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: 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

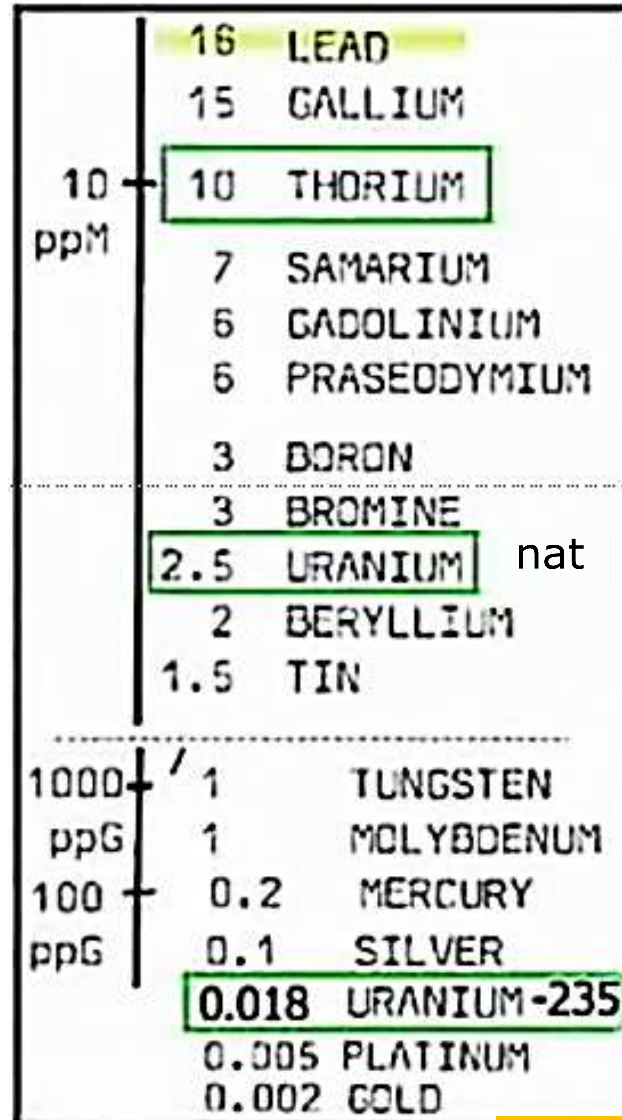
Reprocessing: ~10^3 years
US:174 t weapons grade U +20t/a Pu for fuel mix (→ 0.2 Mt fuel)

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



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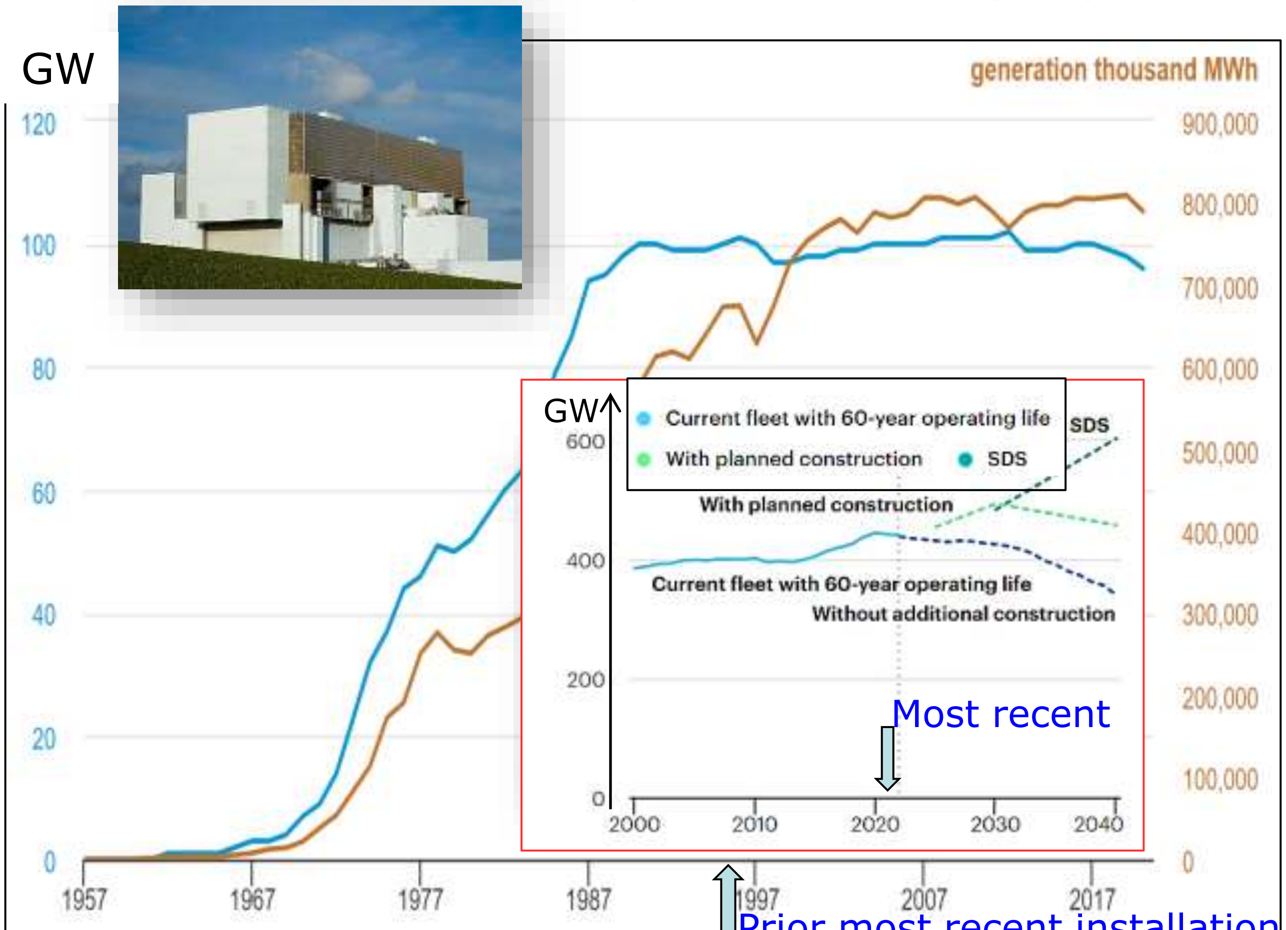
Issue 2: Reliability of Nuclear Energy Production

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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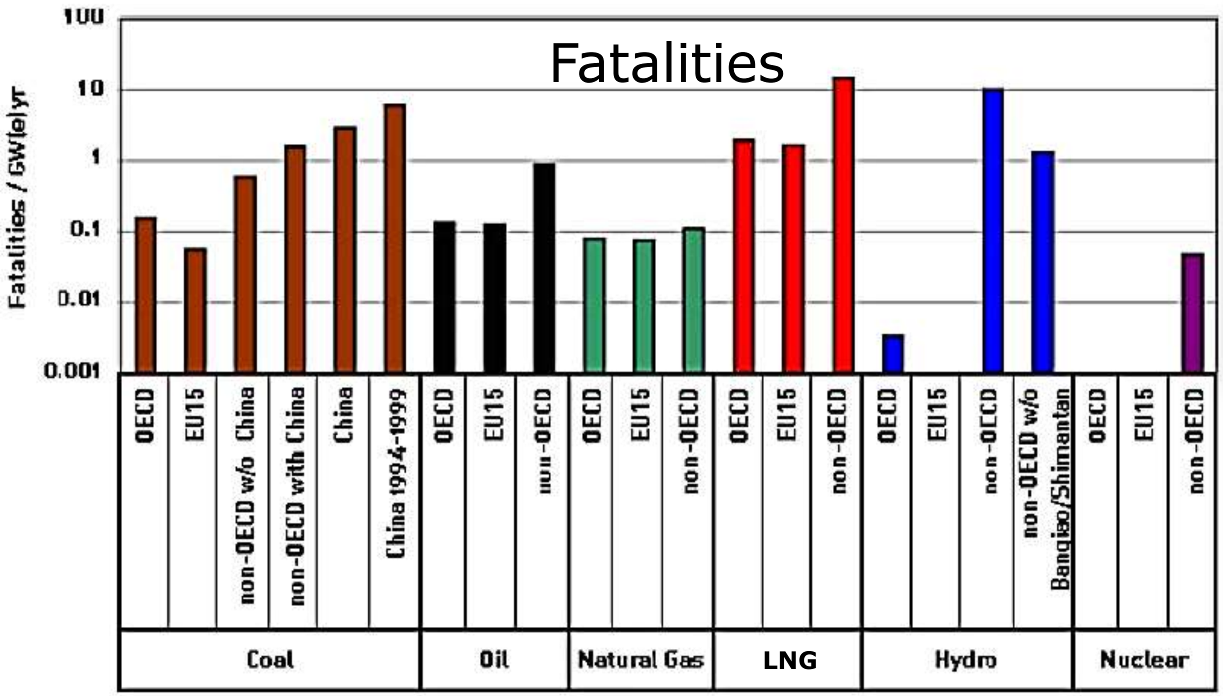
Discussion of TMI, Chernobyl and Fukushima reactor accidents → LNK

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.

