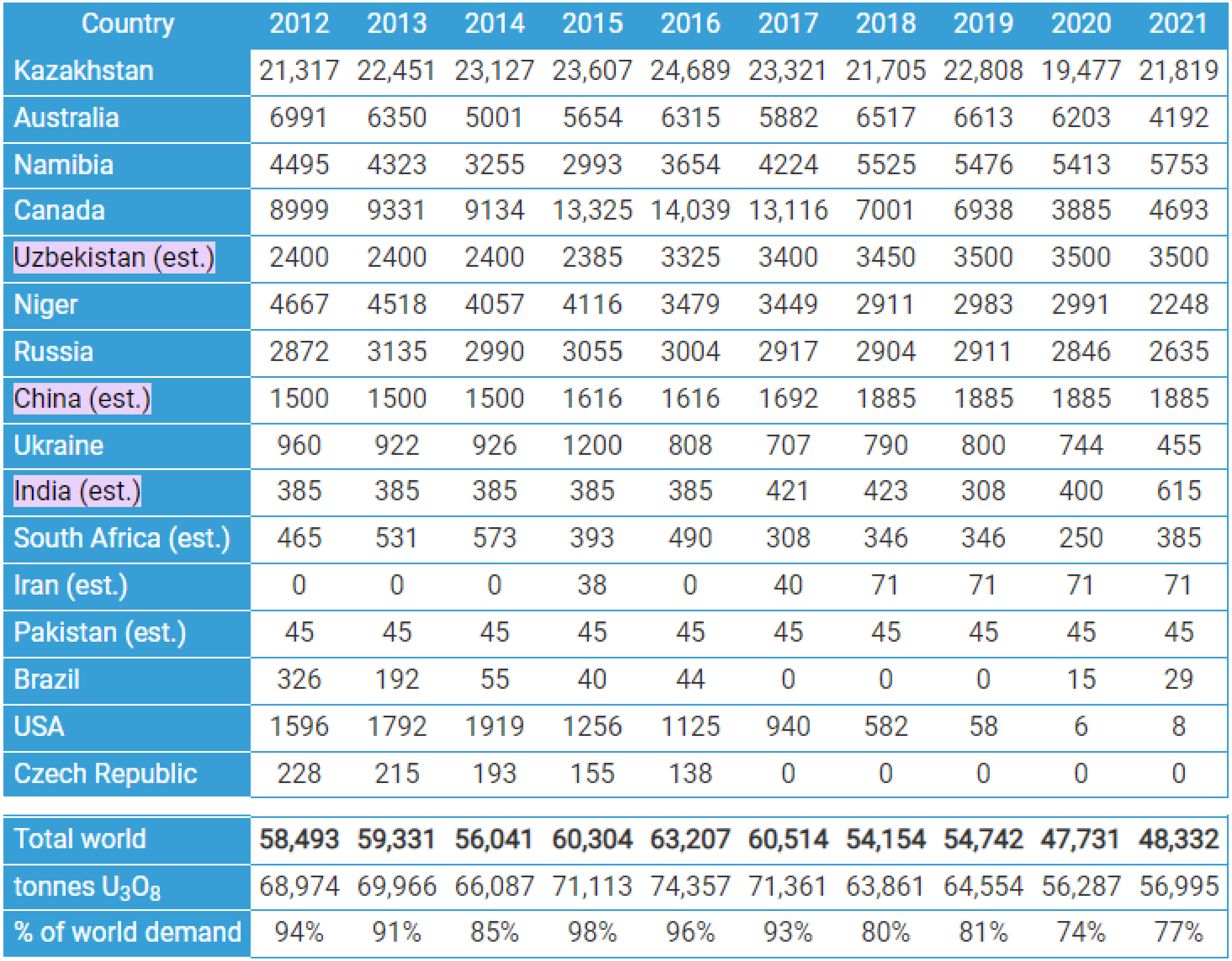
→ Relative risk/benefit analysis, levelized lifetime analysis.

Links to sections

1. Resource limits of nuclear fuel (^{235}U/Pu, Th,…) … LNK
2. Reactor reliability ………………………………………. LNK
3. Operational reactor safety/accidents …………………. LNK / LNK
4. Ecological/resources footprint …………………………… LNK
5. Safe capture and sequestration of spent fuel ……. LNK
6. Proliferation resistance (nations, individuals) …… LNK
7. Economy (Capital plus fuel costs) ………………………. LNK
8. R&D requirements ……………………………………………. LNK
9. Capability for deployment/scalability ………………… LNK
10. Public perception ………………………………………………. LNK

END

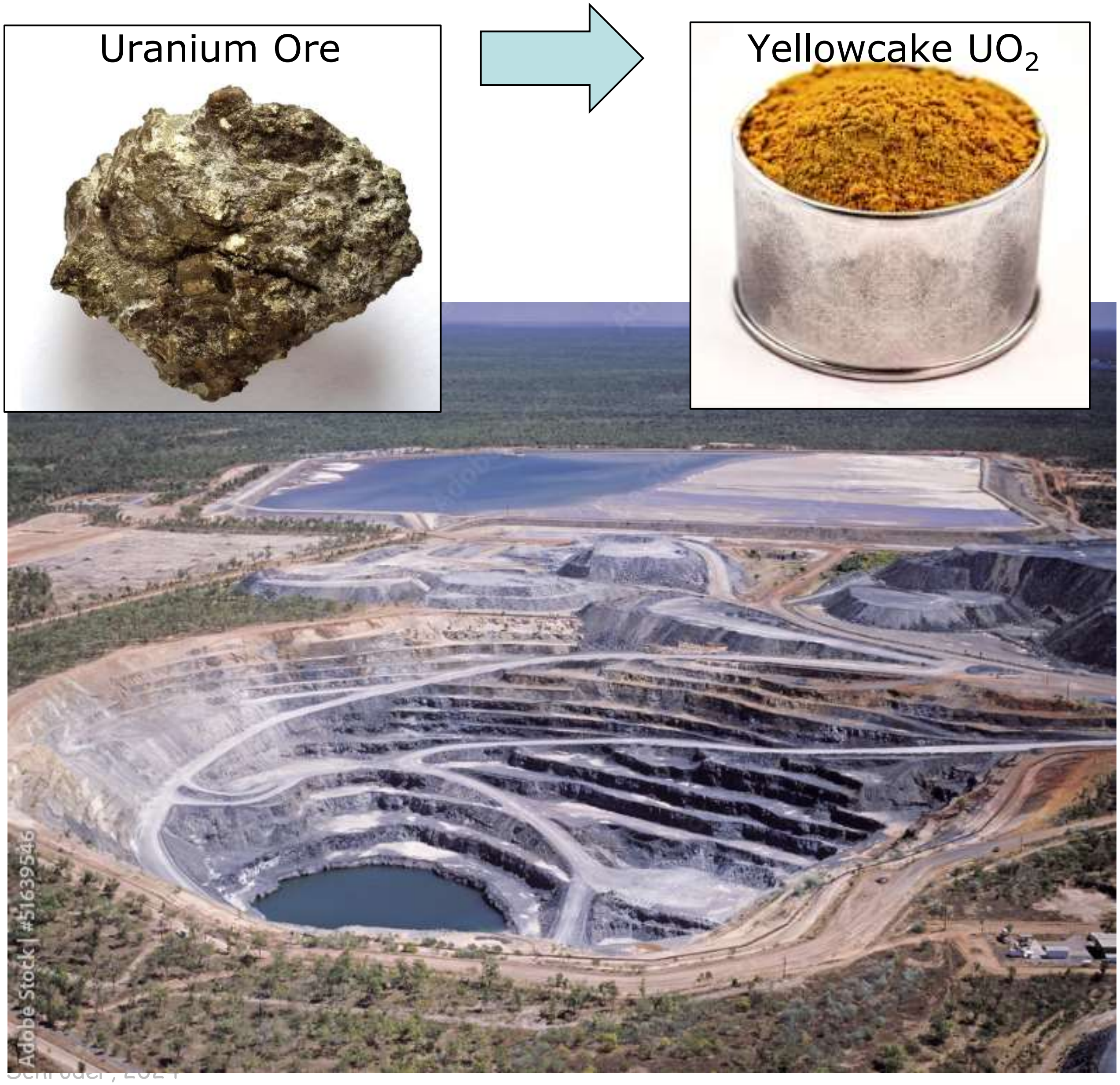
Issue 1: Resources, World Uranium Production



Country	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Kazakhstan	21,317	22,451	23,127	23,607	24,689	23,321	21,705	22,808	19,477	21,819
Australia	6991	6350	5001	5654	6315	5882	6517	6613	6203	4192
Namibia	4495	4323	3255	2993	3654	4224	5525	5476	5413	5753
Canada	8999	9331	9134	13,325	14,039	13,116	7001	6938	3885	4693
Uzbekistan (est.)	2400	2400	2400	2385	3325	3400	3450	3500	3500	3500
Niger	4667	4518	4057	4116	3479	3449	2911	2983	2991	2248
Russia	2872	3135	2990	3055	3004	2917	2904	2911	2846	2635
China (est.)	1500	1500	1500	1616	1616	1692	1885	1885	1885	1885
Ukraine	960	922	926	1200	808	707	790	800	744	455
India (est.)	385	385	385	385	385	421	423	308	400	615
South Africa (est.)	465	531	573	393	490	308	346	346	250	385
Iran (est.)	0	0	0	38	0	40	71	71	71	71
Pakistan (est.)	45	45	45	45	45	45	45	45	45	45
Brazil	326	192	55	40	44	0	0	0	15	29
USA	1596	1792	1919	1256	1125	940	582	58	6	8
Czech Republic	228	215	193	155	138	0	0	0	0	0
Total world	**58,493**	**59,331**	**56,041**	**60,304**	**63,207**	**60,514**	**54,154**	**54,742**	**47,731**	**48,332**
tonnes U_3O_8	68,974	69,966	66,087	71,113	74,357	71,361	63,861	64,554	56,287	56,995
% of world demand	94%	91%	85%	98%	96%	93%	80%	81%	74%	77%

Metric tons

Uranium Surface Mining



2021: Main Uranium producing countries

Kazakhstan (45% of world supply),
Namibia (12%)
Canada (10%) .
Uzbekistan
China
India

Issue 1: Nuclear Fuel Resources

World (US)
443 (103) reactors
365 (100) GW

U use: 2 kt/a
World reserves: 5 Mt known (15 est.)
Once-through cycle:200 years

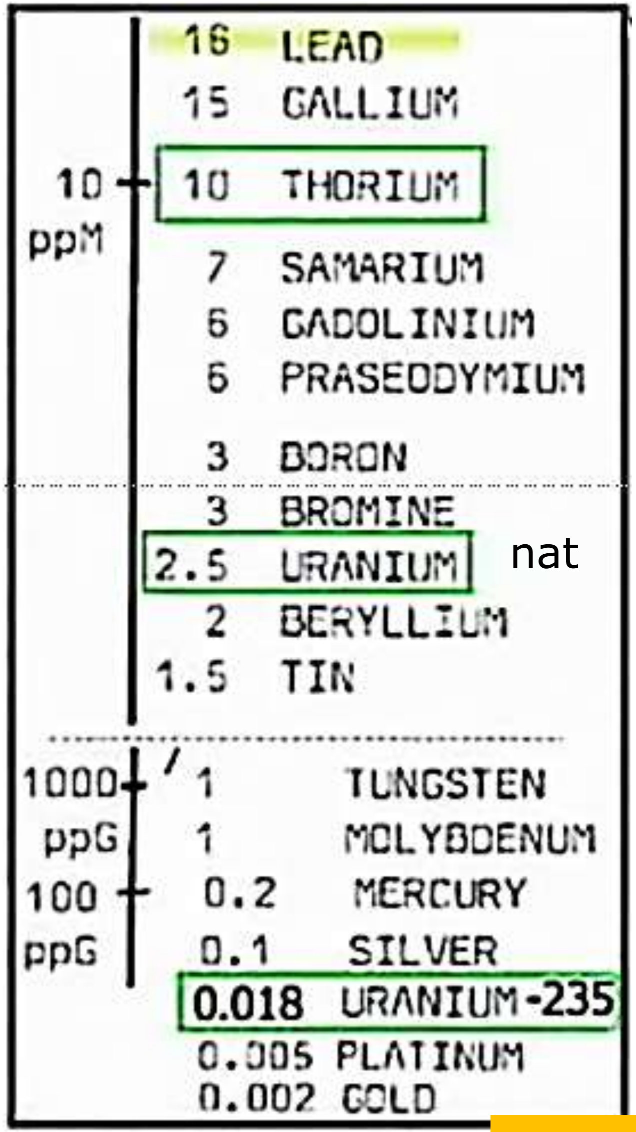
Reprocessing: ~10^3 years
US:174 t weapons grade U +20t/a Pu for fuel mix (→ 0.2 Mt fuel)

Th use: little yet (India ramping up)
World reserves >15 Mt ~10^3 a with reprocessing.

Gen III+ & IV breeder (^{238}U, ^{232}Th) reactors, molten salt reactors

→ essentially sustainable nuclear energy resources

Reserves in Earth crust



16	LEAD
15	GALLIUM
10	THORIUM
7	SAMARIUM
6	GADOLINIUM
6	PRASEODYMIUM
3	BORON
3	BROMINE
2.5	URANIUM
2	BERYLLIUM
1.5	TIN
1	TUNGSTEN
1	MOLYBDENUM
0.2	MERCURY
0.1	SILVER
0.018	URANIUM-235
0.005	PLATINUM
0.002	GOLD

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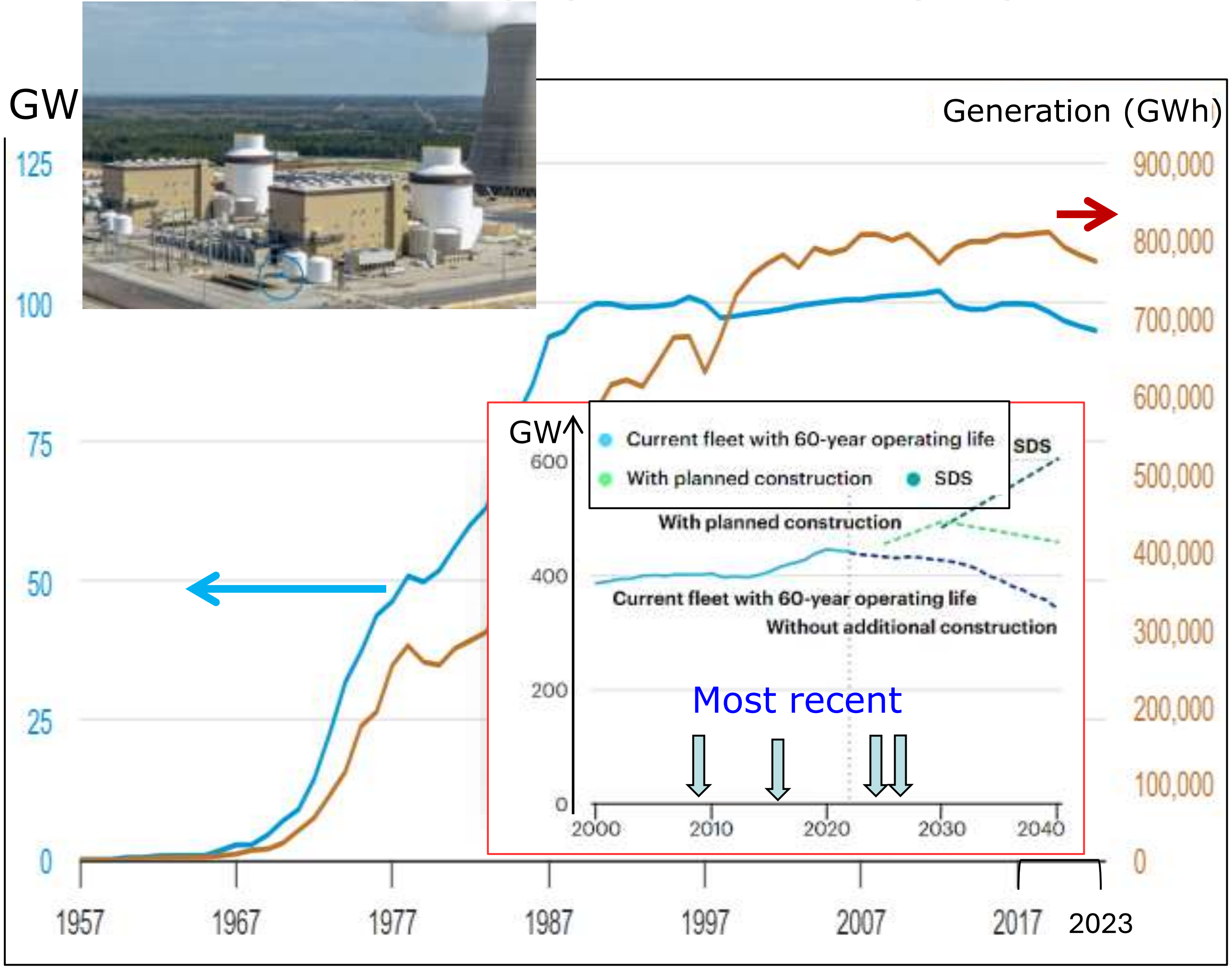
Issue 2:Reliability of Nuclear Power

Steady increase of nuclear power output over 40y. **Efficiency** ε ↗

Now: ε ≧ 90% → equivalent: 24 quads of oil. NPP useful lifetime 40a → **>60a**

World 2023 (US): 440 (92) reactors; 400 (100) GW, 2.5 PWh → Modernize !



