Nuclear Power: Status and Trends

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

Nuclear Fission Energy in the U.S.

Status and Trends in Technology

I. Introduction: Energy Demand and Outlook

II. Principles of Energy Generation from Nuclear Fission

- Fission chain reaction and reactor control
- Open fuel cycle

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- Gen IV reactors
- Closed fuel cycle

V. Conclusion: Nuclear Power in a Sustainable Energy Future

Introduction: World Energy Outlook

Predictions (IEA)

1: World (US) demand up by +50 (28)% (25y: $20T, U.S. >$5T)

Now : 450 Quad Btu/a → 2030: 680 Quad Btu/a

2: Redistribution Industrial World vs. Developing World

40 Bbloe/a (220 GJ/a) vs. 6 Bbloe/a (34 GJ/a))

Boundary conditions

1: Disappearing resources (IEA)

Now, or soon: beyond peak oil
> 2050(??) peak gas, but unconventional gas (shale)
> 2090(??) peak uranium (^{235}U)

2: Mitigate anthropogenic pollution

Improve energy efficiency
Reduce GHG emissions (fossil fuels)
Alternative energy sources (renewables, nuclear)

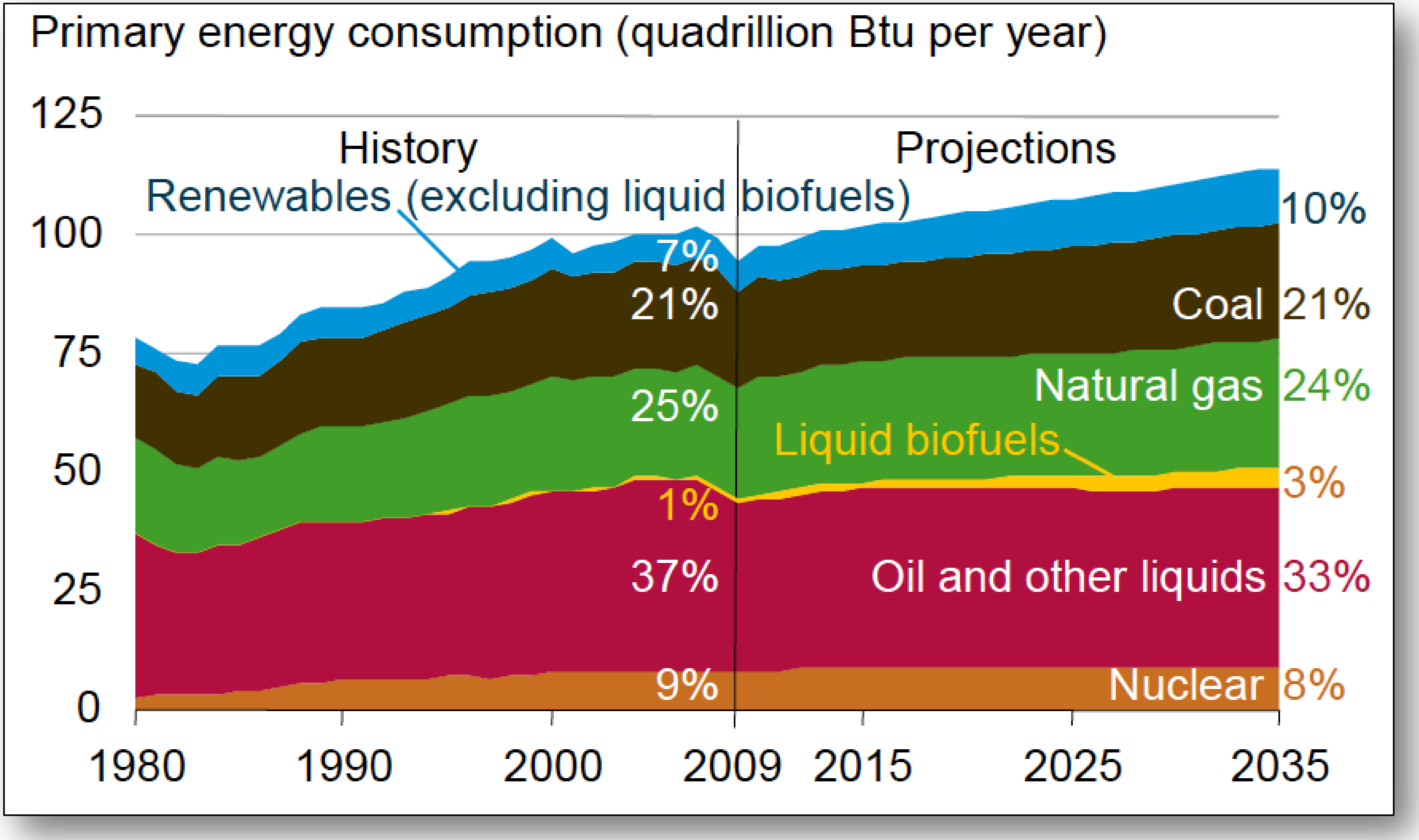
3: → US energy security/independence in global context !?