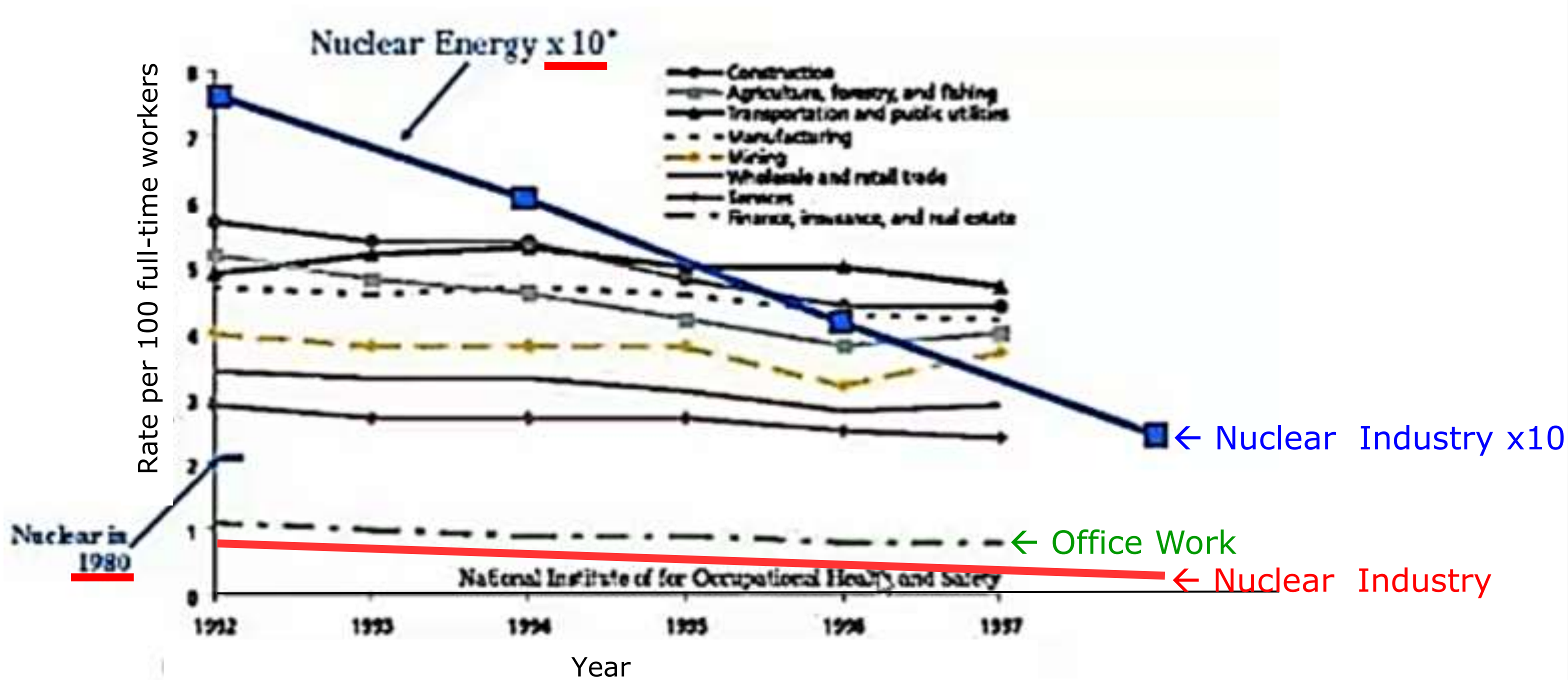
2006 U.S. coal mines : 42† (equivalent 1 Chernobyl nuclear accident/a)
Many fatalities since 2000 in coal mines, on oil fields & drilling rigs, refineries…

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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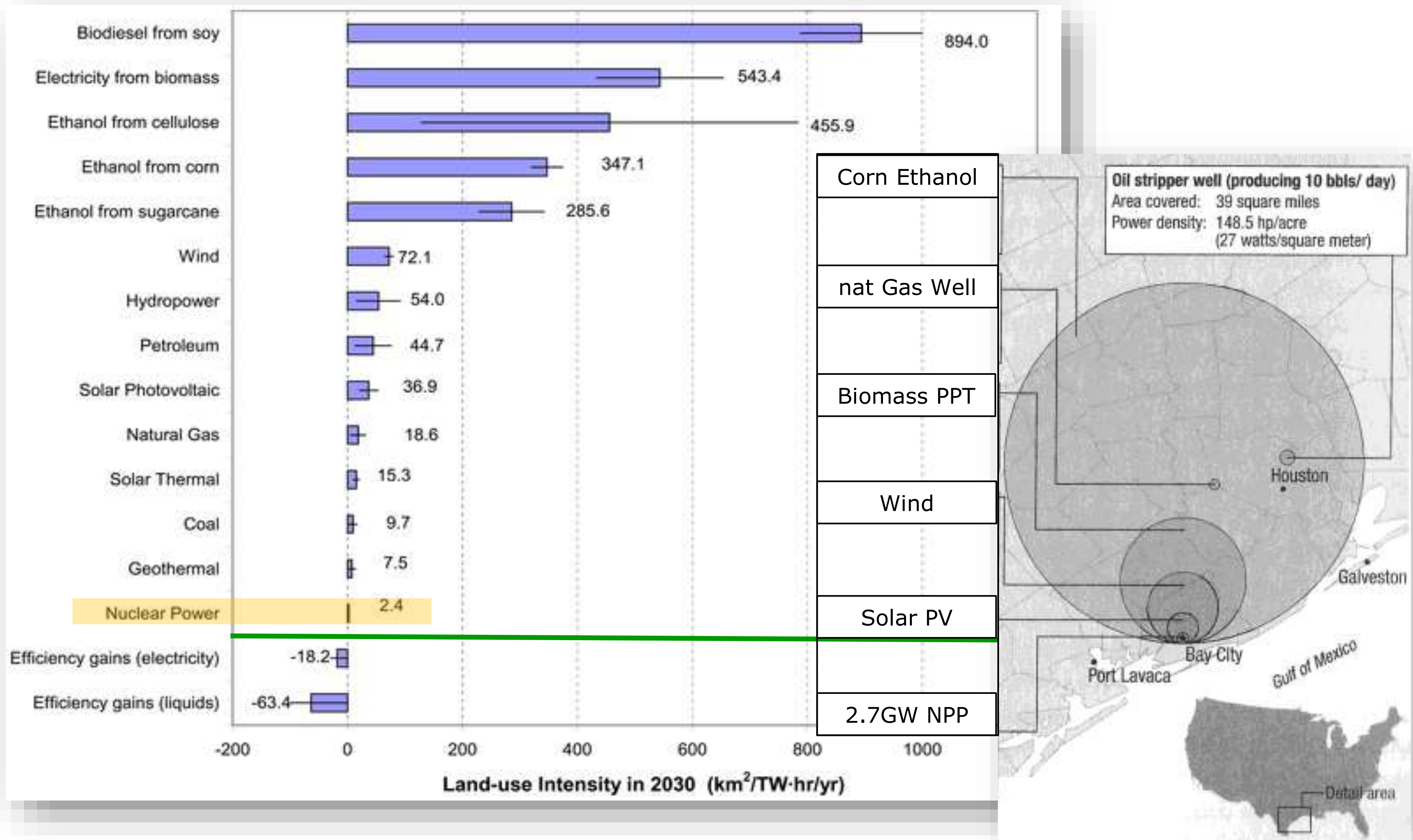
Issue 4: Eco-Footprint, Land Use



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

PLoS one

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

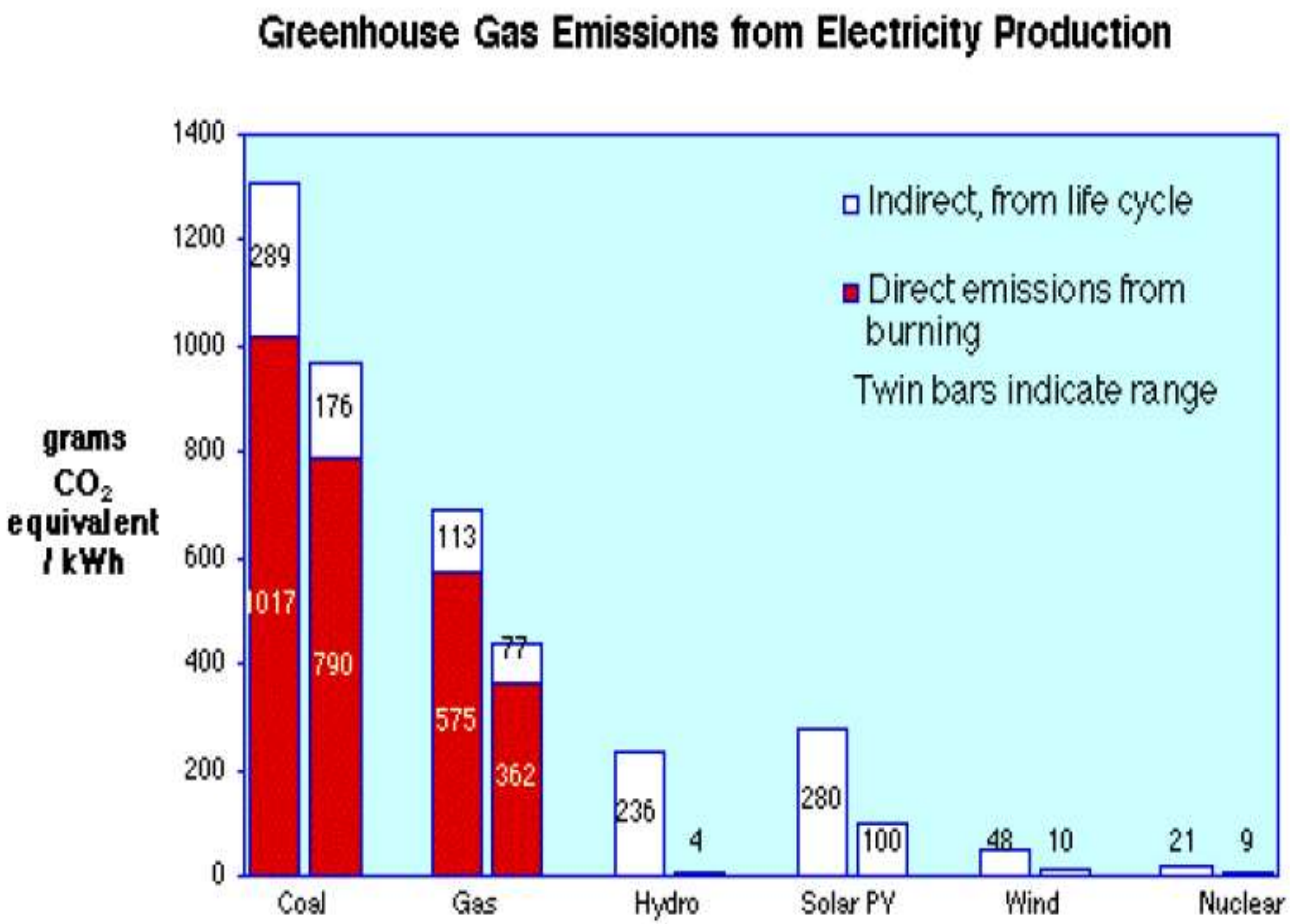
Source: Thesis Marheineke, Stuttgart University