World Trend
>63 under constr
→2050:>600GW
US(>2012):+3-6
> 20 planned (?)
license app, financing risks

US potential:
1.**LTO** Extend plant lifetime, uprate
2.*New* reactors/a
(@ **$**(3-4)**B**/GW$_e$ → (5-10)¢/kWh)

Proved Na/Pb-cooled technology
SMRs deployment
New Microreactors
New companies

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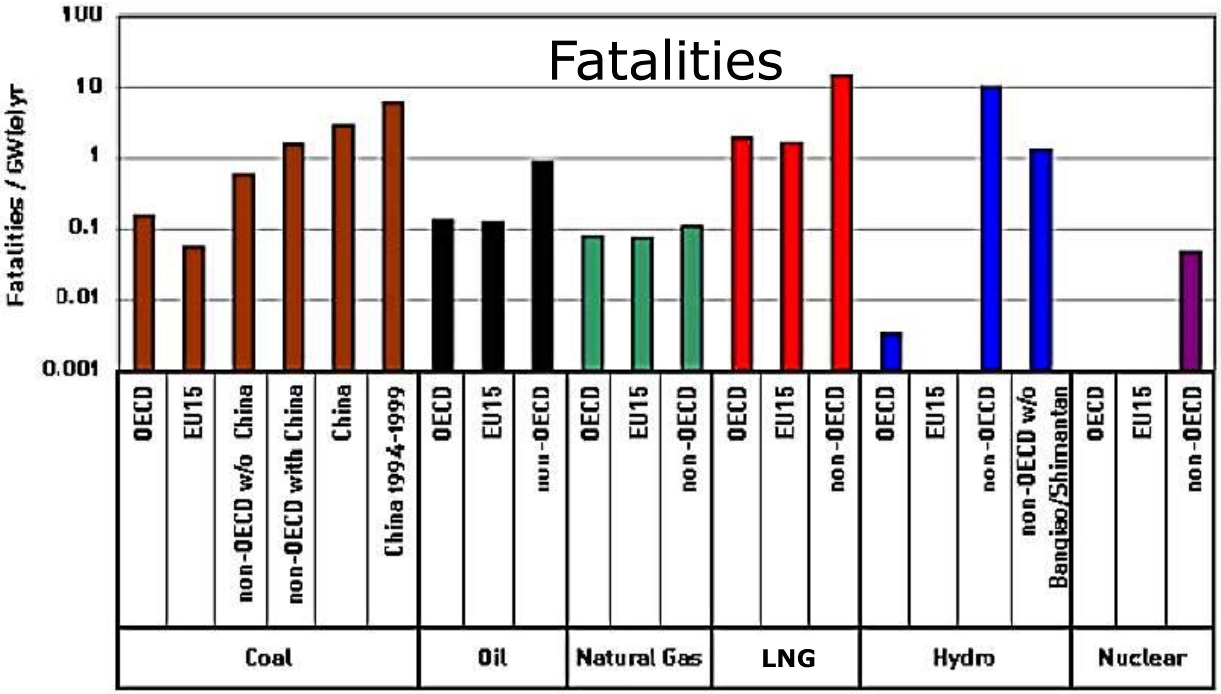
Discussion of TMI, Chernobyl and Fukushima reactor accidents → LNK

Issue 3: Safety in Energy Production (1969-2000)



Chernobyl/Ukraine
1986: 45 † (+2?)
90,000 displaced.

Comparative study by Paul Sherrer-Institute/Switzerland.
Omitted: large hydro disasters Shimantan and Banqiao (China 1976: 26,000†).
1959 Malpasset (Frejus) dam rupture resulted in 423†, 7,000 persons displaced.
2009 Three Gorges Dam (China): > 2,000,000 persons permanently displaced.

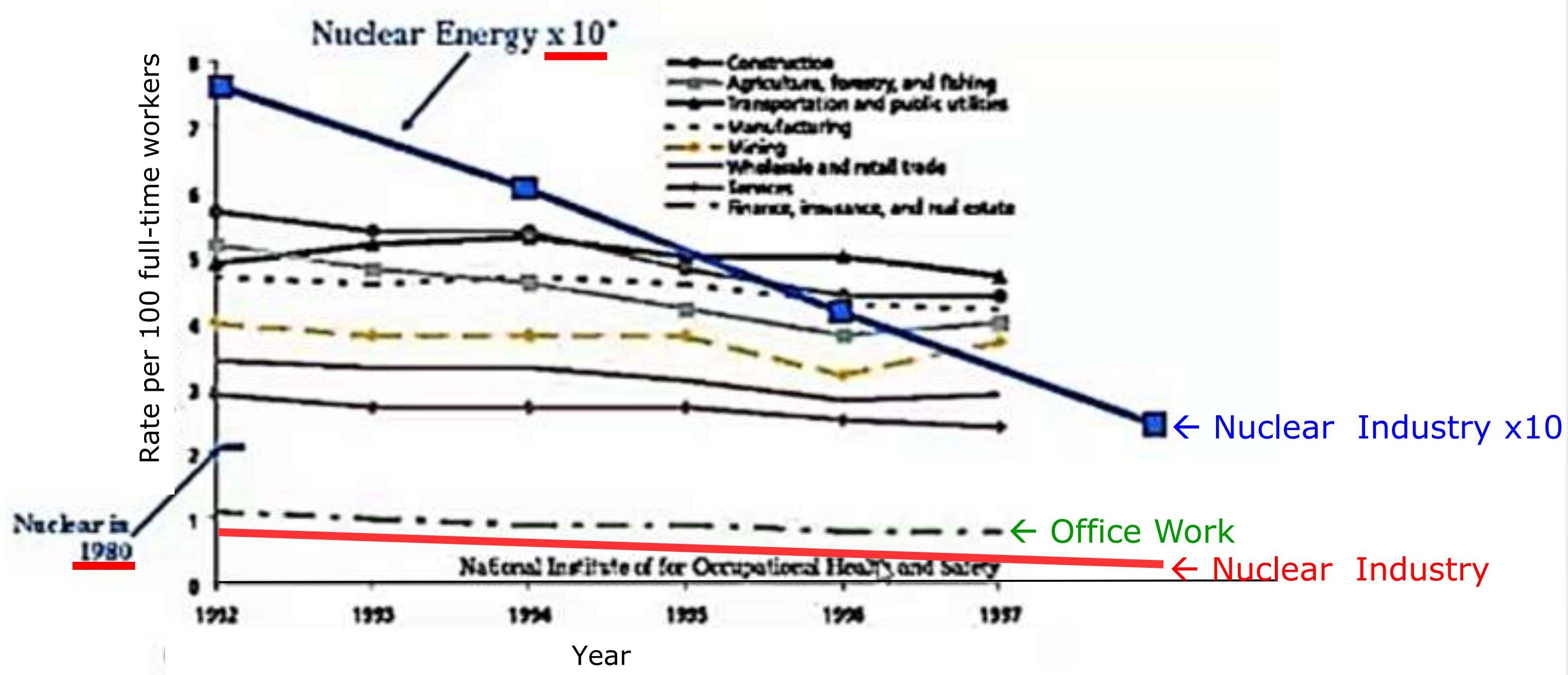
2006 U.S. coal mines : 42† (equivalent 1 Chernobyl nuclear accident/a)
Many fatalities since 2000 in coal mines, on oil fields & drilling rigs, refineries…

Discussion of TMI, Chernobyl and Fukushima reactor accidents → LNK

Issue 3: Worker Safety in Nuclear Power Industry

Significant changes in safety culture since the 1980s → improved safety record, now unparalleled in industry.

Non-fatal accidents in various US industries



After: P. F. Peterson, UC Berkeley, O'Reilly Webcast 2009

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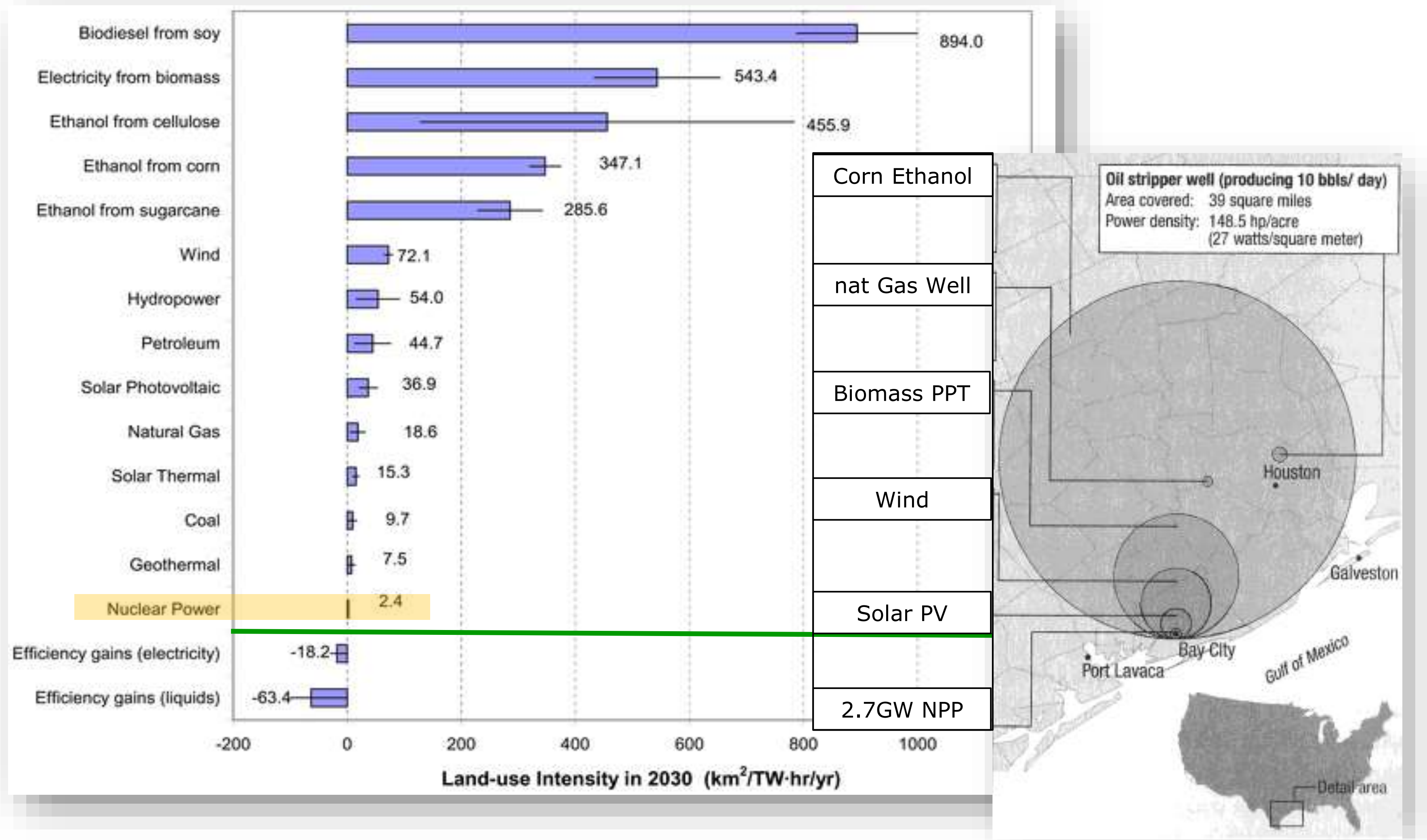
Issue 4: Eco-Footprint, Land Use



Corn Ethanol

nat Gas Well

Biomass PPT

Wind

Solar PV

2.7GW NPP

McDonald RI, Fargione J, Kiesecker J, Miller WM, et al. (2009) Energy Sprawl or Energy Efficiency: Climate Policy Impacts on Natural Habitat for the United States of America. PLoS ONE 4(8): e6802. doi:10.1371/journal.pone.0006802
http://www.plosone.org/article/info:doi/10.1371/journal.pone.0006802

R. Bryce, Power Hungry, Public Affairs, NY, 2010

Issue 4: Commodity Use of Nuclear Technologies

		Iron [kg / GWh$_{el}$]	**Copper** [kg / GWh$_{el}$]	**Bauxite** [kg / GWh$_{el}$]
Coal (43 %)		2308	2	20
Lignite (40 %)		2104	8	19
Gas CC (57.6 %)		969	3	15
Nuclear (PWR, ult. waste dispo.)		445	6	27
PV	poly	6708	251	2100
(5 kW)	amorph	8153	338	2818
Wind	5.5 m/s	5405	66	54
(1 MW)	4.5 m/s	10659	141	110
Hydro (3.1 MW)		2430	5	10

Source: Thesis Marheineke, Stuttgart University

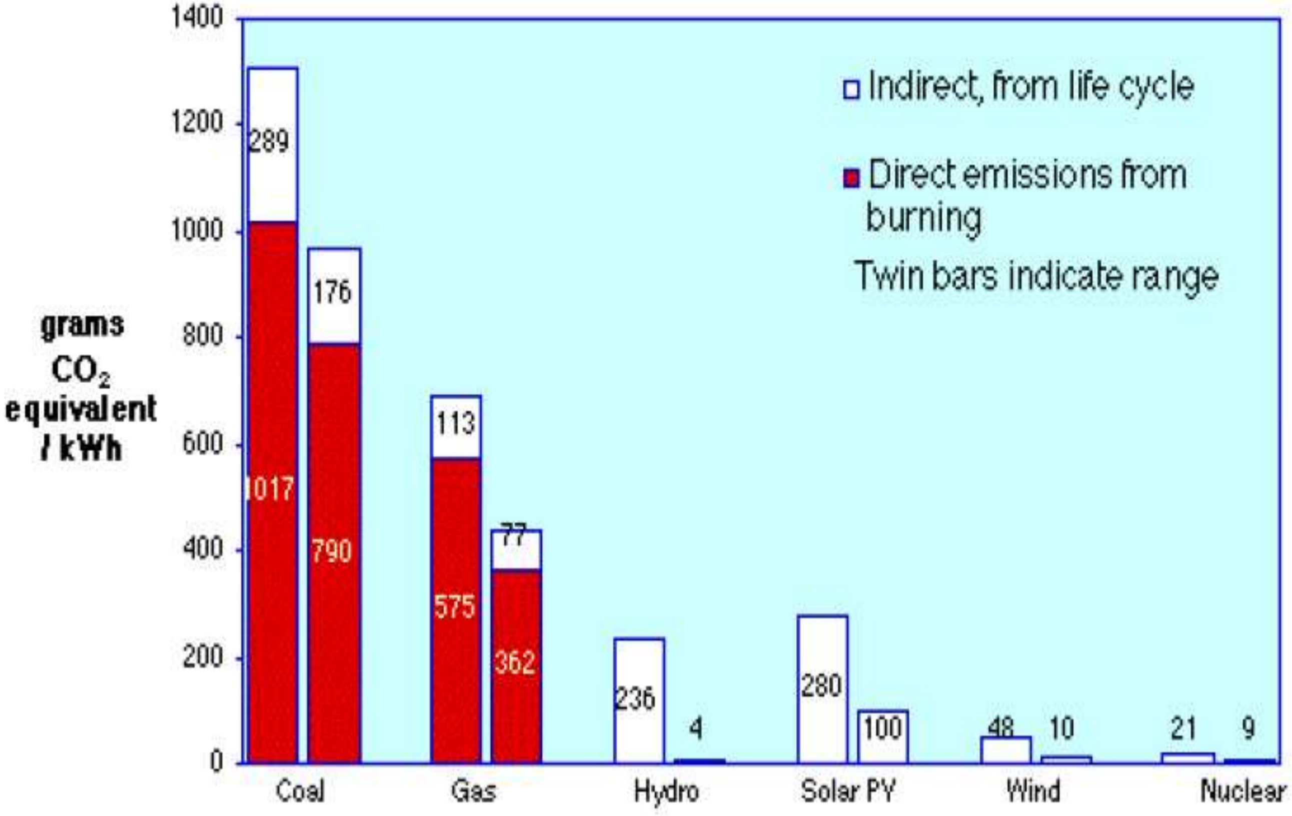
Use of concrete (Ex: Milford Wind Corridor, 300 MW installed, Utah, 2009)
139 turbines @ 40 mi^2, 44,344 m^3 concrete (319 m^3/MW), 14.3 Mgal H_2O,

NPP: 90 m^3/MW concrete, 40 t/MW steel.
Cooling water use is similar for all thermal plants.