How to manage significant increases @ Boundary conditions?

Moderate growth potential of individual technologies → need diverse energy portfolio

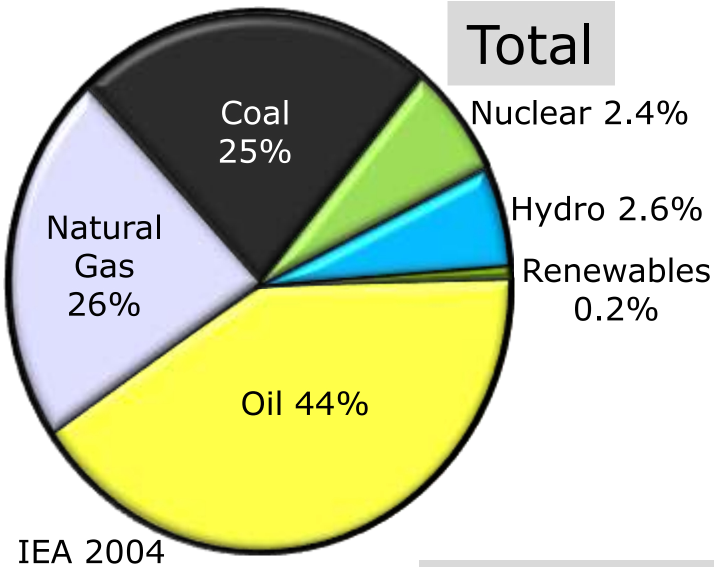
Energy Demand (US)

100 Quad Btu/a = 49 GJ/a

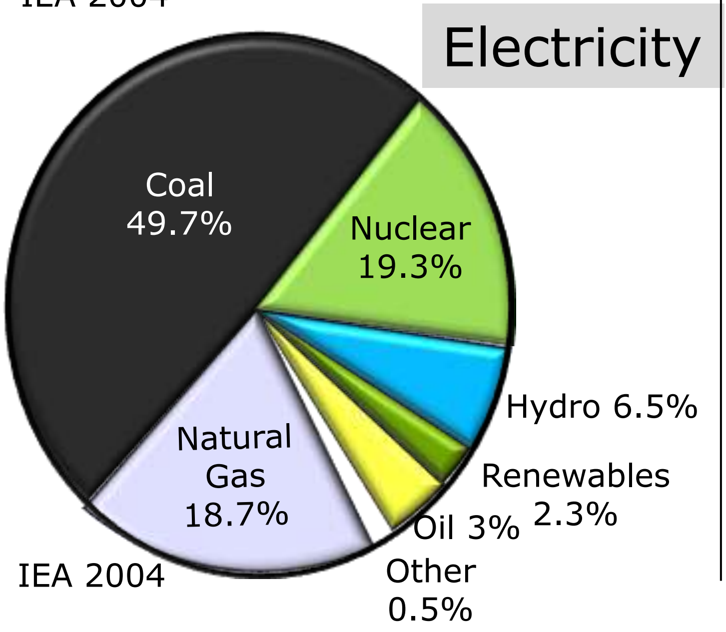


EIA: Annual Energy Outlook 2011

Present Energy Demand (U.S.)