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)



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

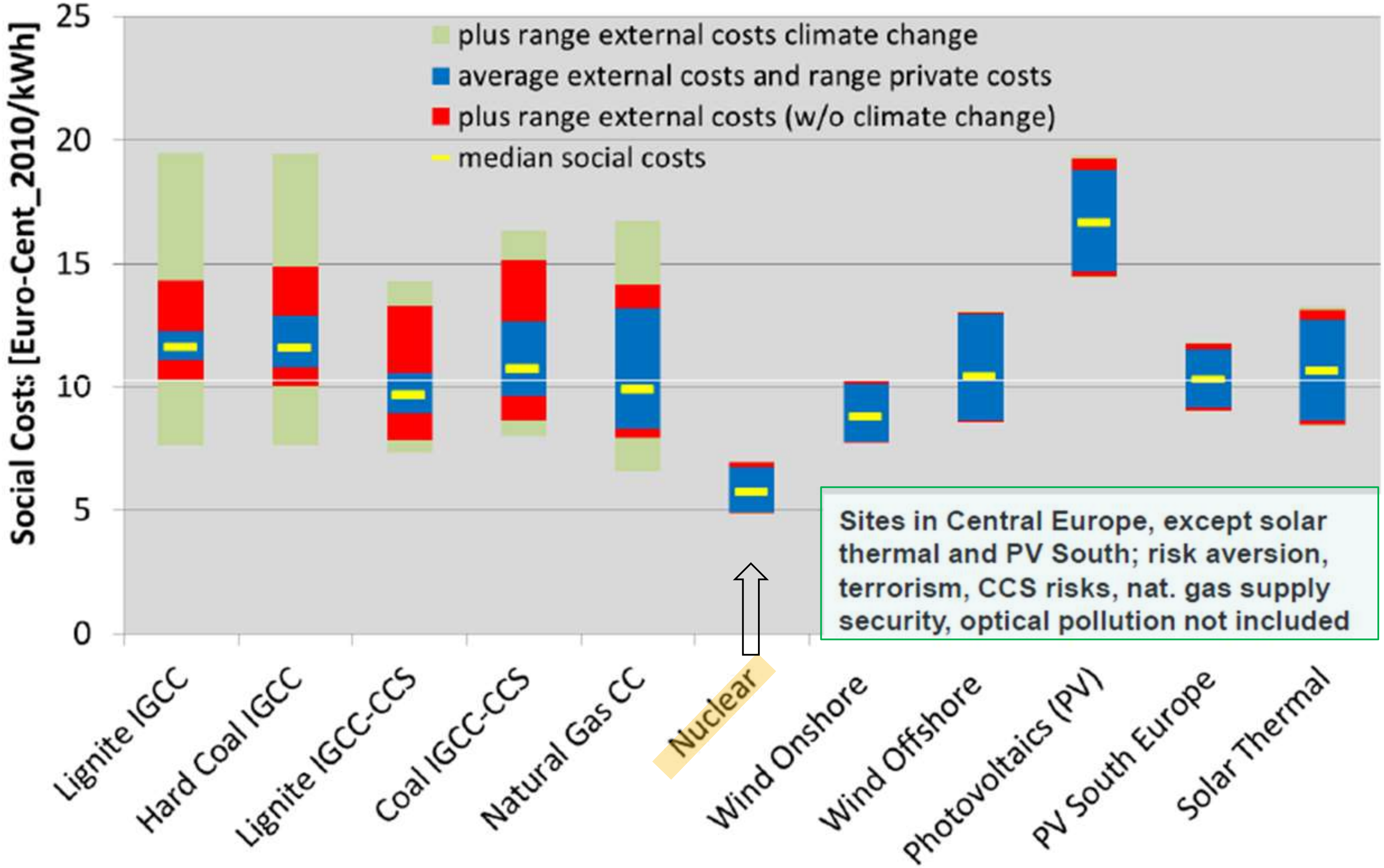
Other (fossile):
Particles $PM_{2.5}$,

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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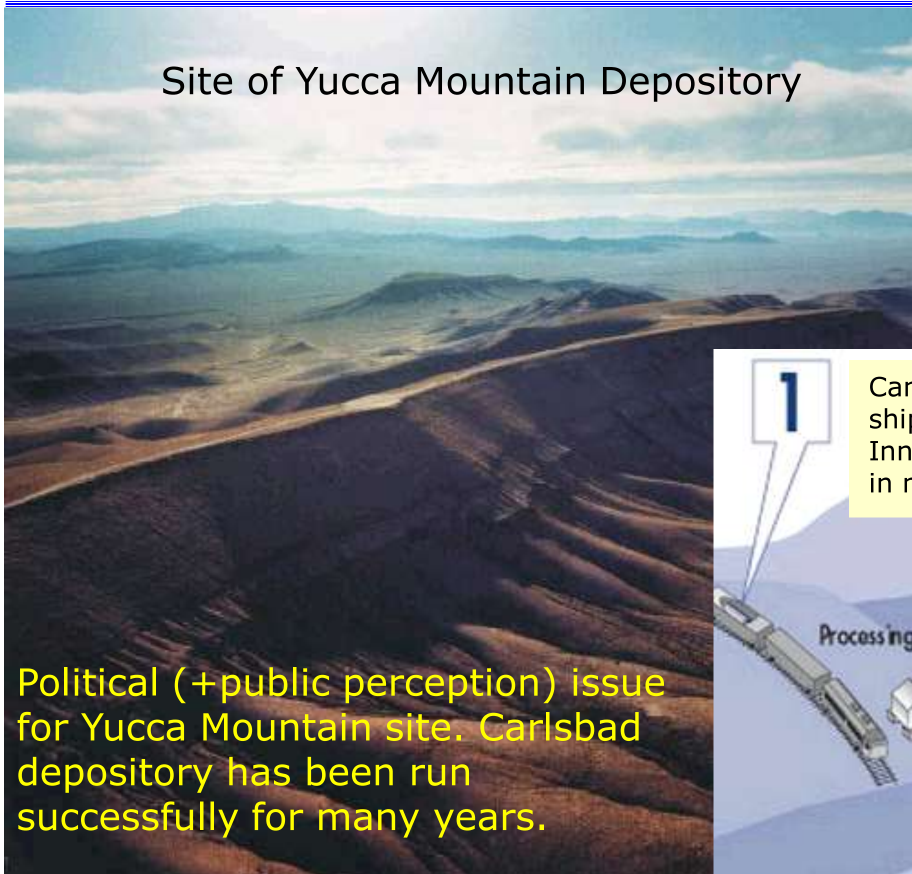
Issue 5: Capture and Sequestration of HL Waste