R. Bryce, Power Hungry, Public Affairs, NY, 2010

Issue 4: Eco-Footprint, Emissions (GHG, Particles, Toxins)

Greenhouse Gas Emissions from Electricity Production



Source: IAEA 2000

Nuclear power: High power density → small environmental footprint, low emissions

GHG (fossile):
CH_4, CO_2, NO_x, SO_x, H_2O

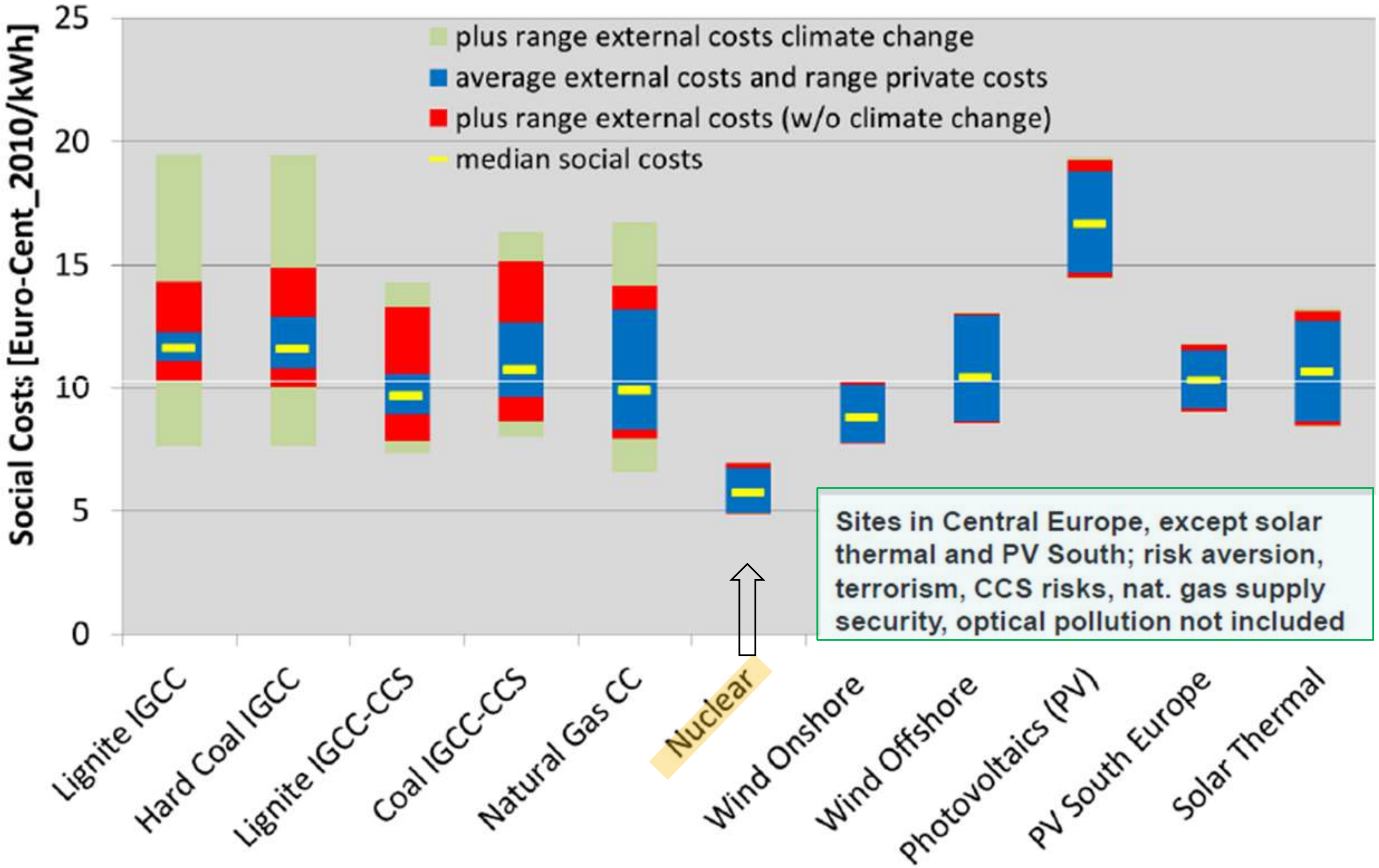
Other (fossile):
Particles $PM_{2.5}$,

Metals (coal, oil):
(Be,…., Hg, U, Th)

Chemical toxins
(Solid-state PV)

Radiotoxins
(99% from coal, airbn: 80-100 t U/a
nuclear fuel residues: Fiss Frgm, Min Actin., localized + decays)

Issue 4: Eco/Social Costs of Energy Technologies



Sites in Central Europe, except solar thermal and PV South; risk aversion, terrorism, CCS risks, nat. gas supply security, optical pollution not included

Courtesy A. Mueller, NNC2012,
Data from R. Friedrich, E2C Maastricht 2012

Universität Stuttgart
Institut für Energiewirtschaft und Rationelle Energieanwendung
IER

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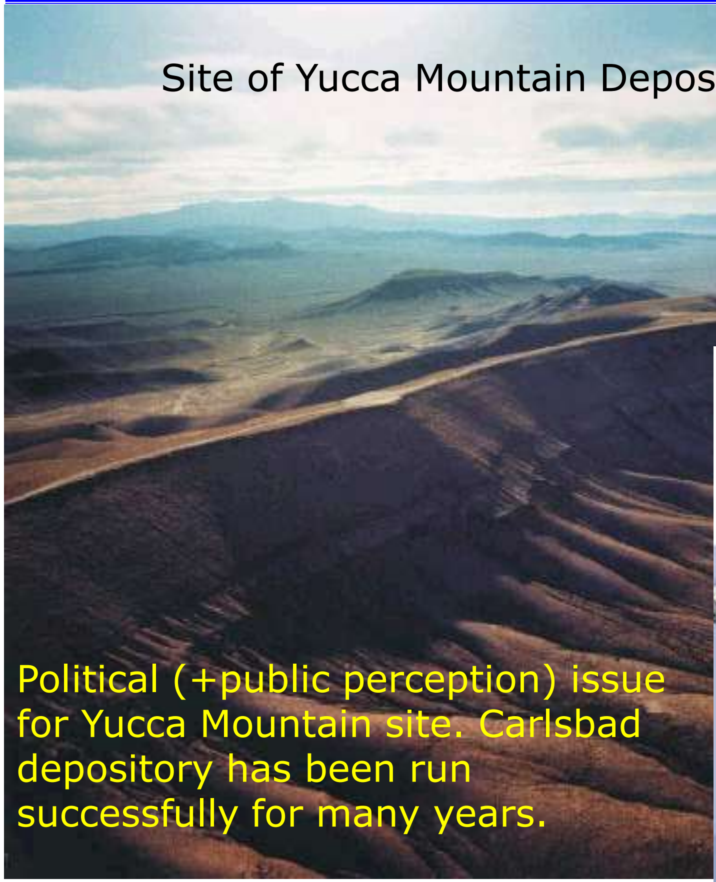
Issue 5: Capture and Sequestration of HL Waste

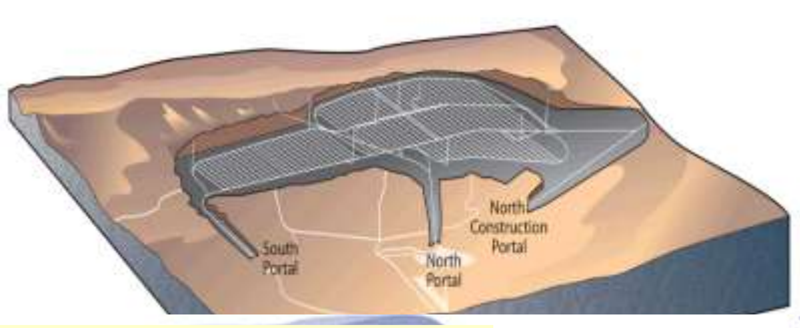


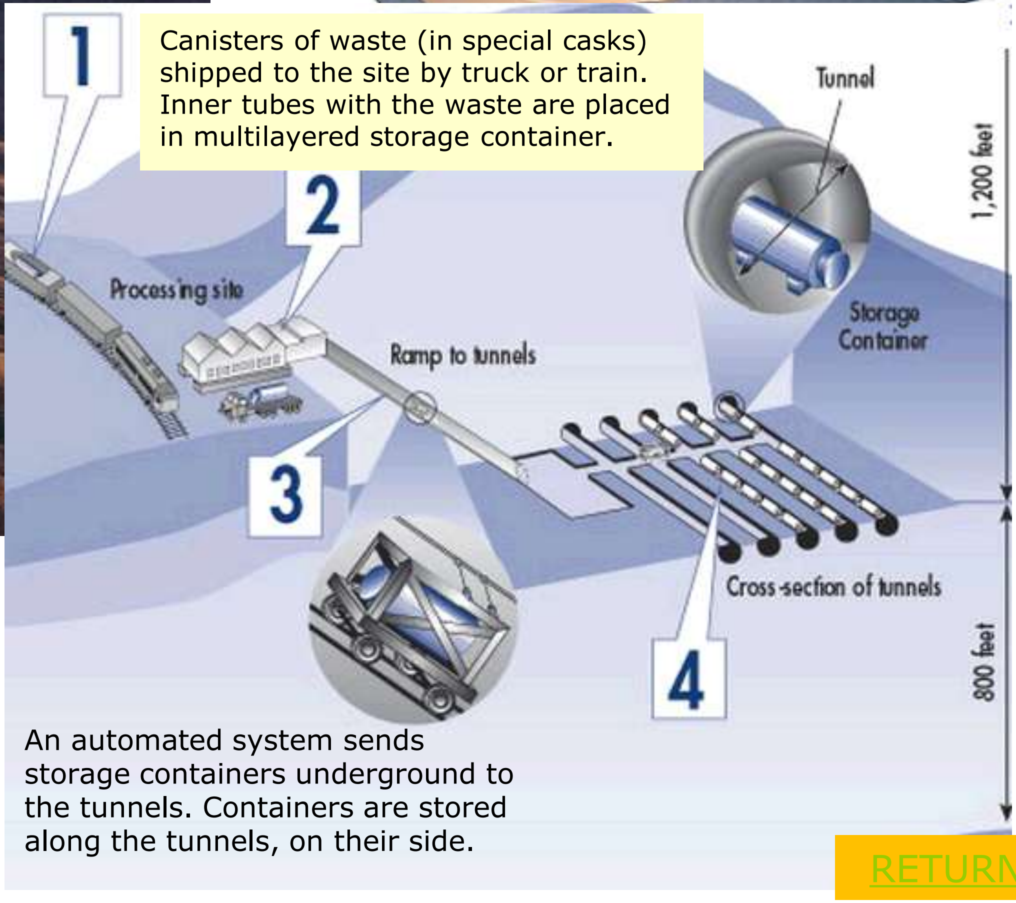
Site of Yucca Mountain Depository

Political (+public perception) issue for Yucca Mountain site. Carlsbad depository has been run successfully for many years.

Costs have been paid by industry.

→ Change public opposition to depository by education, Gen IV Th reactors, reprocessing/ incineration, reduce lifetime & amount of HL waste.





Canisters of waste (in special casks) shipped to the site by truck or train. Inner tubes with the waste are placed in multilayered storage container.

An automated system sends storage containers underground to the tunnels. Containers are stored along the tunnels, on their side.

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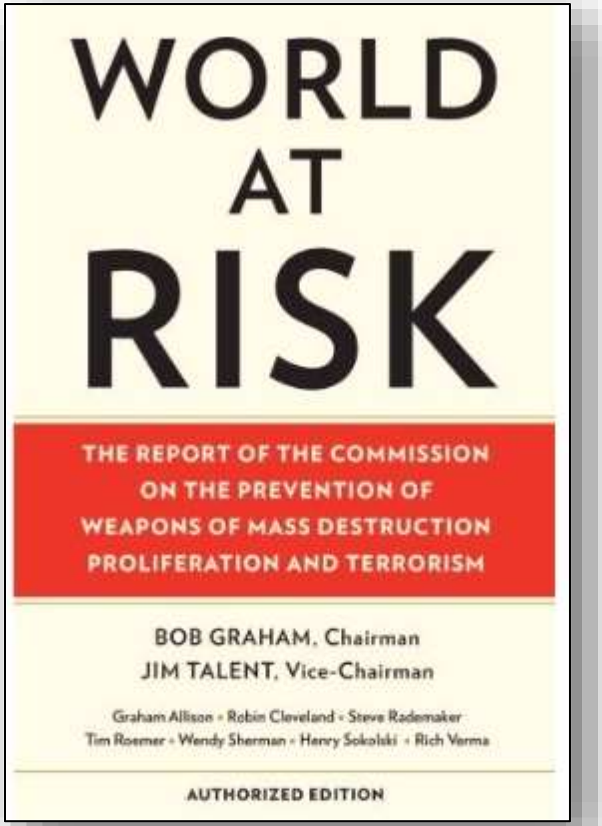
Issue 6: Nuclear Proliferation



WORLD AT RISK

THE REPORT OF THE COMMISSION ON THE PREVENTION OF WEAPONS OF MASS DESTRUCTION PROLIFERATION AND TERRORISM

BOB GRAHAM, Chairman
JIM TALENT, Vice-Chairman

Graham Allison · Robin Cleveland · Steve Rademaker
Tim Roemer · Wendy Sherman · Henry Sokolski · Rich Verma

AUTHORIZED EDITION

Threat from individuals, not from nation states.
Illicit trade in weapons-grade ^{235}U or ^{239}Pu.