IEA 2004



IEA 2004

450 Quad Btu/a = 220GJ/a

U.S. uses 25% of total global energy demand, 65% imported (Canada, Mexico,.., Middle East)

Oil & nat. Gas & Coal 95%

Main Energy Uses:

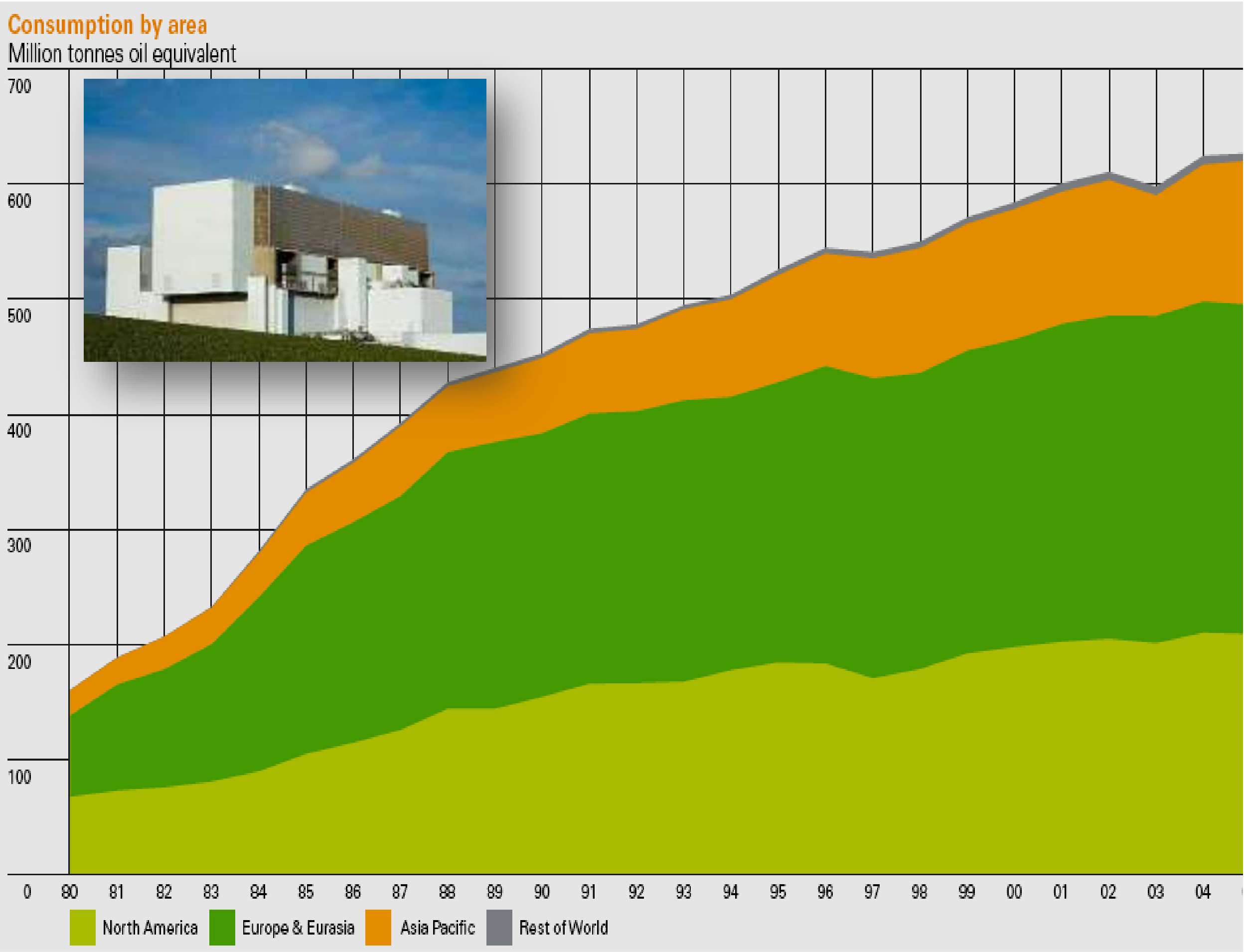
- Industry
- Transportation (liquid fuels)
- Agriculture
- Commercial & public
- Residential

Growth potential | bound. cond's.

→ Nuclear Energy: high power density, scalability, economics

Trends in Nuclear Energy Production

Steady increase of nuclear power output over past 20 years.
Now equivalent: 24 quads of oil



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

World
53 new reactors,
US:3-4,
> 20 planned,
license
applications

US potential:
several new
reactors/a
(@ $\$(2-3)B/GW_e$,
→ 5¢/kWh)