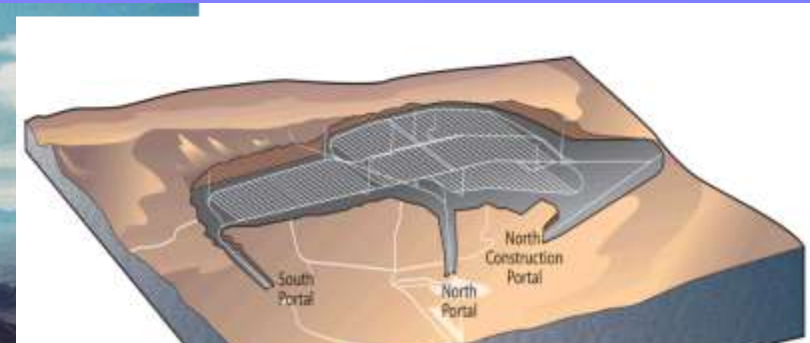


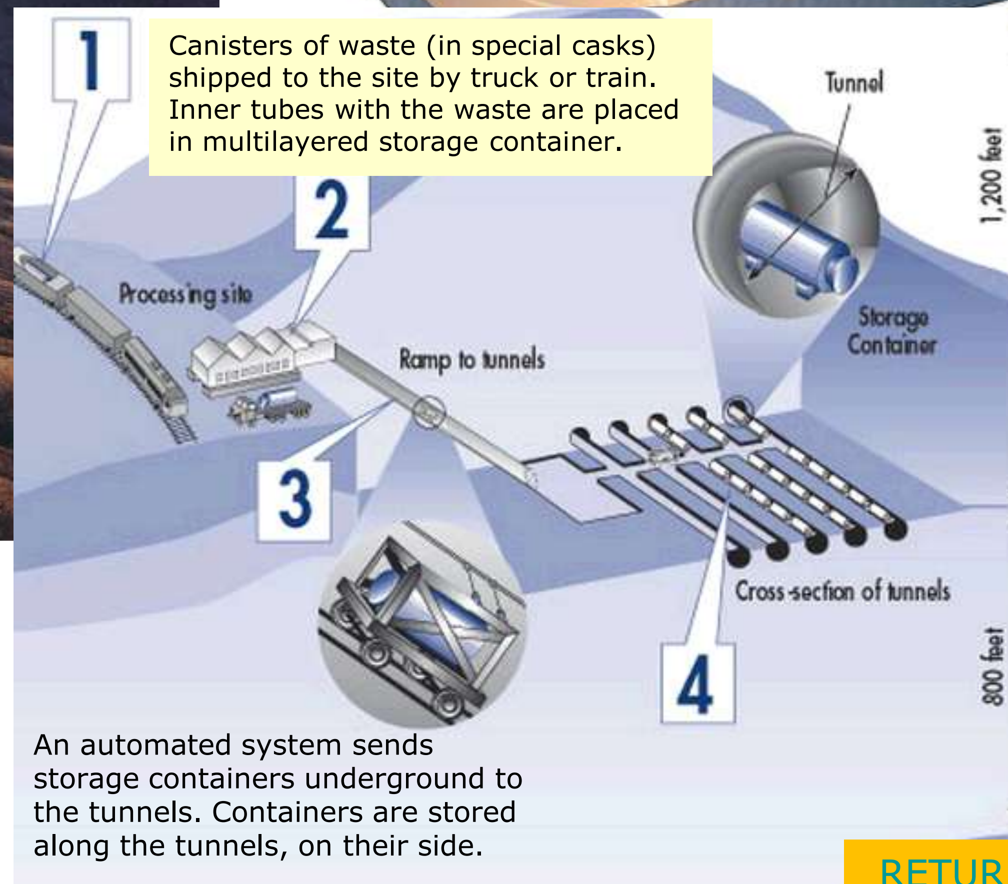
Site of Yucca Mountain Depository

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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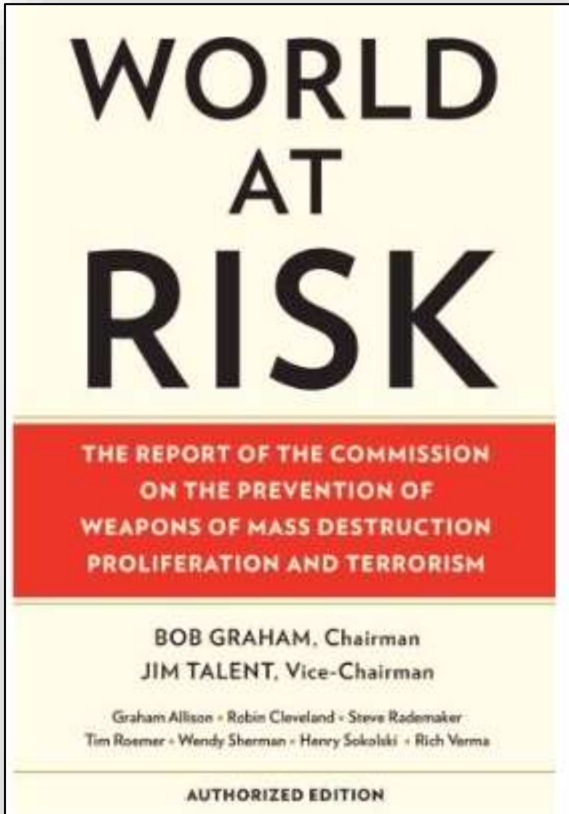
Issue 6: Nuclear Proliferation



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 Fluid-ized 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: Comparison of Normalized LCOEs

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

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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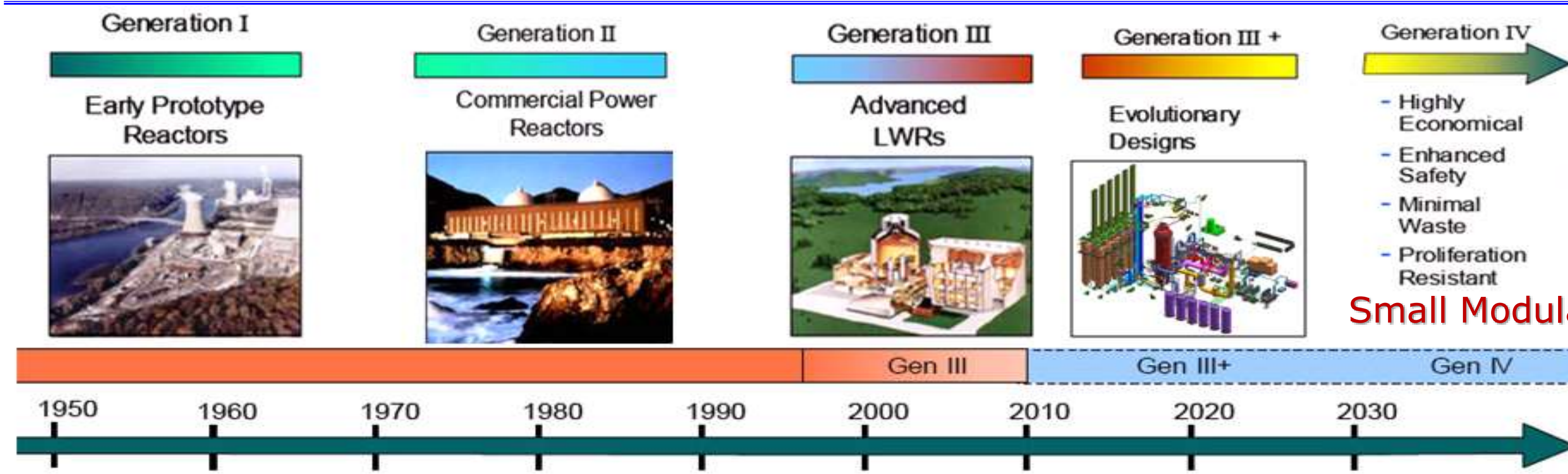
Timeline of Advanced Reactors/Fuel Cycles



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)

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

Enhance

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

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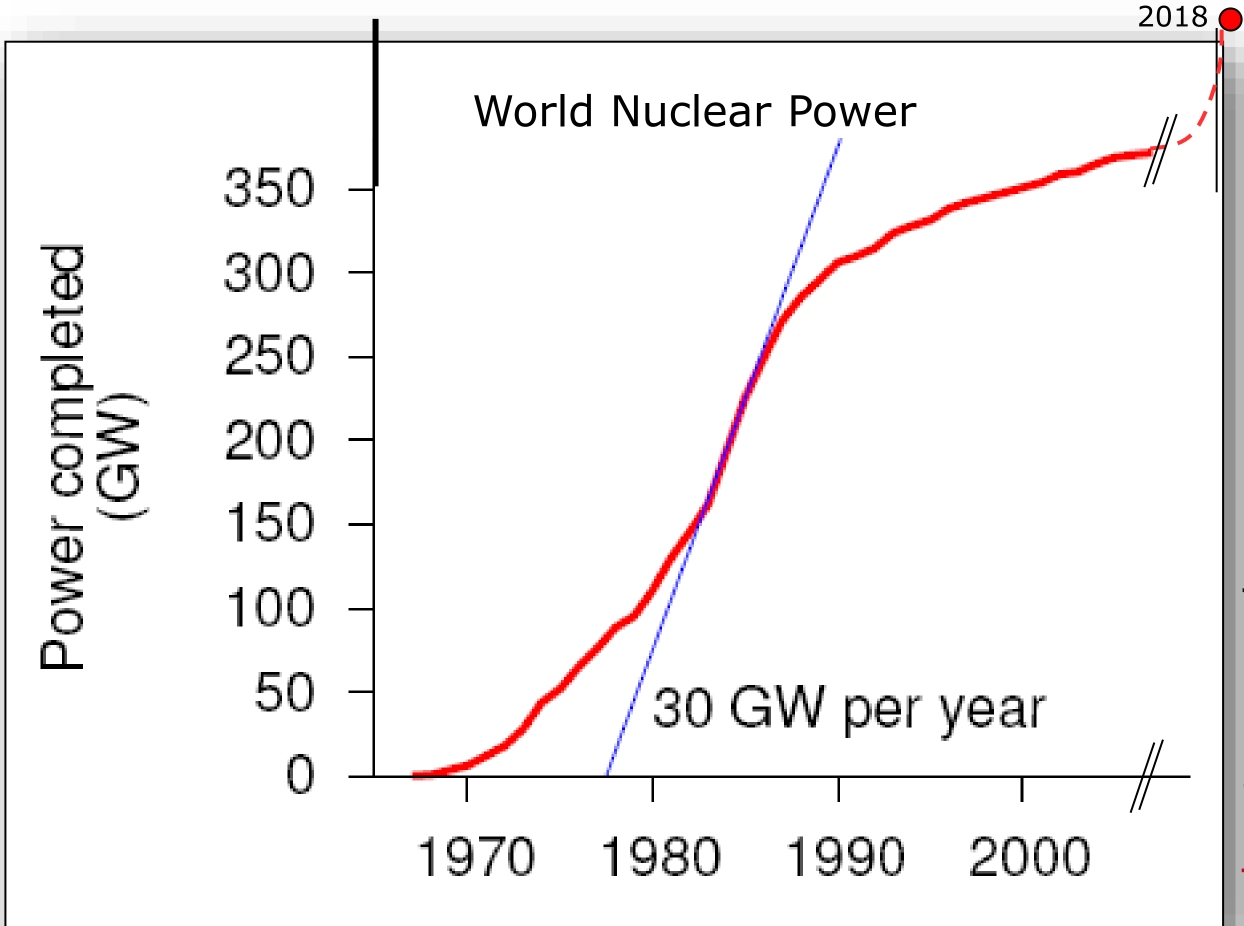
Issue 9: Deployment Potential/Scalability

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 operator manpower

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Issue 10: Public Perception

→ Address genuine concerns,
→ Educate, convey factual information –
→ Eliminate irrational fear .

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.