Weaponized ^{235}U or ^{239}Pu: > 90% enriched
Need ~ (10-20) kg for one weapon.

Reactor materials: low-enriched mix of isotopes

Nuclear power plants in a specific country are neither necessary nor sufficient for production of nuclear weapons.

Minimize residual risk: Th fuels (MSR), close reprocessing/fuel cycle,
deploy small, self-contained reactor units,...

" At present, nine countries have developed and possess nuclear weapon stockpiles, each in the proclaimed interest of national security. In fact, for a nuclear-armed country the presumed retaliation for a first-strike nuclear attack on another nuclear country is a strong deterrence of such use and of war-like conflict resolution in general.

And perhaps for these reasons, despite much international tension and a number of armed conflicts, in 63 years the U.S. has remained the only nation that has ever engaged in nuclear warfare. This action was taken in an epoch when nuclear retaliation was not an option for an adversary. " (from the above report)

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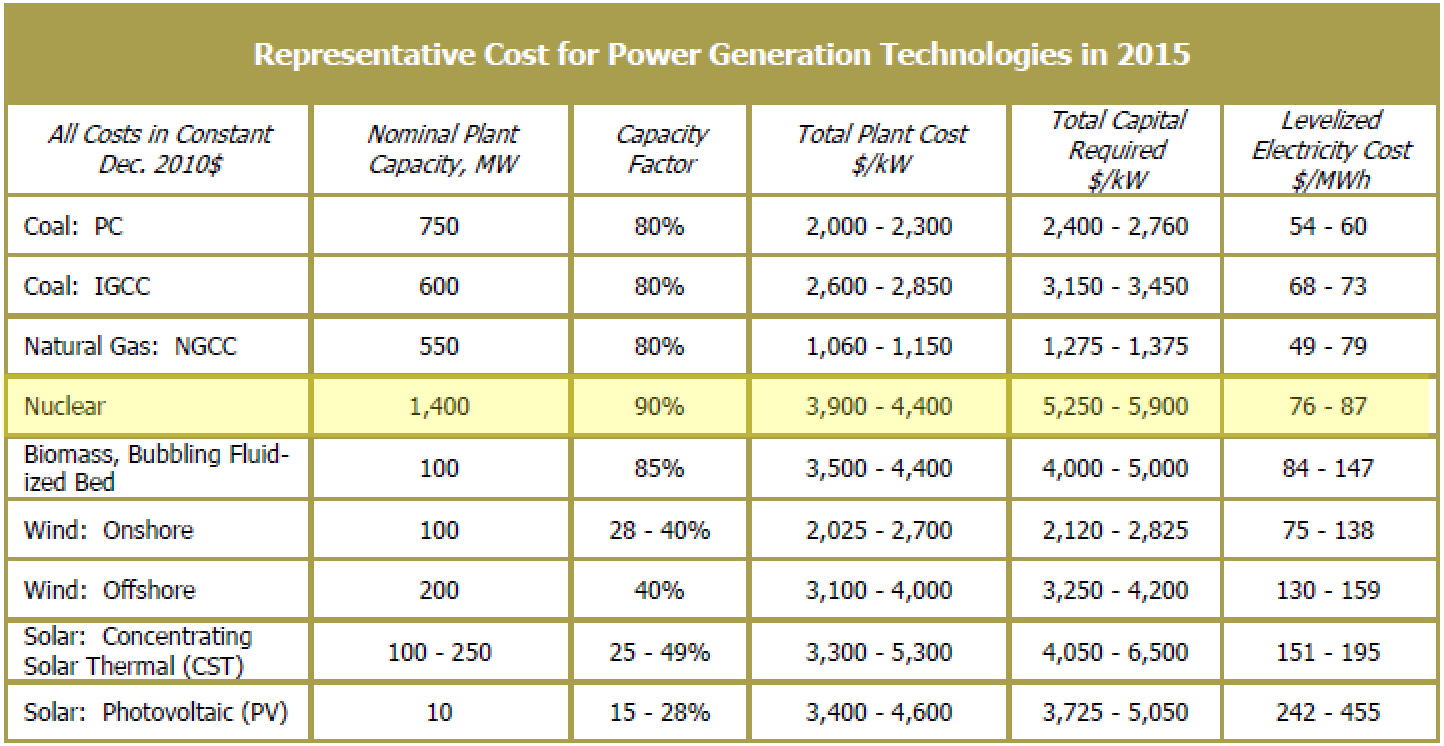
Issue 7: Cost of Nuclear Power



Representative Cost for Power Generation Technologies in 2015					
All Costs in Constant Dec. 2010$	*Nominal Plant Capacity, MW*	*Capacity Factor*	*Total Plant Cost $/kW*	*Total Capital Required $/kW*	*Levelized Electricity Cost $/MWh*
Coal: PC	750	80%	2,000 - 2,300	2,400 - 2,760	54 - 60
Coal: IGCC	600	80%	2,600 - 2,850	3,150 - 3,450	68 - 73
Natural Gas: NGCC	550	80%	1,060 - 1,150	1,275 - 1,375	49 - 79
Nuclear	1,400	90%	3,900 - 4,400	5,250 - 5,900	76 - 87
Biomass, Bubbling Fluidized Bed	100	85%	3,500 - 4,400	4,000 - 5,000	84 - 147
Wind: Onshore	100	28 - 40%	2,025 - 2,700	2,120 - 2,825	75 - 138
Wind: Offshore	200	40%	3,100 - 4,000	3,250 - 4,200	130 - 159
Solar: Concentrating Solar Thermal (CST)	100 - 250	25 - 49%	3,300 - 5,300	4,050 - 6,500	151 - 195
Solar: Photovoltaic (PV)	10	15 - 28%	3,400 - 4,600	3,725 - 5,050	242 - 455

Over 40a

Source: Electric Power Research Institute Program on Technology Innovation: Integrated Generation Technology Options, June 2011.

Fuel, 1 GWe BWR or PWR: Average (2011) ¢0.68 /kWh.
One reload (replacing 1/3 of core) = $40 million (18-month refueling cycle).

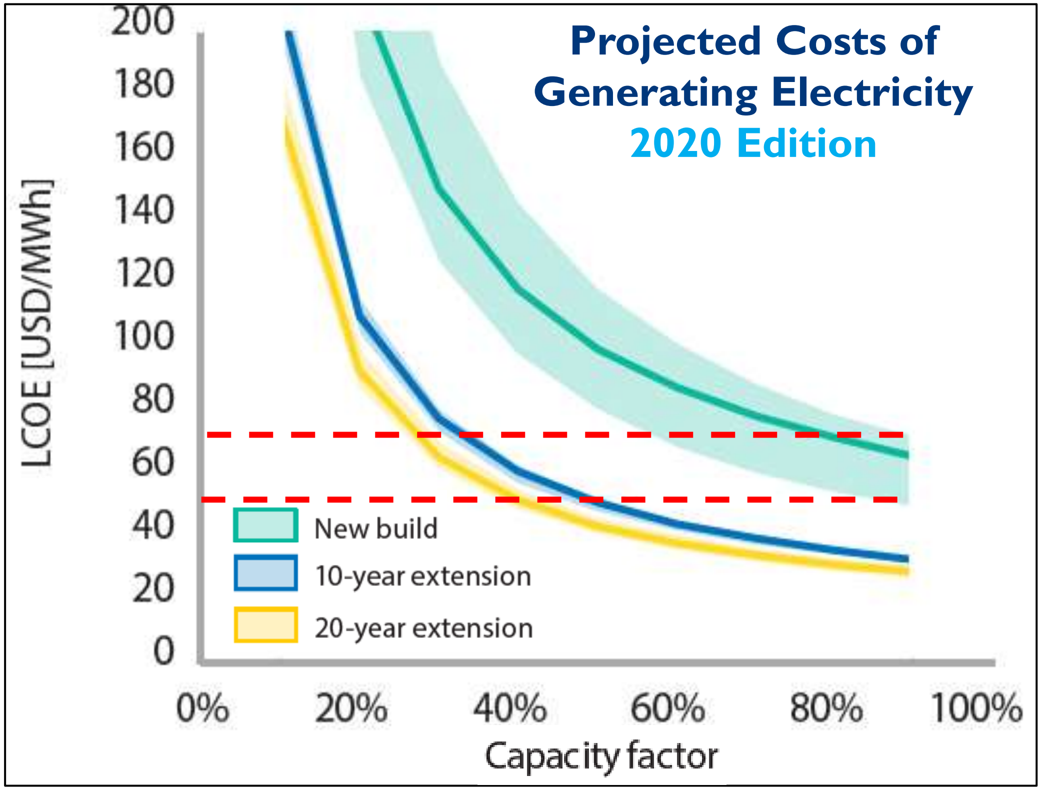
Non-fuel O&M cost for NPP (2011) =1.51 cents / kWh.

Nuclear Waste Fund $35.8 billion (¢0.1/kWh of generated electricity since 1983), included in the fuel costs. $10.8 billion spent (Yucca Mountain).

Capital investment at the start (construction of plant vs. costs in fuel and O&M).

Long useful life of NPPs > 40-60 a.

Issue 7: Cost of Nuclear Plants & Electricity



2020 Report IEA & NEA

U.S. EIA: 2023 (<2050) Advanced NP LCOE ≈ $110/MWh

PV LCOE ≈ $55/MWh (2023) → $25/MWh (2050).

Wind (on sh.) LCOE ≈ $40/MWh (2023) → $35/MWh (2050).

Similar trends for EU, China, India

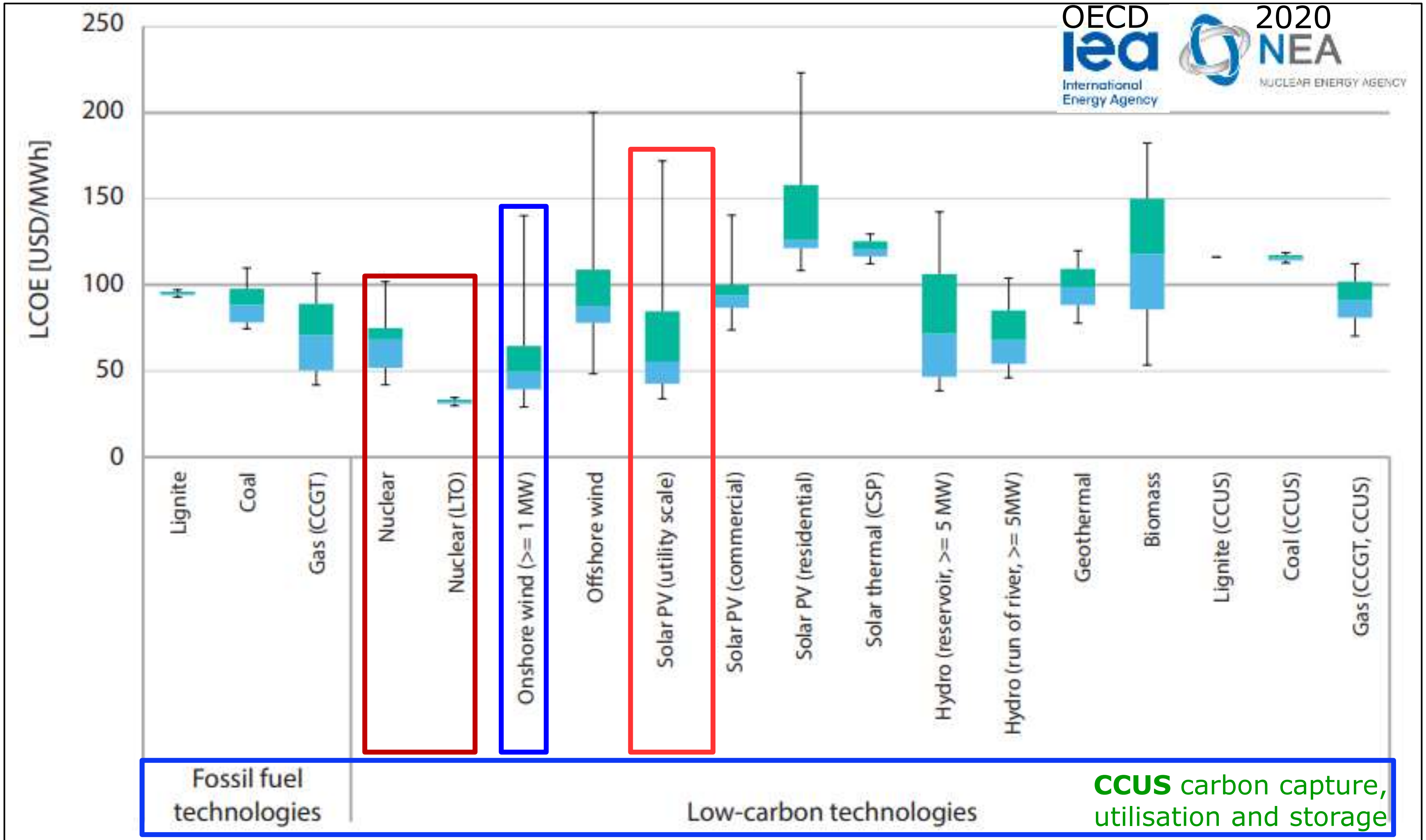
Sugg. economic strategy: Extended Lifetime Operations **(LTO)** of existing plants, with substantial upgrades (Electrical, Instrumentation Civil Works,..)

Overnight LTO investment costs (USD/kWe)	LWR LTO LCOE (USD/MWh)					
	10 years			20 years		
	Discount rate			Discount rate		
	3%	7%	10%	3%	7%	10%
	Capacity factor = 85%					
450	29.4	31.2	32.6	26.4	28.6	29.7
700	33.4	36.1	38.3	28.7	31.4	33.8
950	37.4	41.1	44.1	31.0	34.7	38.0

Discount Rate:
a)financing cost
b) perceived risk
c) inflation

~$0.03/kWh

Issue 7: Levelized Cost of Electricity (2020)

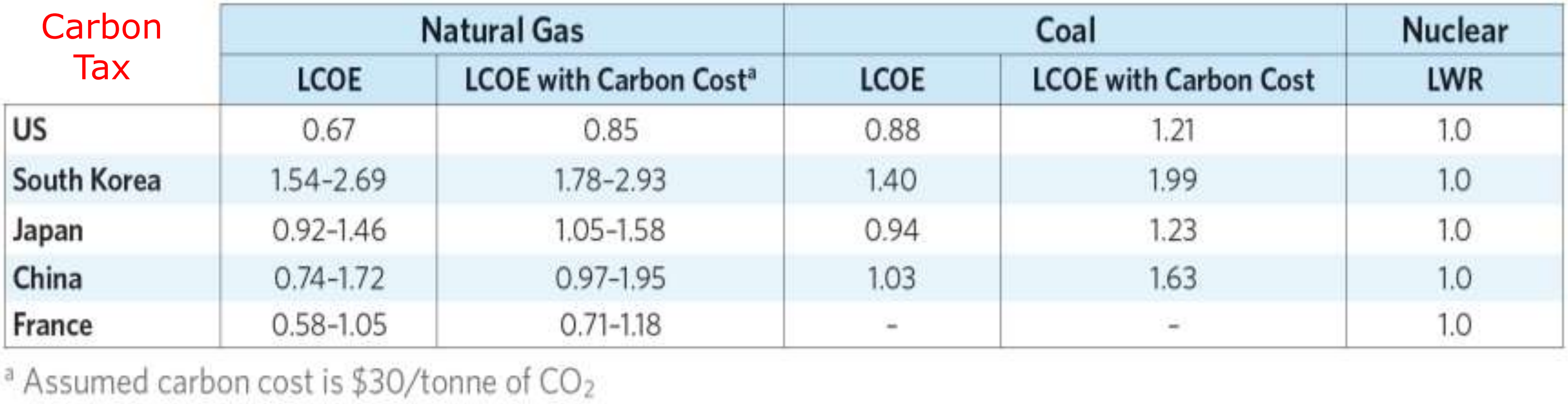


CCUS carbon capture, utilisation and storage

Note: Values at 7% discount rate. Box plots indicate maximum, median and minimum values. The boxes indicate the central 50% of values, i.e. the second and the third quartile.