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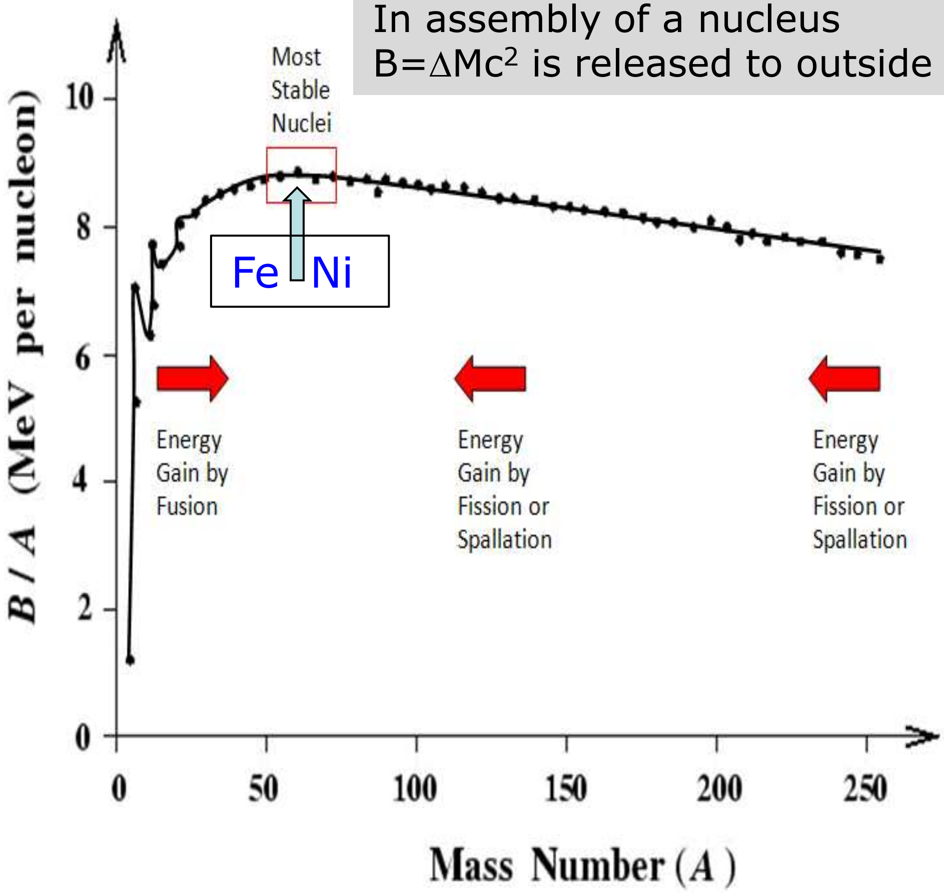
Nuclear Rearrangement Energies

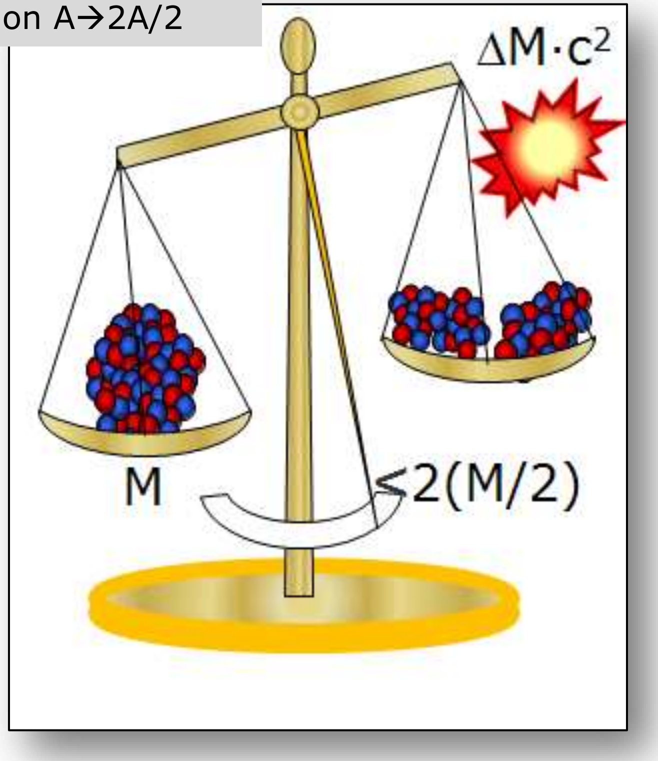
$M_{(N,Z)} < N \cdot M_n + Z \cdot M_p \rightarrow \Delta M \square B(A=N+Z)$