Links to sections

END

Reactor Accidents

Three-Mile Island

Chernobyl

Fukushima

RETURN

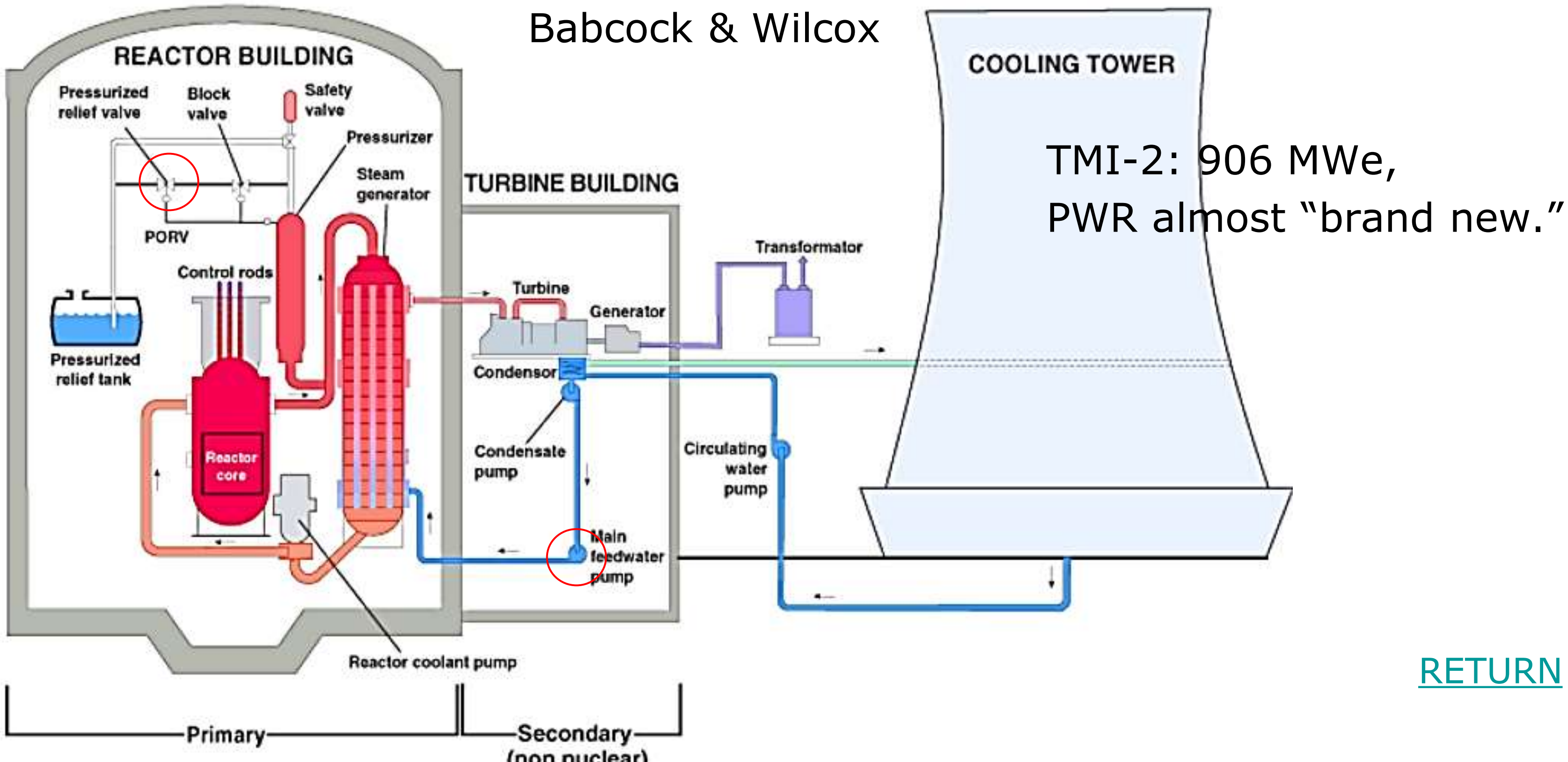
Three-Mile Island Reactor Accident 3/28/1979

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



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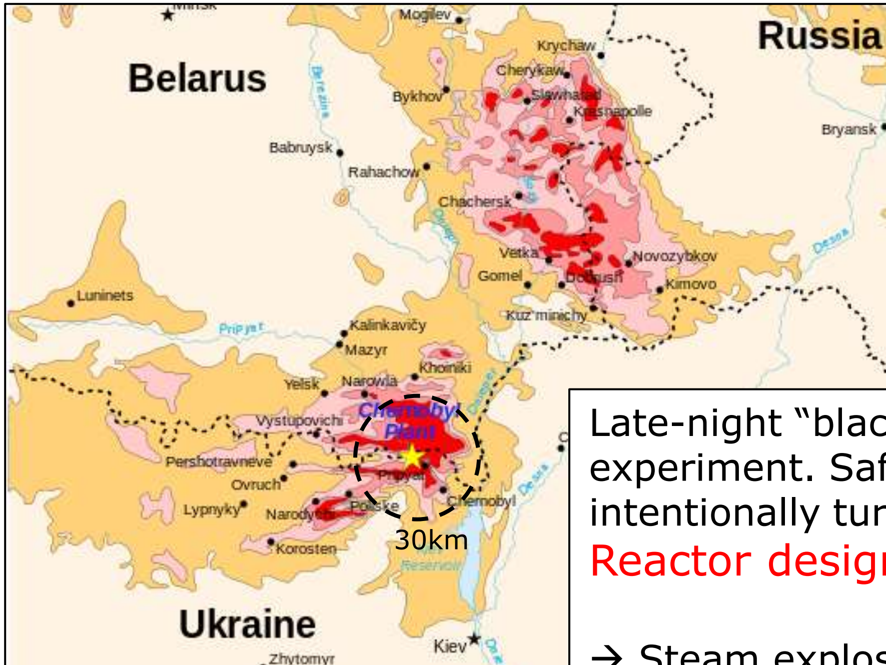
Chain of events: malfunction in the secondary cooling circuit → $T_{coolant}$ increased → automatic reactor shut down. PORV relief valve failed to close (no warning)→ primary coolant drained out of core → automatic refill from main feed was starting up but was stopped by confused operators → core overheats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

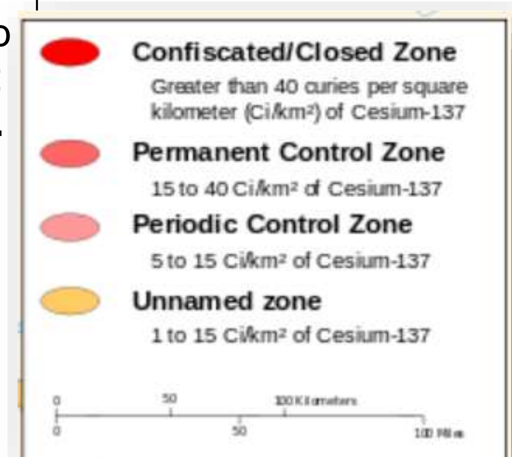


Isotope	Radiation	Half-life
Strontium-90/yttrium-90	β	28 years
Cesium-137	β,γ	30 years
Iodine-131	β,γ	8.05 days

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



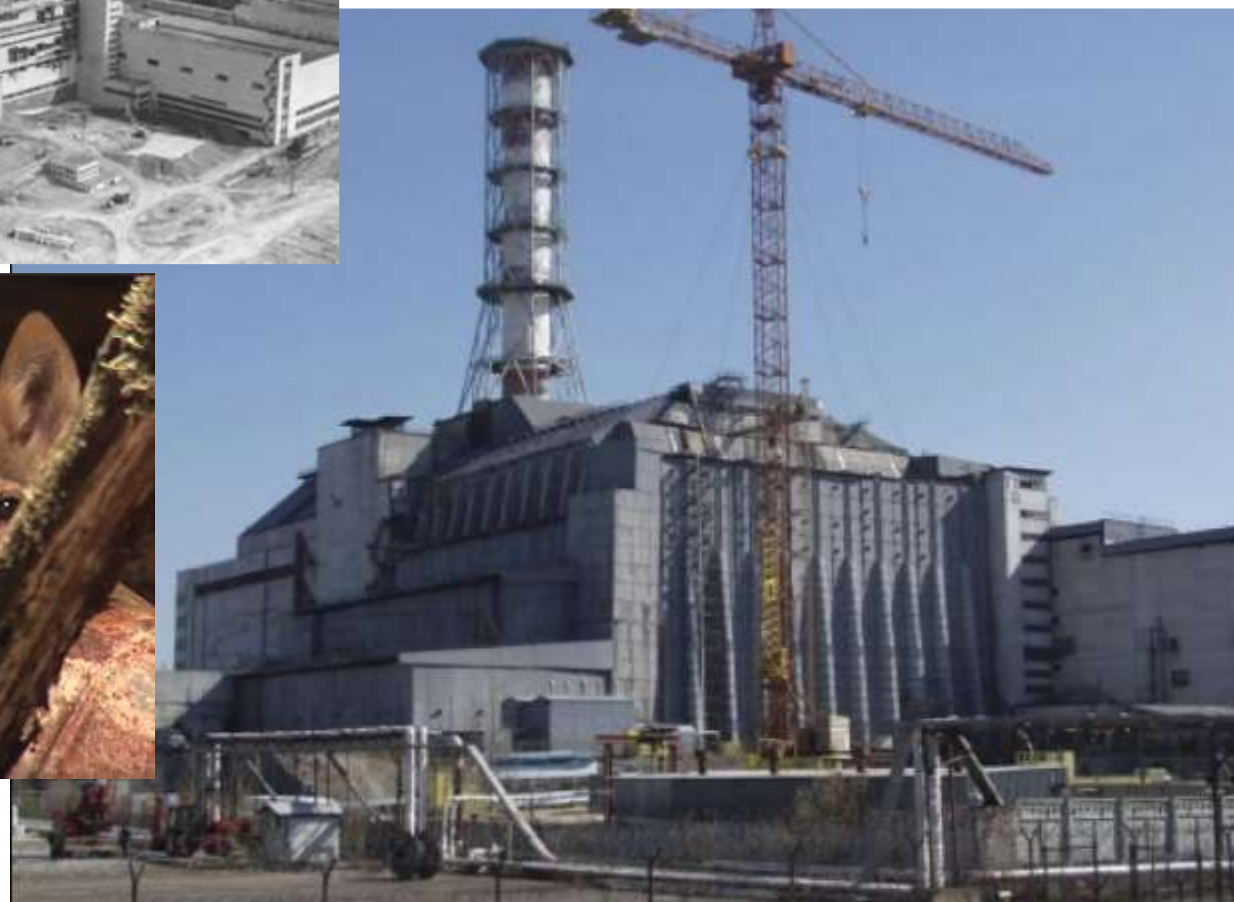
US(>1979, 3-Mi-Island): Simulator control room for every reactor !