Issue 7: Comparison of LCOEs w/wo Carbon Tax

Carbon Tax



	Natural Gas		Coal		Nuclear
	LCOE	LCOE with Carbon Cost[a]	LCOE	LCOE with Carbon Cost	LWR
US	0.67	0.85	0.88	1.21	1.0
South Korea	1.54-2.69	1.78-2.93	1.40	1.99	1.0
Japan	0.92-1.46	1.05-1.58	0.94	1.23	1.0
China	0.74-1.72	0.97-1.95	1.03	1.63	1.0
France	0.58-1.05	0.71-1.18	-	-	1.0

[a] Assumed carbon cost is \$30/tonne of CO_2

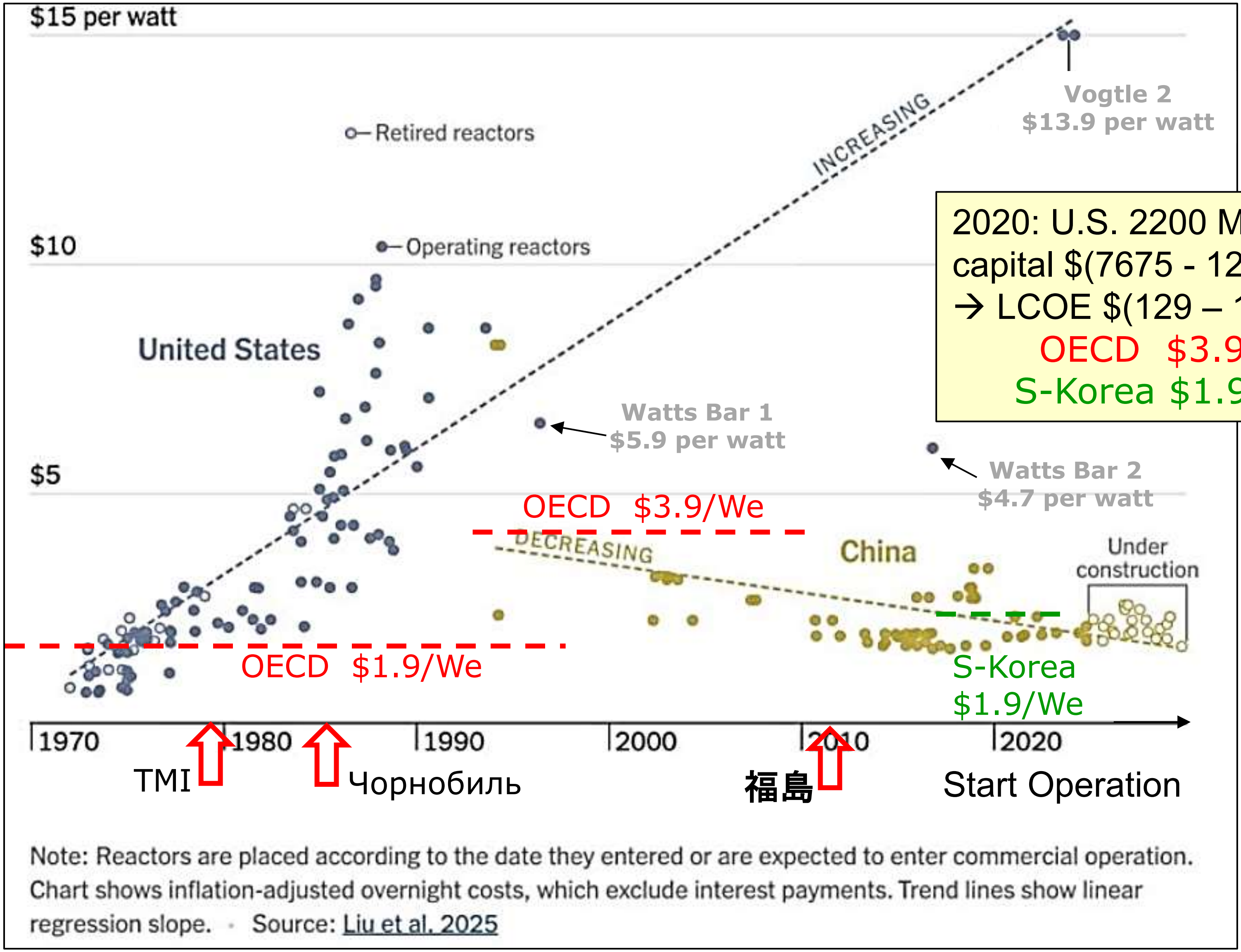
- Currently: New NPP not profitable investment in US and EU.
  - Capital on-site construction costs too high (➔modern modular, factory).

- Cost not dominated by reactor and turbine islands but by
  - civil works, structures and buildings, electrical installation; associated indirect costs for this work on site.

- Cost reductions and/or revenue enhancement accomplished by
  - standardizing design, modus of reactor construction (prefab, modular), reduced commodity use, incorporating modern fabrication/construction technologies from other fields applicable to nuclear power.

MIT Report: The future of Nuclear Power in a Carbon-Constrained World

Nuclear Fission Reactors: Historical Construction Cost



Note: Reactors are placed according to the date they entered or are expected to enter commercial operation. Chart shows inflation-adjusted overnight costs, which exclude interest payments. Trend lines show linear regression slope. · Source: Liu et al. 2025

2020: U.S. 2200 MWe plant:
capital $(7675 - 12,500)/kW
→ LCOE $(129 – 198)/MWh.
OECD $3.9/We
S-Korea $1.9/We

Issue 7: Economics/Capital Requirements

Carbon-free energy technology. Expensive to build, economic to operate over long period. Is nuclear energy infrastructure scalable? (Answers, economical: probably yes, political: ?)

→ Economic & environmental necessity, growth of high-tech industry

→ Economics of scale for standardized, modular NPP

- ☐ Loan guarantees
- ☐ Combined licensing for construction and operation
- ☐ Limited number of standardized, safe reactor designs
- ☐ Mass fabrication of modular designs (combine for size)
- ☐ Integrated self-contained modules (on site disposal)

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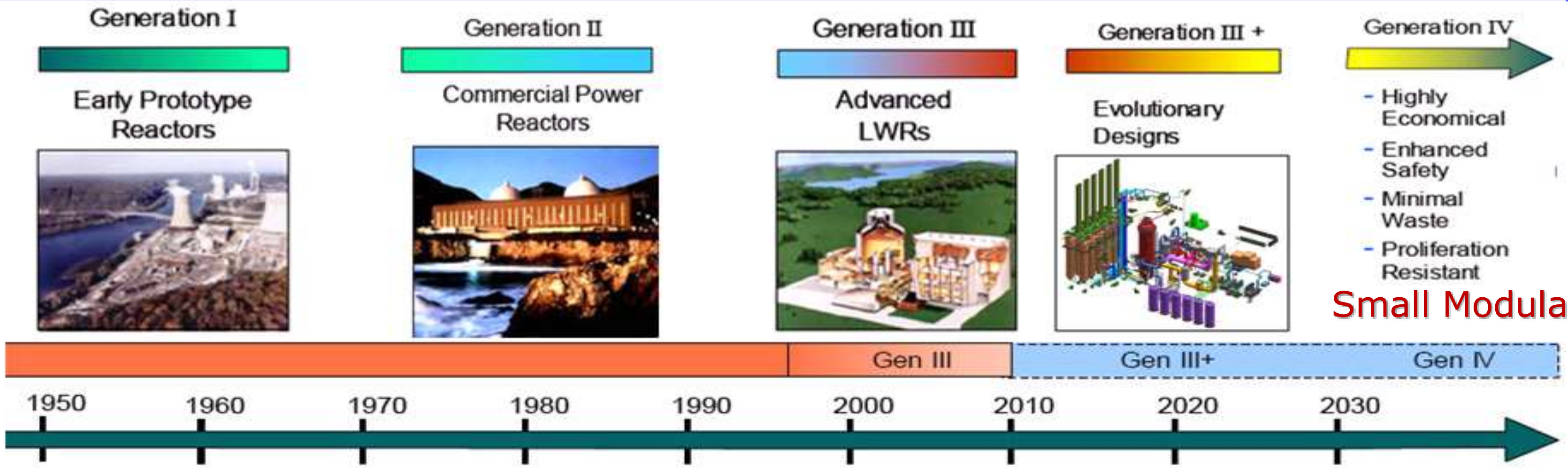
Timeline of Advanced Reactors/Fuel Cycles



Small Modular R

GNEP framework (U.S., U.K., India,…) → IRIS 2030: Gen IV designs

- Very high-temperature reactors (VHTR)
- Sodium-cooled fast reactors (SFR)
- Reactors cooled by supercritical water (SCWR)
- Lead-cooled fast reactors (LFR)
- Gas-cooled fast reactors (GFR)
- Molten-salt reactors (MSR, LIFTR)
- 4-S reactors
- Accelerator driven ADS
- Radioisotope thermo-electric generators (RTG)

Enhance

- Operational reactor safety;
- Nuclear fuel (^{235}U/Pu) resources;
- Safe capture, storage, sequestration of radiotoxic waste;
- Prevention of proliferation of nuclear materials for weapons;
- Economy of nuclear energy.

Russia: fast breeder BN-600 (600MW$_e$) since 1980
Also tested Gen IV: France, Japan, S-Africa, China, India. ADS: Belgium "Myrrha"

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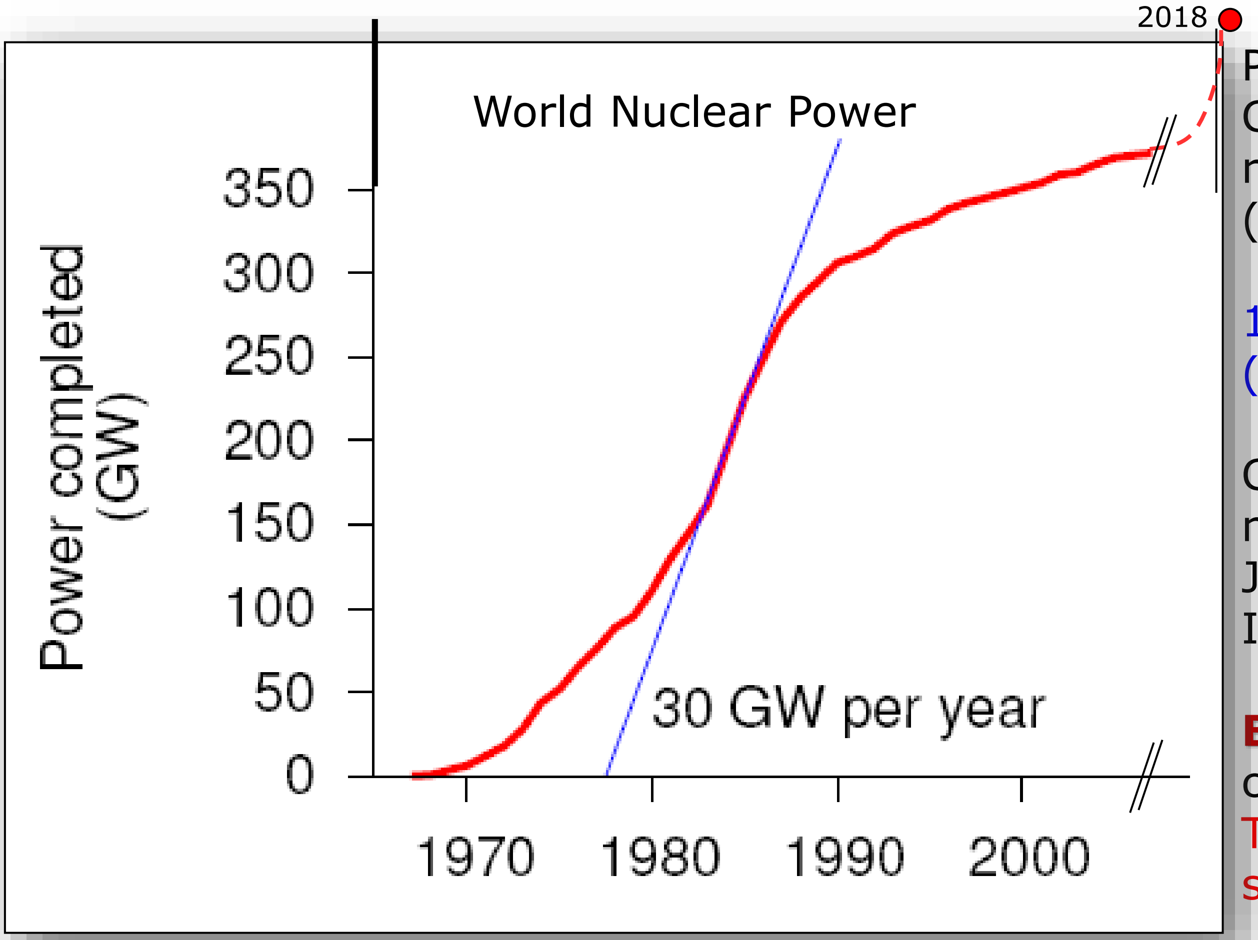
Issue 9: Deployment Potential/Scalability

Potential for doubling nuclear capacity over next 25 years:
100 GW/25y = 4 GW/a = (2-3) NPPT/a → requires $(8-12)B/a
= 12,000 construction workers continuously and +2500 operators/a.



D. McKay: *Sustainable energy without the hot air*, 2009

Past performance: Construction dates of reactors still operating (GW$_e$ vs. year).

1985: France built (completed) 2.5 GW/a

Construction time now 2-3 years/NPP Japan, Korea, China, India

Bottle necks: Steel containment fabrication, Technical operators, skilled manpower.

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Issue 10: Public Perception

→ Address genuine concerns,

→ Educate, convey factual information –

→ Eliminate irrational fear .

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Conclusion: Nuclear Power in a Sustainable Future (?)

Western Gen III plants have good safety record (safest dispatchable energy). But 3 *preventable* accidents with core damage (“melt down”), 1 accident fatal, temporary evacuation.
Gen III, III+ proven/mature technologies (PWR, U based), breeder reactors

To develop and employ advanced nuclear power in the U.S.:

- Continue to improve the safety of nuclear reactors and processing plants.
- Test/construct advanced modular nuclear reactors @ sites of existing plants.
- Test/construct advanced burner/transmuter → reduce radiotoxic waste.
- Import/develop closed nuclear fuel cycle technologies.
- Develop/test proliferation-safe reprocessing methods (e.g., UREX+).
- Test/develop a closed Th/U breeder fuel cycle.
- Develop ADS systems, high current accelerator technology.
- Develop the material chemistry of molten salt mixtures, molten salt reactor.
- Expand the radio-chemistry of actinides, transactinides and fission products.
- Operating a semi-permanent nuclear waste depository, flexible strategy.
- Train personnel in nuclear and radiation technologies !

The End

AKW Krümmel

Strategic Issues of Nuclear Technology, Real and Perceived

Issues for any production technology:
Sustainability, reliability, safety, eco-foot print, cost, scalability
Specific issue for nuclear power: proliferation safety

→ Relative risk/benefit analysis, levelized lifetime analysis.

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END

Reactor Accidents

Three-Mile Island

Chernobyl

Fukushima

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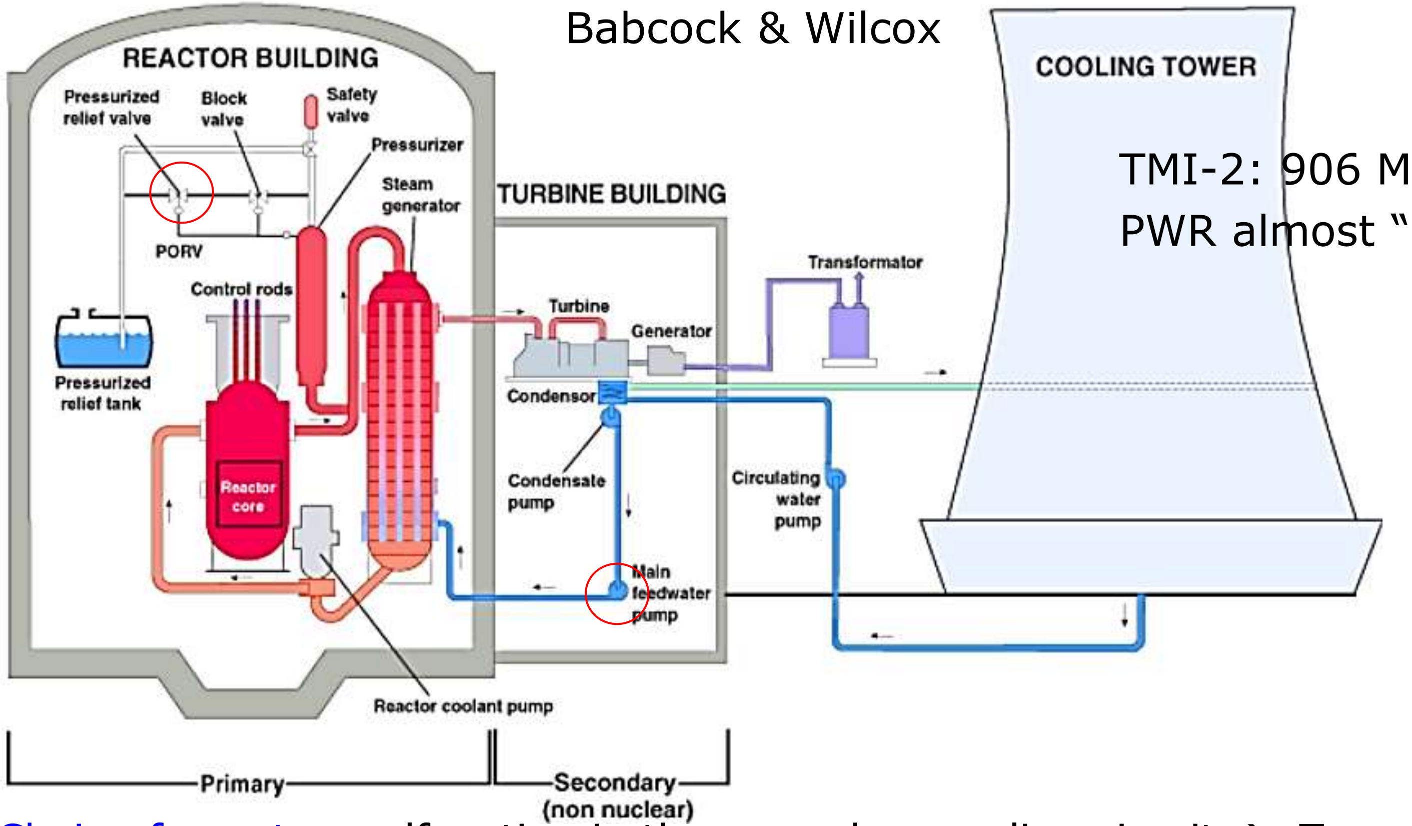
Three-Mile Island Reactor Accident 3/28/1979

1979: Cooling malfunction at Three Mile Island NPP#2 → partial core melt-down. → Minor radioactivity release. No injuries or adverse health effects.

But major media event, public confusion (kindled by movie *China Syndrome*).

Change in public attitude & serious improvements in reactor safety/prevention

TMI-2 Accident



Babcock & Wilcox

TMI-2: 906 MWe,
PWR almost “brand new.”

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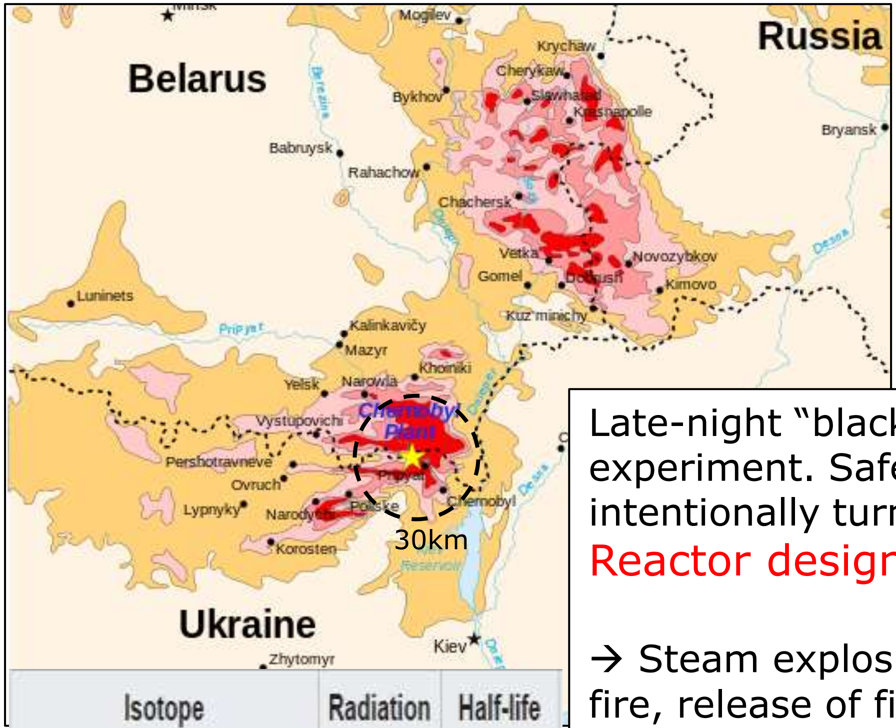
Chain of events: malfunction in the secondary cooling circuit → $T_{coolant}$ increased → automatic reactor shut down. PORV relief valve failed to close (no warning)→ primary coolant drained out of core → automatic refill from main feed was starting up but was stopped by confused operators → core overheats and melts.

→ Media frenzy, needless evacuation of population. Major new safety regulations.

Auto shutdown would have worked perfectly, without operator interference
→ simulator training, instrument diagnostics: layout/functionality redesign

Chernobyl Reactor Accident (25–26 April 1986)



45† over dose
90,000 displaced.

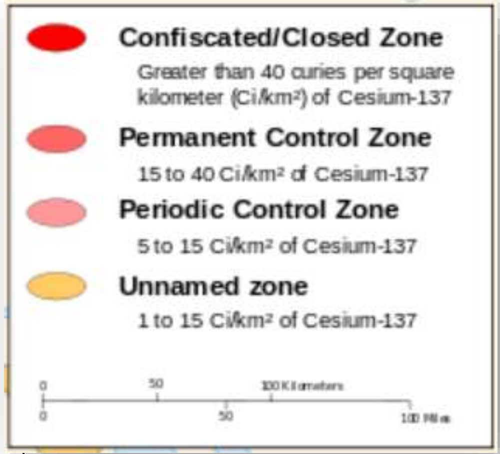
Late-night “blackout” simulation experiment. Safety systems intentionally turned off.
Reactor design reactivity > 0

→ Steam explosion → Graphite fire, release of fission products to atmosphere. → downwind fallout detected over parts of W Europe. Soviet government gave delayed notice.

⇩

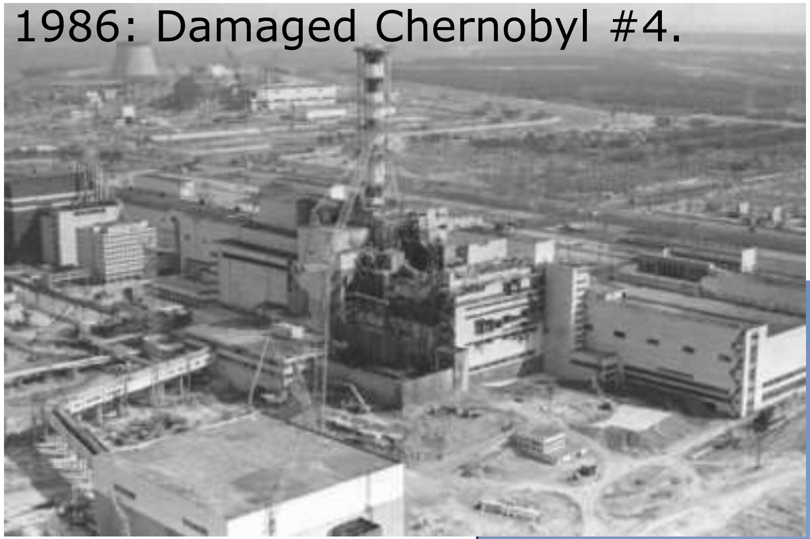
Effective counter measures:
Dilute radio isotopes with stable isotopes (^{127}I → ^{131}I)
Natural dilution

Isotope	Radiation	Half-life
Strontium-90/yttrium-90	β	28 years
Cesium-137	β,γ	30 years
Iodine-131	β,γ	8.05 days



US(>1979, 3-Mi-Island):
Simulator control room for every reactor !

Chernobyl Now (2018)



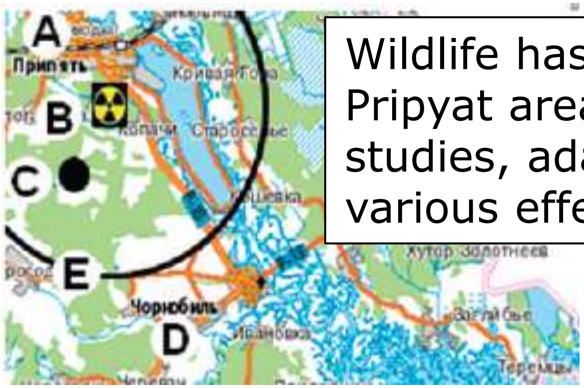
1986: Damaged Chernobyl #4.

1986: 2 cases thyroid cancers, treated. Since then, normal cancer rates.

2016: Permanent concrete safety shroud over Reactor #4.

Wildlife took over, seems ok.

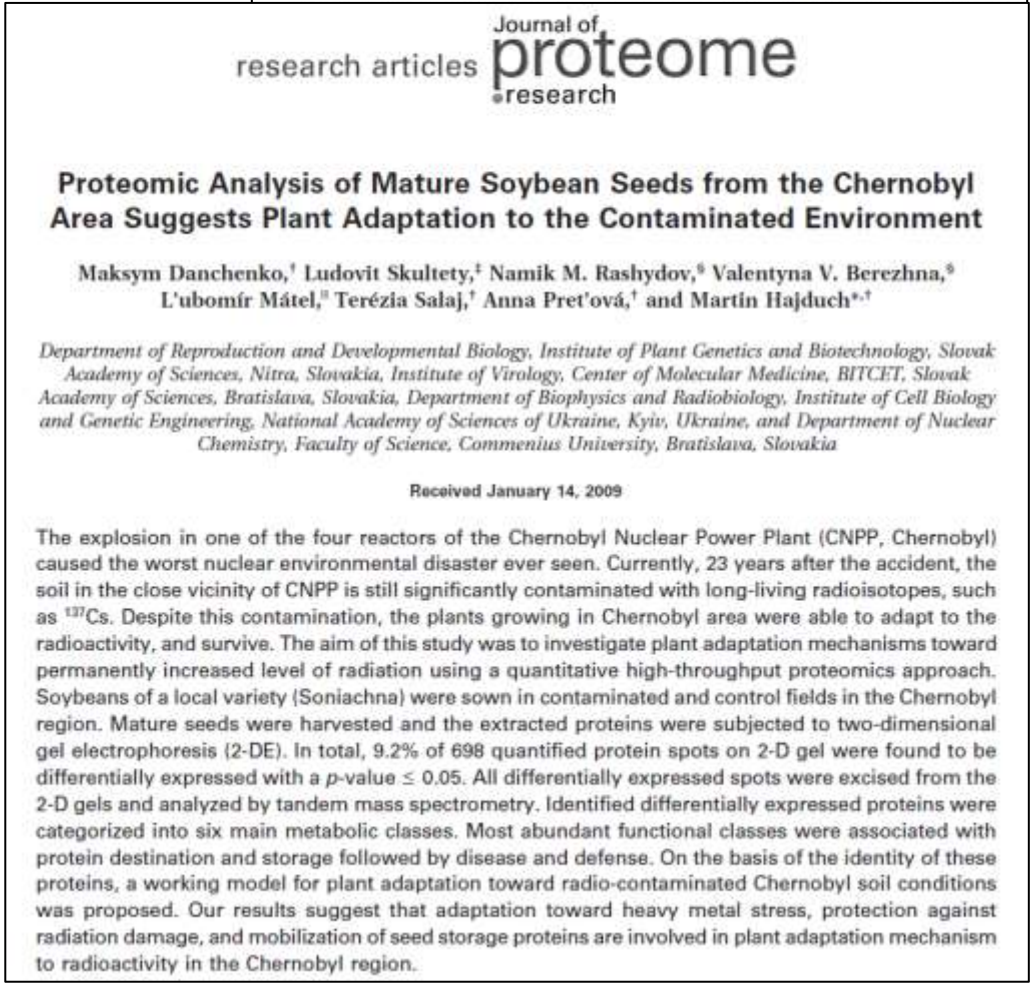
Chernobyl and Consequences



Wildlife has returned to Pripyat area. Many bio/med studies, adaptation & various effects.

The Radioactivity of ^{137}Cs in the Soil and the Seeds[a]

field	contamination soil (Bq·m^{-2})	seed (Bq·kg^{-1})
control	$44.8 \times 10^3 \pm 2.9 \times 10^3$	<2.9
contaminated	$7.3 \times 10^6 \pm 2.4 \times 10^6$	3.3×10^3



research articles Journal of proteome research

Proteomic Analysis of Mature Soybean Seeds from the Chernobyl Area Suggests Plant Adaptation to the Contaminated Environment

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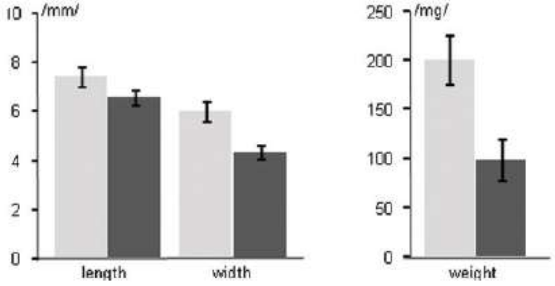
Received January 14, 2009

The explosion in one of the four reactors of the Chernobyl Nuclear Power Plant (CNPP, Chernobyl) caused the worst nuclear environmental disaster ever seen. Currently, 23 years after the accident, the soil in the close vicinity of CNPP is still significantly contaminated with long-living radioisotopes, such as ^{137}Cs. Despite this contamination, the plants growing in Chernobyl area were able to adapt to the radioactivity, and survive. The aim of this study was to investigate plant adaptation mechanisms toward permanently increased level of radiation using a quantitative high-throughput proteomics approach. Soybeans of a local variety (Soniachna) were sown in contaminated and control fields in the Chernobyl region. Mature seeds were harvested and the extracted proteins were subjected to two-dimensional gel electrophoresis (2-DE). In total, 9.2% of 698 quantified protein spots on 2-D gel were found to be differentially expressed with a p-value ≤ 0.05. All differentially expressed spots were excised from the 2-D gels and analyzed by tandem mass spectrometry. Identified differentially expressed proteins were categorized into six main metabolic classes. Most abundant functional classes were associated with protein destination and storage followed by disease and defense. On the basis of the identity of these proteins, a working model for plant adaptation toward radio-contaminated Chernobyl soil conditions was proposed. Our results suggest that adaptation toward heavy metal stress, protection against radiation damage, and mobilization of seed storage proteins are involved in plant adaptation mechanism to radioactivity in the Chernobyl region.