Chernobyl Now (2018)

1986: Damaged Chernobyl #4.

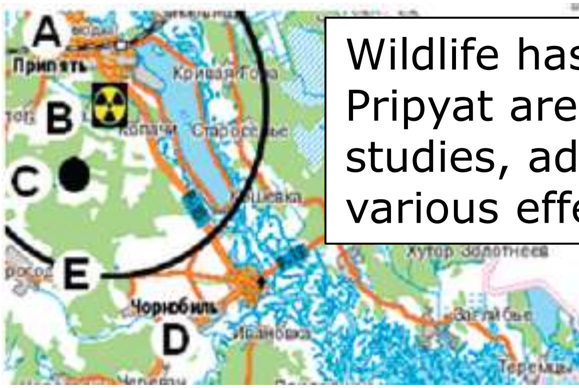
1986: 2 cases thyroid cancers, treated.
Since then, normal cancer rates.

2016: Permanent concrete safety shroud over Reactor #4.



Wildlife took over, seems ok.

Chernobyl and Consequences



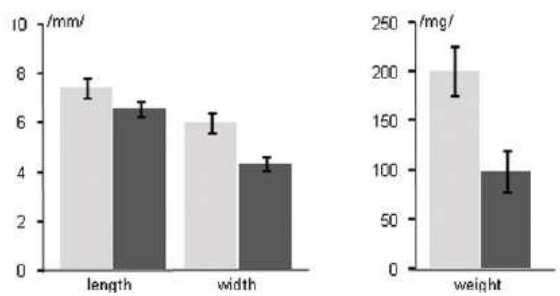
Wildlife has returned to Pripyat area. Many bio/med studies, adaptation & various effects.

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

field	contamination: soil (Bq·m^{-2})	contamination: 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}

Soybean Crops

Control Contaminated



Are correlations causal ??

research articles Journal of proteome research

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

Maksym Danchenko,[†] Ludovit Skultety,[‡] Namik M. Rashydov,[§] Valentyna V. Berezhna,[§] L'ubomír Mátel,[∥] Terézia Salaj,[†] Anna Pret'ová,[†] and Martin Hajduch[*,†]

Department of Reproduction and Developmental Biology, Institute of Plant Genetics and Biotechnology, Slovak Academy of Sciences, Nitra, Slovakia, Institute of Virology, Center of Molecular Medicine, BITCET, Slovak Academy of Sciences, Bratislava, Slovakia, Department of Biophysics and Radiobiology, Institute of Cell Biology and Genetic Engineering, National Academy of Sciences of Ukraine, Kyiv, Ukraine, and Department of Nuclear Chemistry, Faculty of Science, Commenius University, Bratislava, Slovakia

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.

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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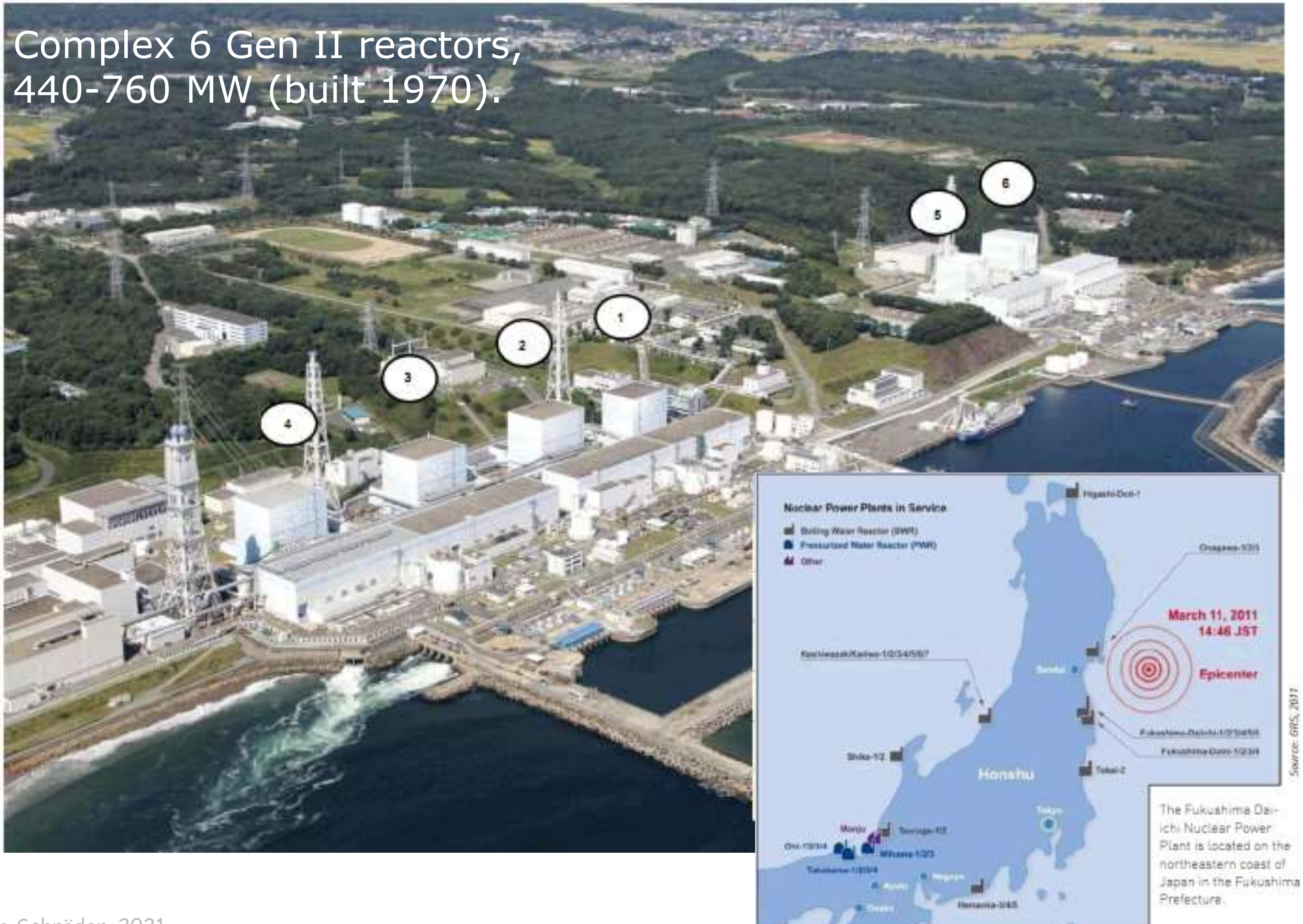
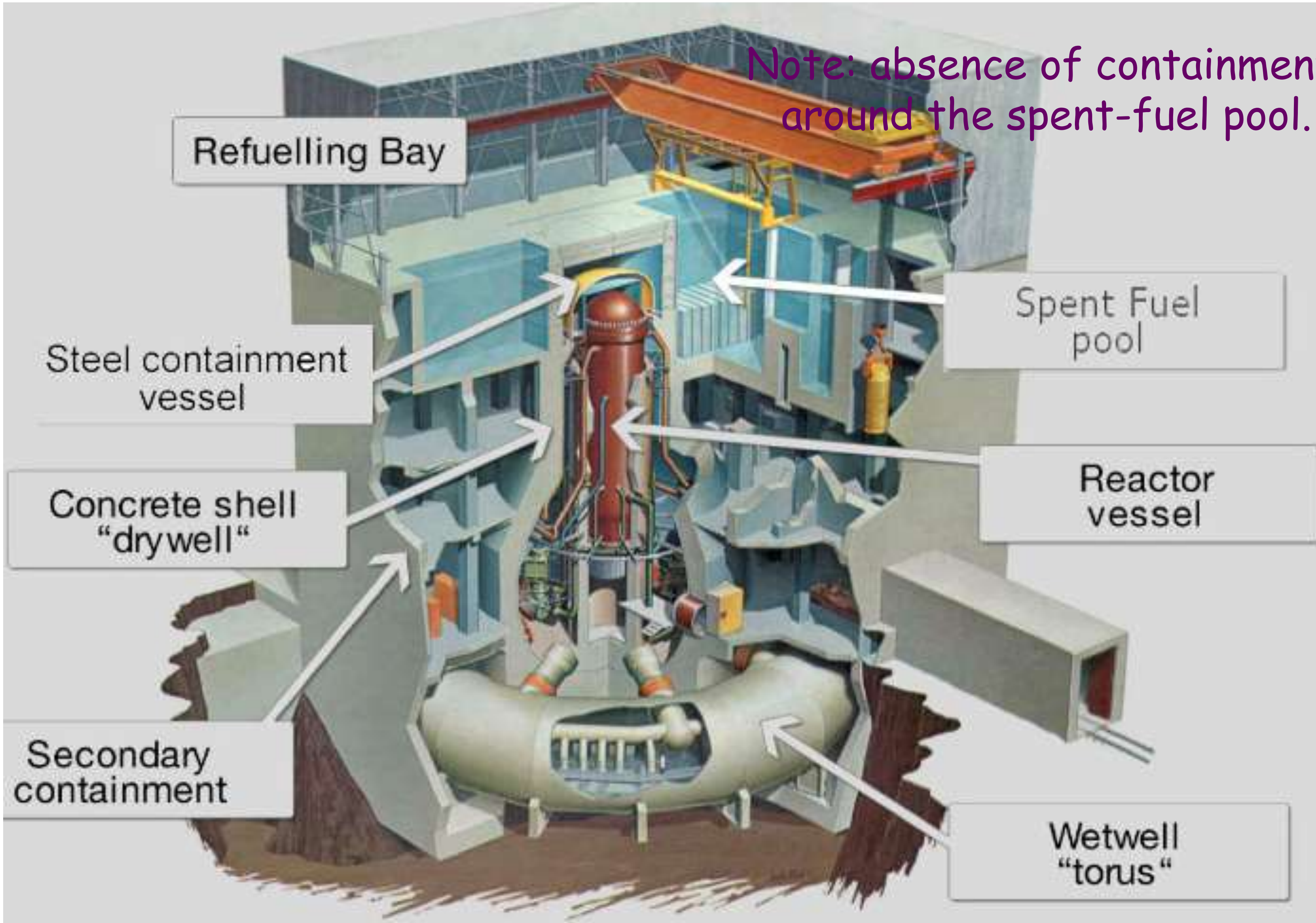
Fukuchima-Daiichi NPP

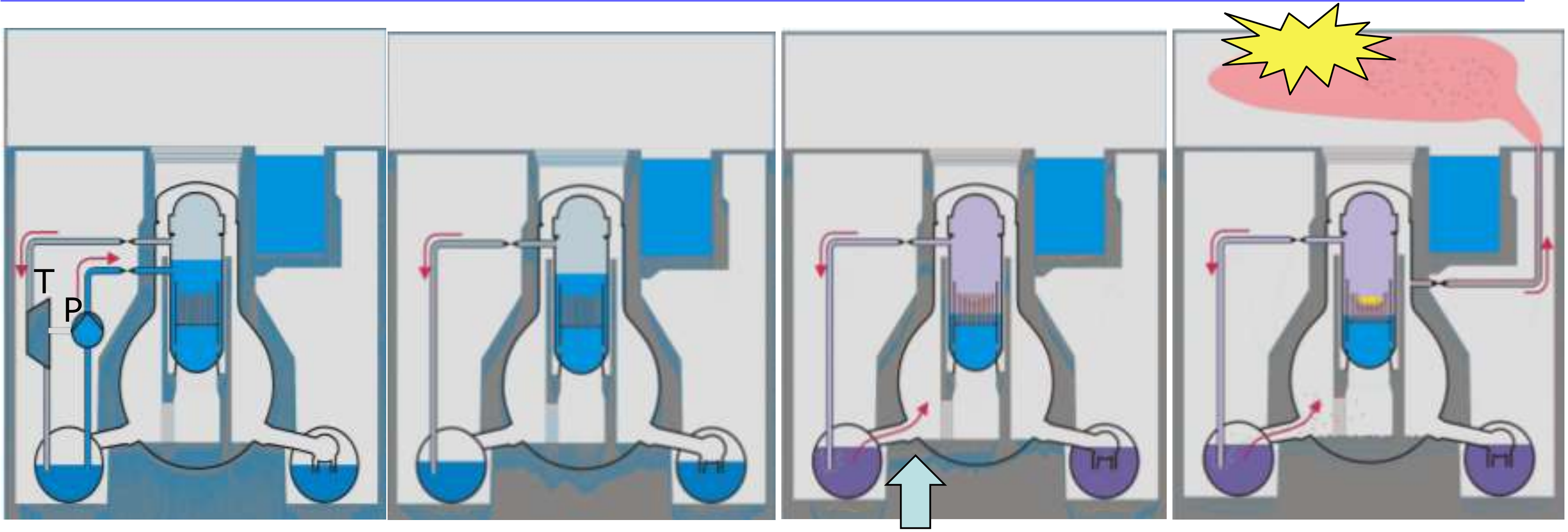


The Fukushima Dai-ichi Nuclear Power Plant is located on the northeastern coast of Japan in the Fukushima Prefecture.

Fukushima BW Reactor Design (GE & Toshiba)



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

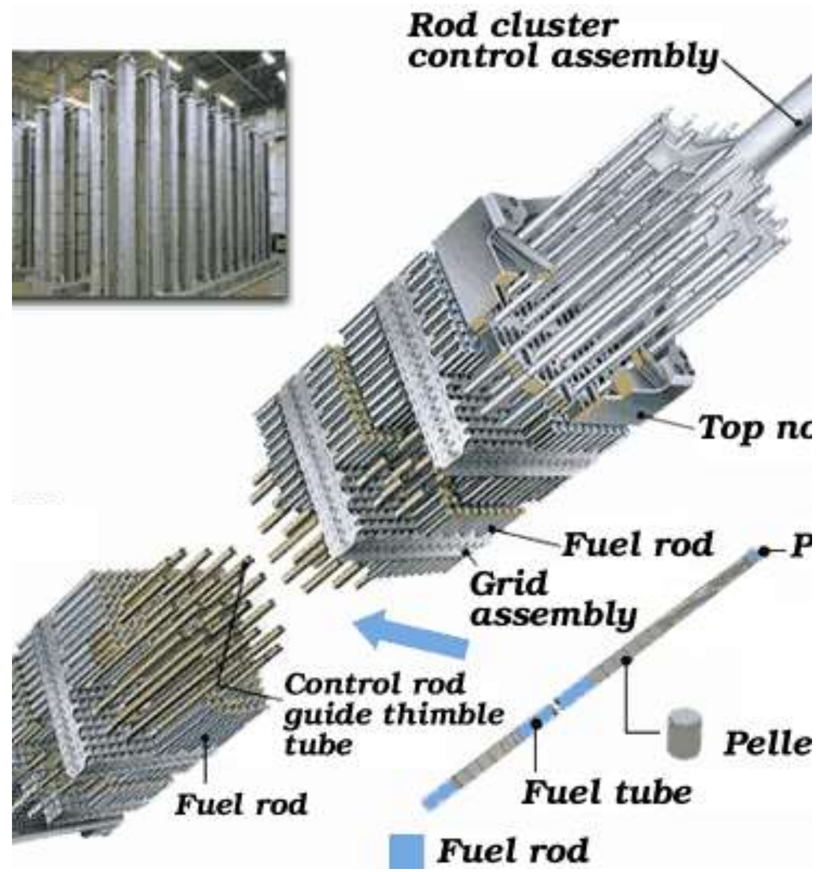
What Went Wrong, Hydrogen Explosion

Nuclear fuel rods clad in Zr alloys (little corrosion, low capture cross section).
But: reactivity against water (1,200°C)

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

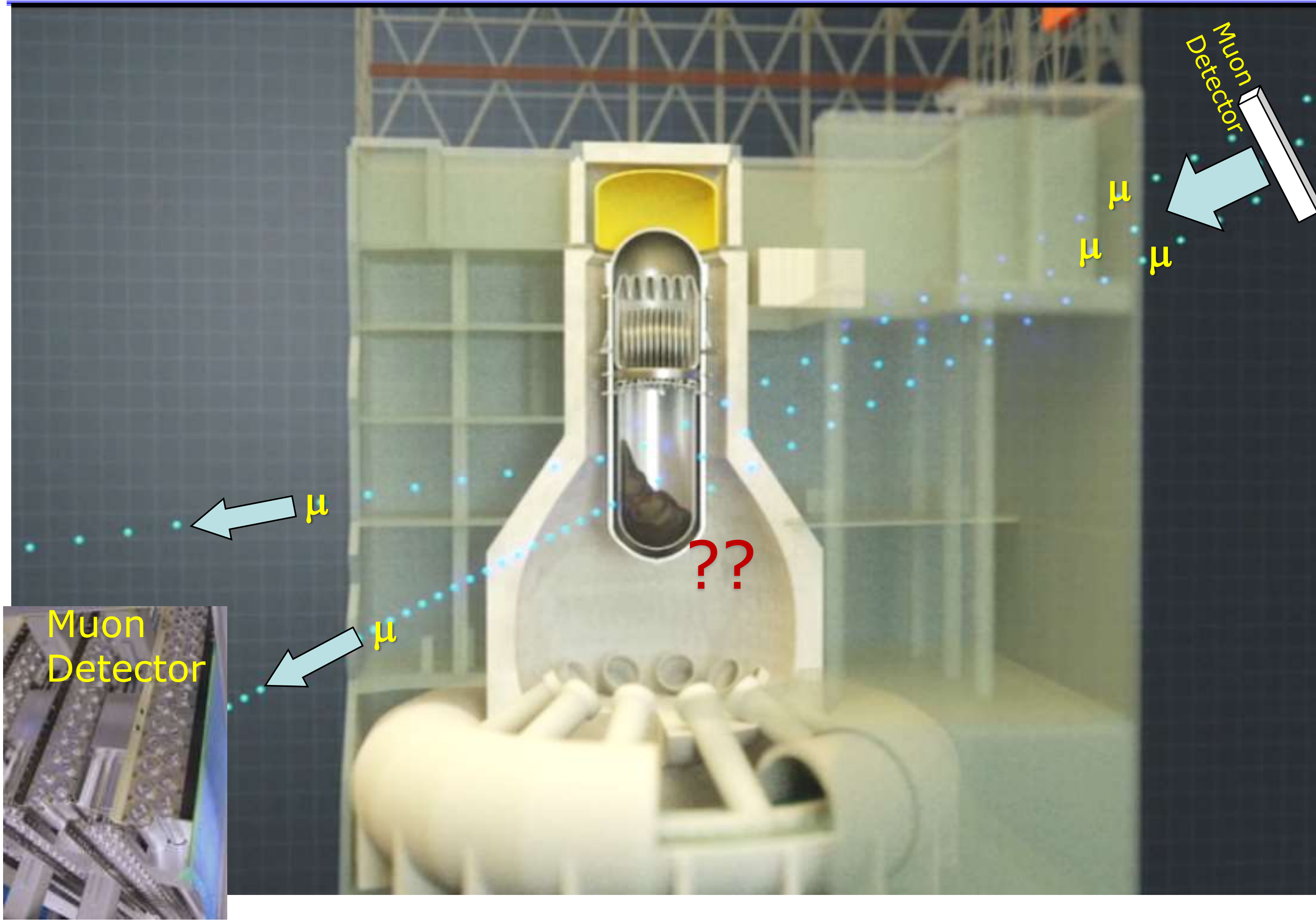
- Reactor operators vented H into the maintenance halls of Reactors 1,2,3 → H_2/O_2 mix detonated.
  Direct venting of H_2 into atmosphere would have been advisable.
- Modern reactors have a catalyst-based recombinators, converting hydrogen and oxygen into water at room temperature.