Soybean Crops

Control **Contaminated**



Are correlations causal ??

Lessons from Reactor Accidents

TMI & Chernobyl → Emphasize passive design safety (reactivity<0), operator training (simulators), uniform functional/operational design. Limit size/power.

Influence on design criteria for future nuclear power stations, Reports by government commissions and independent expert conferences.

→ Standardized designs, stricter regulations.

Sequential permits: 1) construction, 2) operation

Reduce general misinformation/panic → better communications inform public

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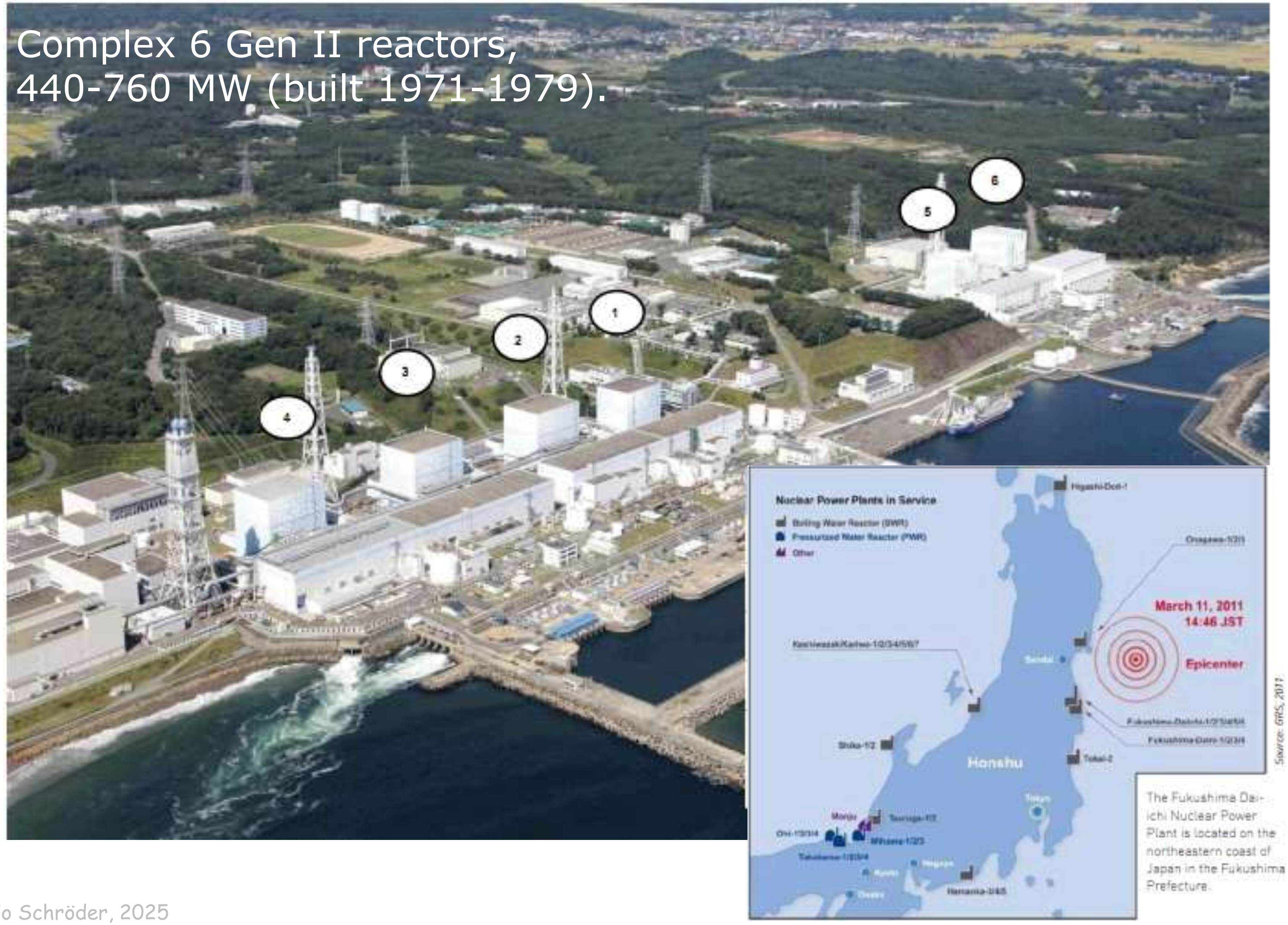
Fukuchima-Daiichi NPP

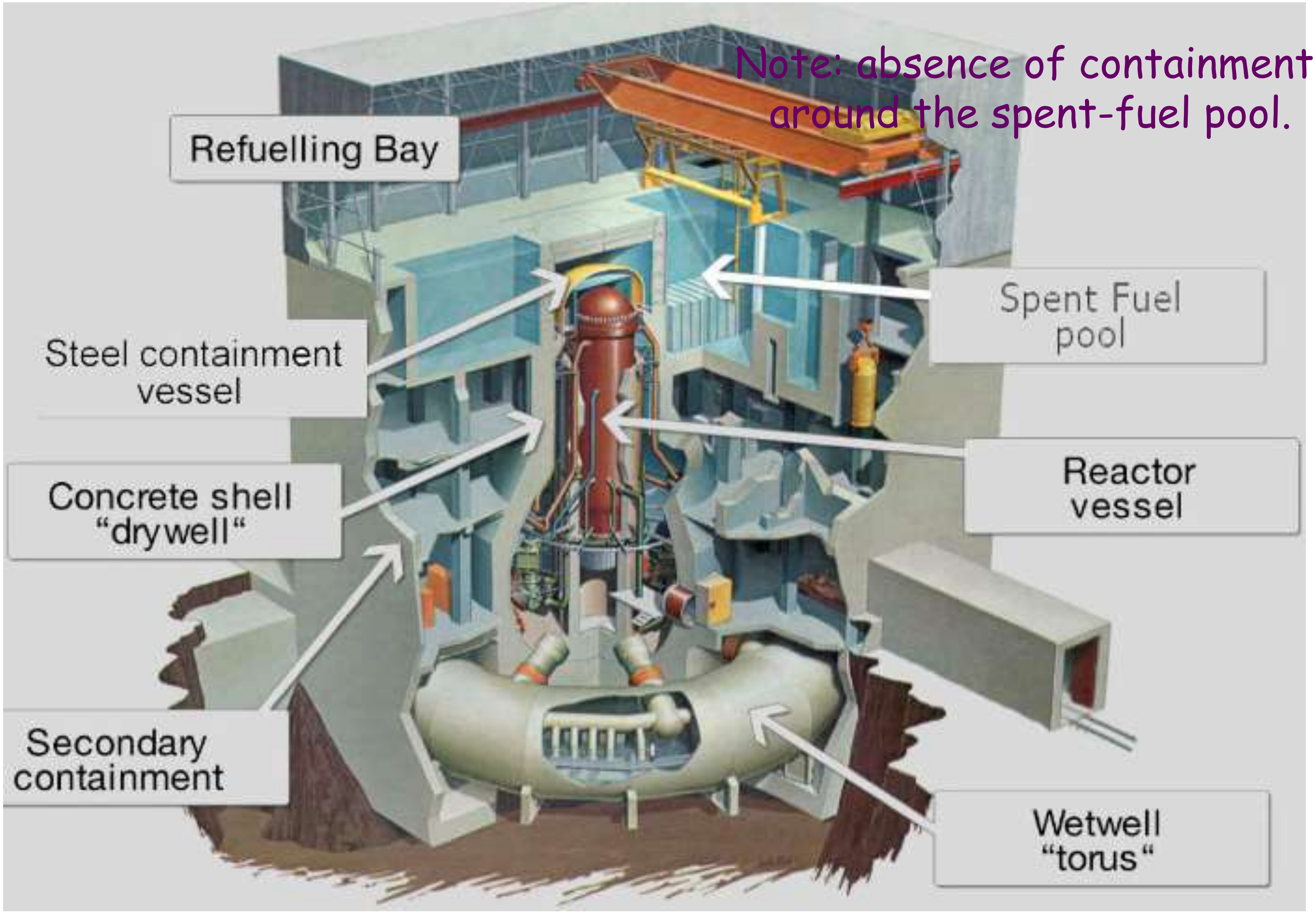


Complex 6 Gen II reactors,
440-760 MW (built 1971-1979).

Source: GRS, 2011

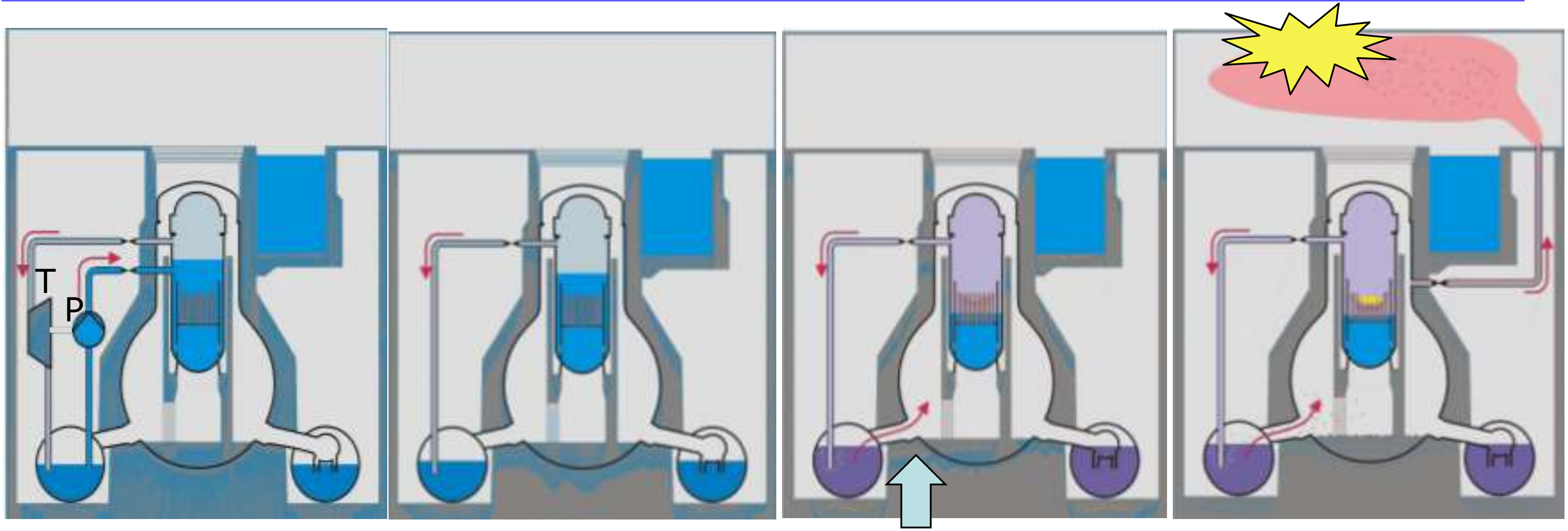
The Fukushima Daiichi Nuclear Power Plant is located on the northeastern coast of Japan in the Fukushima Prefecture.

Fukushima BW Reactor 1960 Design (GE & Toshiba)



Note: absence of containment around the spent-fuel pool.

Fukushima Station Blackout Event Sequence



Normal operation: Steam from reactor drives turbine (T), condenses in wetwell Electric pump (P) pumps coolant water into reactor vessel.

External power failure, pump stops pumping coolant into reactor vessel. Temperature T_{core} increases.

Steam relieve valves open, discharge steam into wetwell, coolant heats up, core is exposed, Zr cladding of fuel elements burns in steam atmosphere, produces H_2. No H_2 recombining units exist.

Melt-down of core, release of H_2 and fission products (Xe, Cs, I,..). H_2/O_2 explosion with release of radio-activity.

After: F. Mis, RSO Univ. Rochester

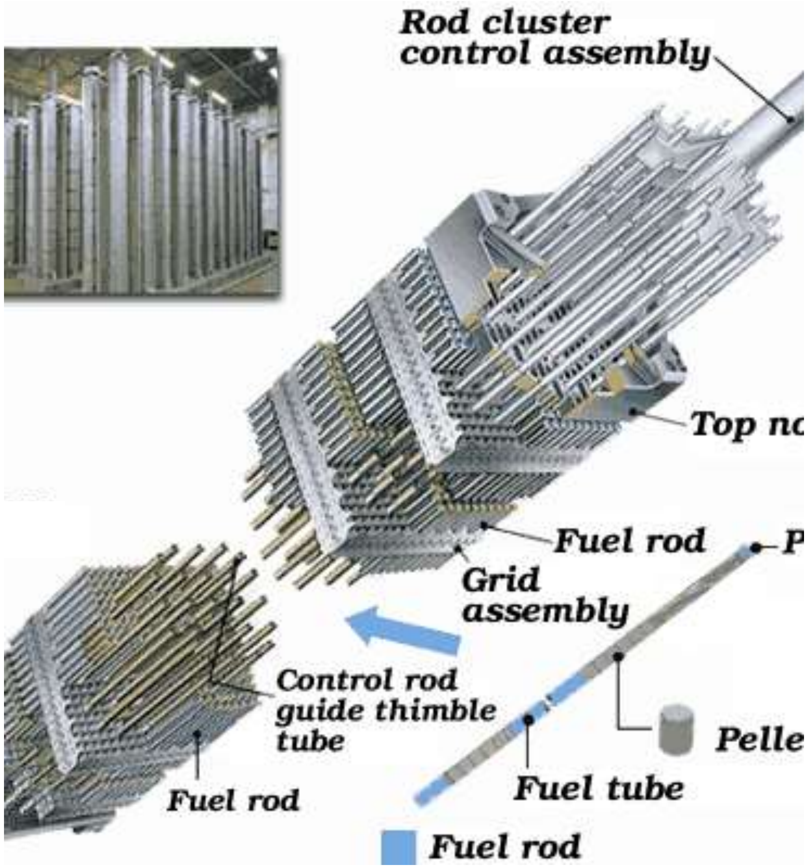
What Went Wrong, Hydrogen Explosion

Nuclear fuel rods clad in Zr alloys (little corrosion, low capture cross section).