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

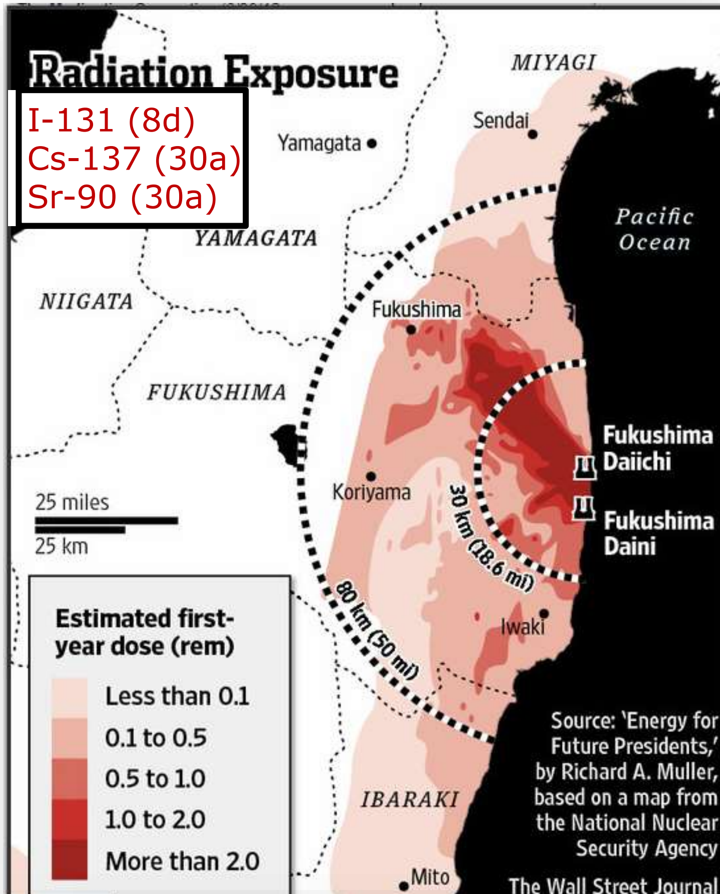


Obvious need for more comprehensive safety analyses for all stations.
Better operator training→ realistic control room simulators.

Muon Imaging of Fukushima Core



Fukushima Radiation Dose in Perspective



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)

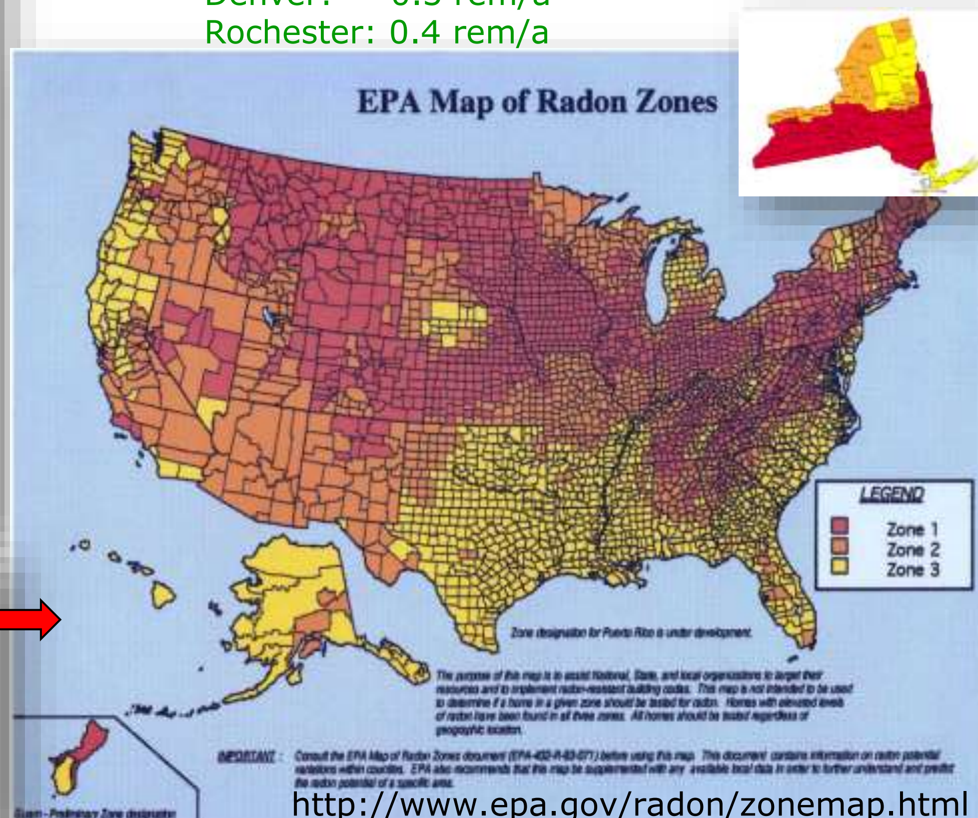
Natural radiation exposure, mostly radon (+cosmic)

1pCi/L=0.09 rem/a ≈ 0.1 rem/a

Denver: 0.3 rem/a

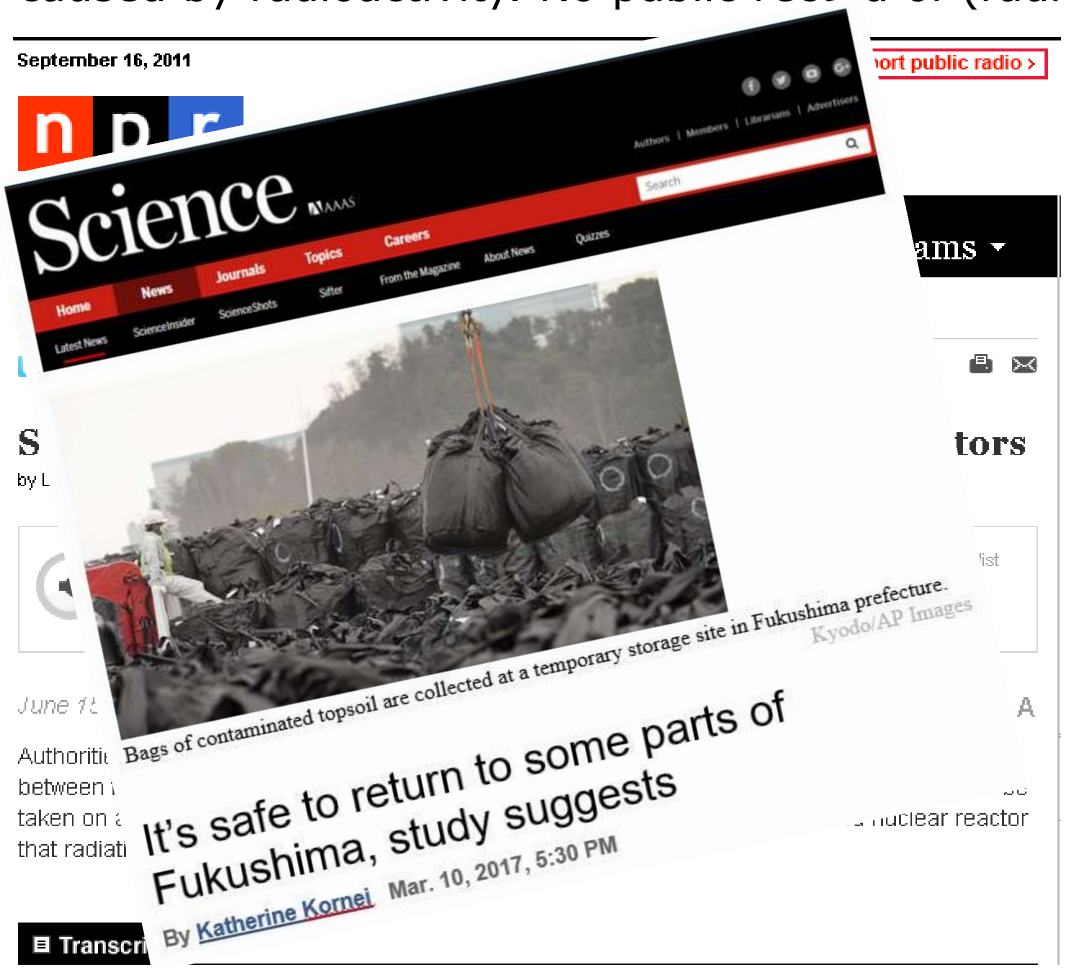
Rochester: 0.4 rem/a

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**	



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.



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

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

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

RETURN

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.

RETURN

End

RETURN