But: reactivity against water (1,200°C)

→ $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$

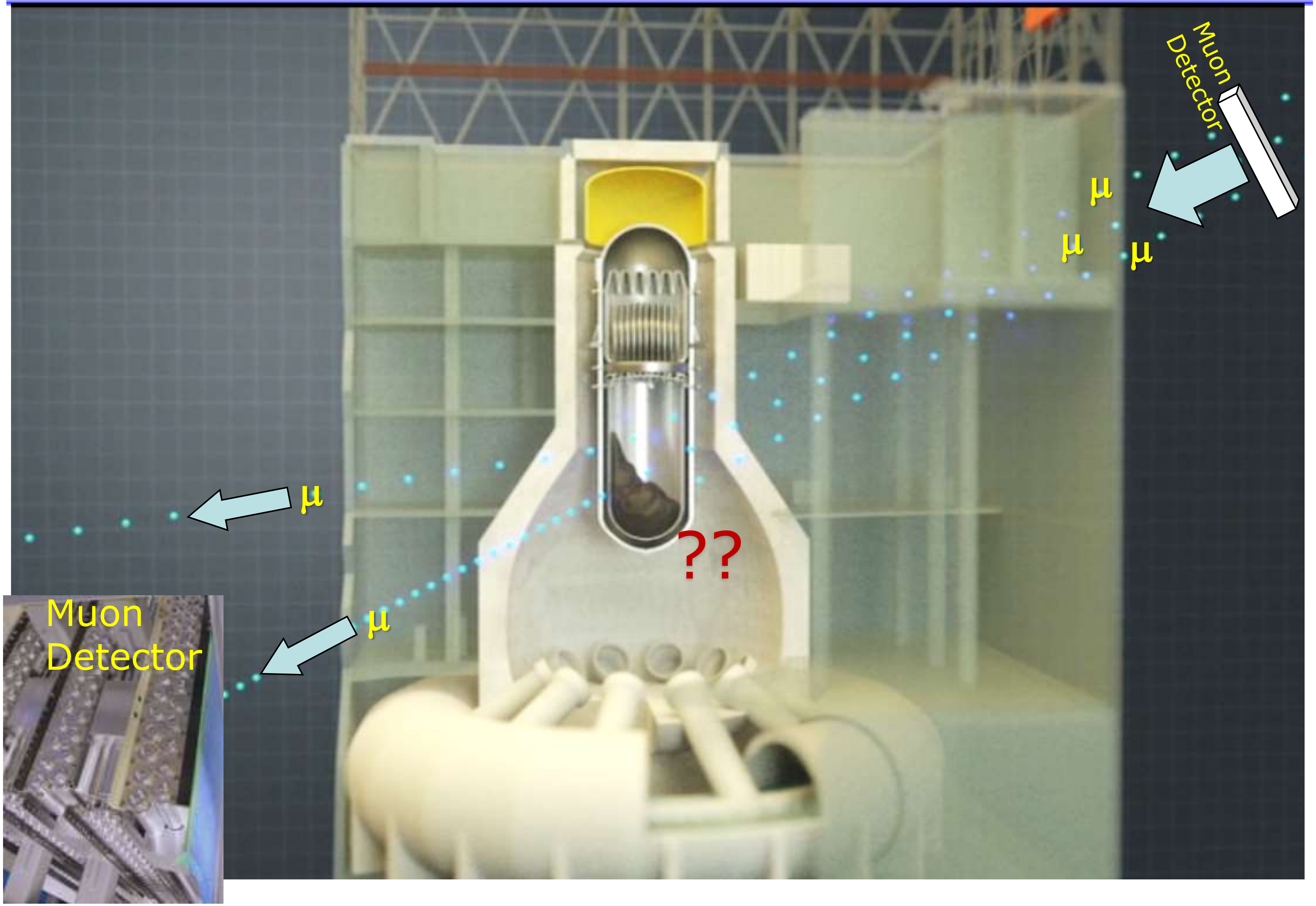
- Reactor operators vented H into the maintenance halls of Reactors 1,2,3 → H_2/O_2 mix detonated.
  Direct venting of H_2 into atmosphere would have been advisable.
- Modern reactors have a catalyst-based recombinators, converting hydrogen and oxygen into water at room temperature.



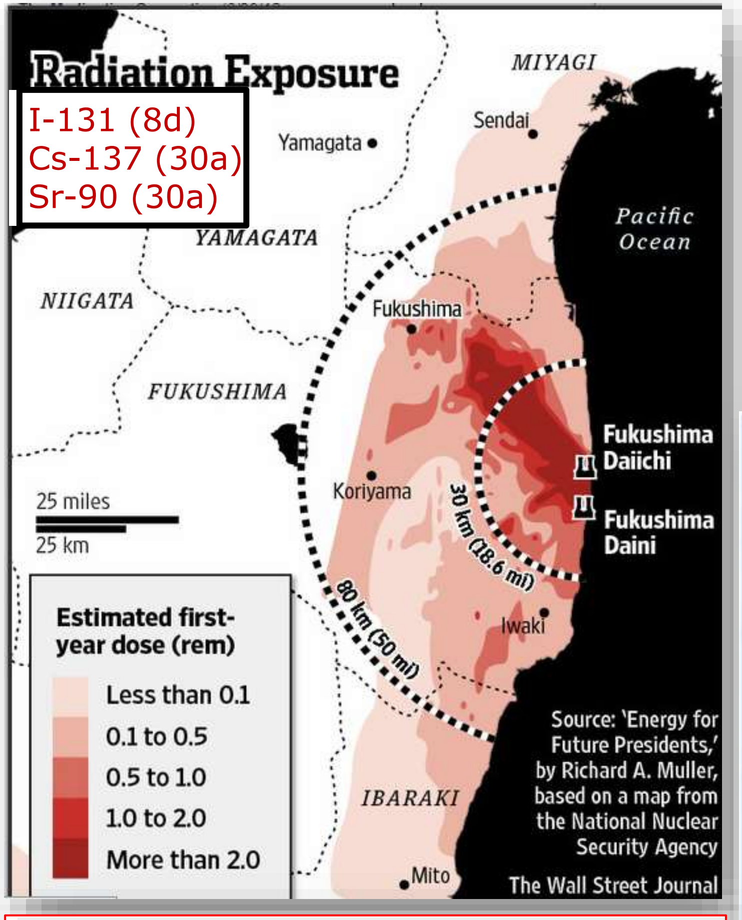
Similar events would not have happened with the modern U.S. stations.

Obvious need for more comprehensive safety analyses for all stations.
Better operator training→ realistic control room simulators.

Muon Imaging of Fukushima Core

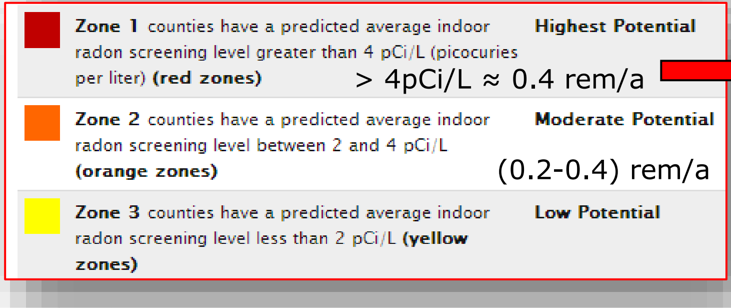


Fukushima Radiation Dose in Perspective



I-131 (8d)
Cs-137 (30a)
Sr-90 (30a)

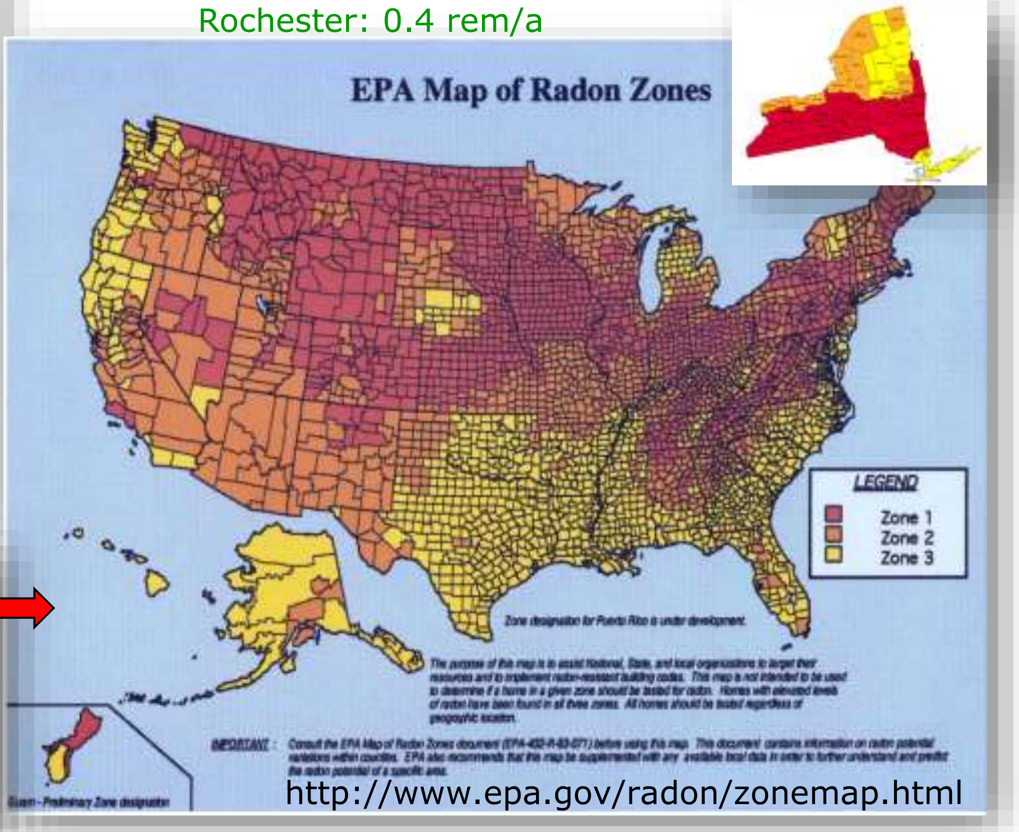
Source: 'Energy for Future Presidents,' by Richard A. Muller, based on a map from the National Nuclear Security Agency
The Wall Street Journal



🟥	**Zone 1** counties have a predicted average indoor radon screening level greater than 4 pCi/L (picocuries per liter) **(red zones)**	**Highest Potential** > 4pCi/L ≈ 0.4 rem/a
🟧	**Zone 2** counties have a predicted average indoor radon screening level between 2 and 4 pCi/L **(orange zones)**	**Moderate Potential** (0.2-0.4) rem/a
🟨	**Zone 3** counties have a predicted average indoor radon screening level less than 2 pCi/L **(yellow zones)**	**Low Potential**

Cancer risk from radiation exposure: "Linear-no threshold"
Probability: d_c=25 rem/person → ΔP=+1%/person
→ $N_{pers}\times d_c$ = 2500 rem = 1 case with certainty
→ Note: All cancers: risk = *P*≈20%/person
Highest dose: d=22 rem received by N_{pers}=22,000 @Namie
484000rem/2500rem/per≈193 pers (so far no evidence)

Natural radiation exposure, mostly radon (+cosmic)
1pCi/L=0.09 rem/a ≈ 0.1 rem/a
Denver: 0.3 rem/a
Rochester: 0.4 rem/a



http://www.epa.gov/radon/zonemap.html

Return of the People

There have been no fatalities in the Fukushima reactor event in 2011, none caused by radioactivity. No public record of (radiation induced) extra cancers.

September 16, 2011

Bags of contaminated topsoil are collected at a temporary storage site in Fukushima prefecture.
Kyodo/AP Images

It's safe to return to some parts of Fukushima, study suggests

By Katherine Kornei Mar. 10, 2017, 5:30 PM

Close vicinity of the Fukushima NPP is polluted by radioactivity released in the H_2 explosions.
Clean-up of affected areas: remove topsoil (+rain).

Heavily polluted area → evacuate 20,000 persons for several years.

April 2019: return of 400 Okuma inhabitants (population: 10,000).

→ Now good data on pollution risk in major nuclear accident.

→ Compare relative risks.

More Lessons from Reactor Accidents

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Influence on design criteria for future nuclear power stations, Reports by government commissions and independent expert conferences.

→ Standardized designs, stricter regulations.

Sequential permits: 1) construction, 2) operation

Lessons taken from Fukushima event have had consequences for upgrades of all current U.S. nuclear stations. Preventing hydrogen-oxygen gas explosions. → costs

Prevent/reduce general misinformation/panic → better communications to inform public

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Reactor Simulator (Duke Energy)

Lessons adopted by US, EU, China (?) from airplane design: Few standardized models, controls, & procedures; airline training: Operator trained in identical simulator(s). U.S. reactors are operationally as safe as airline transport.

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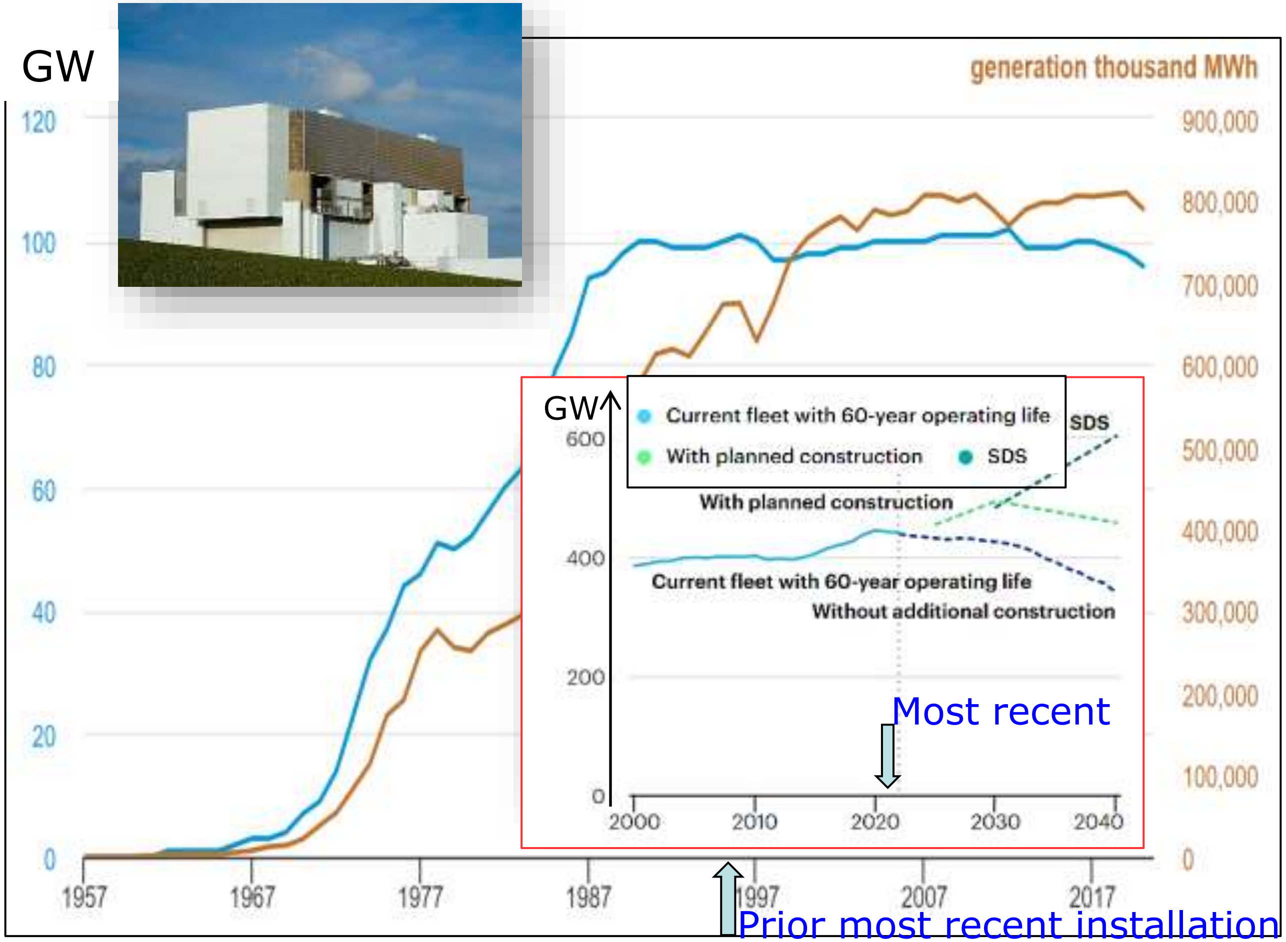
End

RETURN

Issue 2: Reliability of Nuclear Energy Production

Steady increase of nuclear power output over past 3 decades. Efficiency ε ↗
Now: ε > 90% → equivalent: 24 quads of oil. NPP lifetime 40a → > 60a

World 2012 (US): 443 (103) reactors; 365 (100) GW



World Trend
+53 new reactors,

US(>2012):
+2 -6
> 20 planned (?) license app

US potential:
1. Extend plant lifetime,
2. *N* new reactors/a (@ \$(3-4)B/GW$_e$ → (5-10)¢/kWh)

Several new companies → SMR, Na-cooled

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Discussion of TMI, Chernobyl and Fukushima reactor accidents → LNK