Einstein: equivalence
mass = energy **$E = M \cdot c^2$**

In assembly of a nucleus
$B = \Delta Mc^2$ is released to outside



Energy release in fission A→2A/2

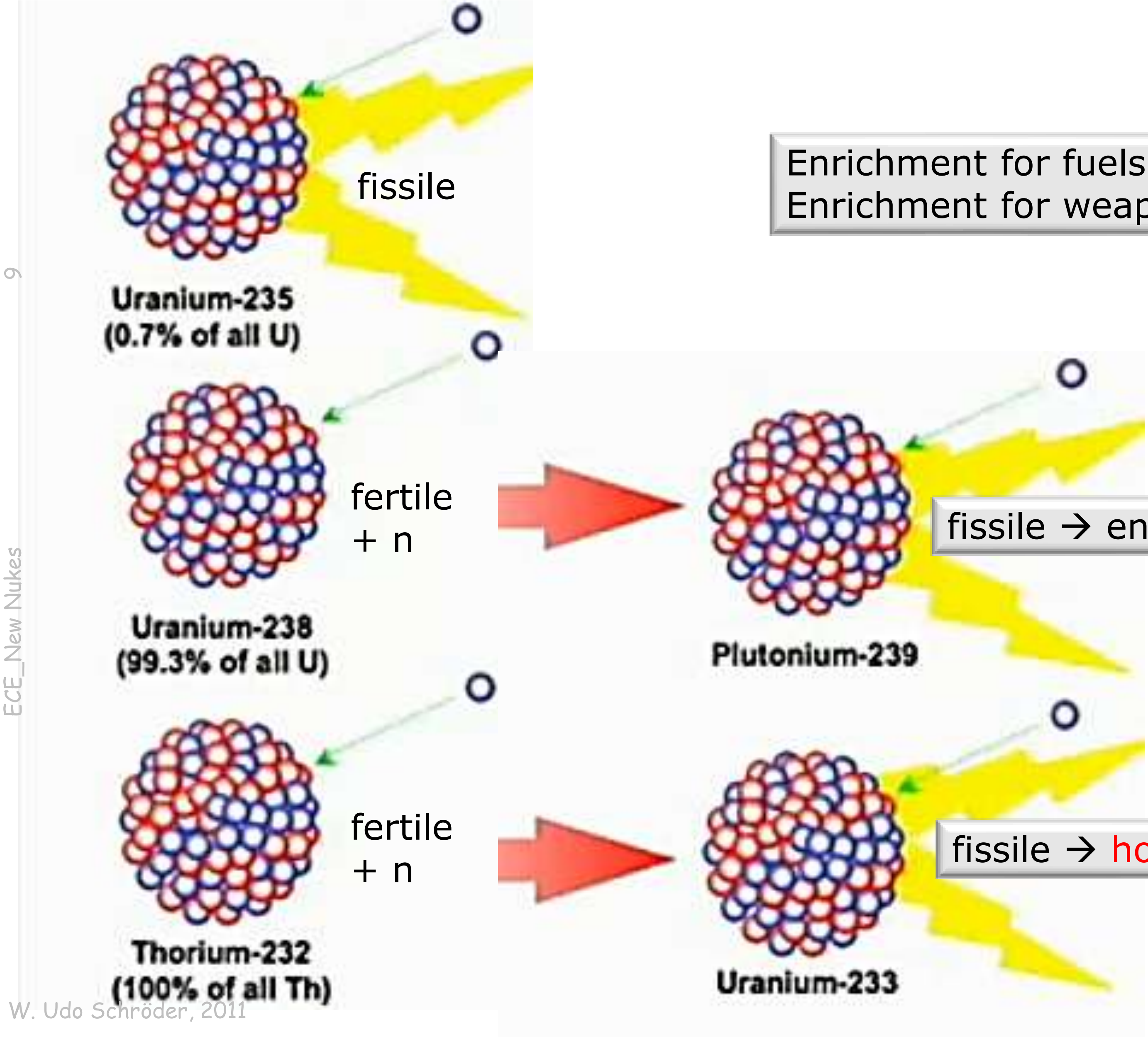


$$M\left({}^{235}U\right) = 47\,mg \xrightarrow[fission]{\Delta M = M \times 10^{-3}} \Delta E = 47\,\mu g \cdot c^2 \approx 4 \cdot 10^9\,J$$

$$M\left(TNT\right) = 1\,t \xrightarrow[combustion]{\Delta M = M} \Delta E \approx 4 \cdot 10^9\,J$$

Nuclear Fuels

Enrichment for fuels → 3-4 % fissile
Enrichment for weapons → >90 % fissile



fissile

fertile
+ n

fissile → enrichment→ weapons

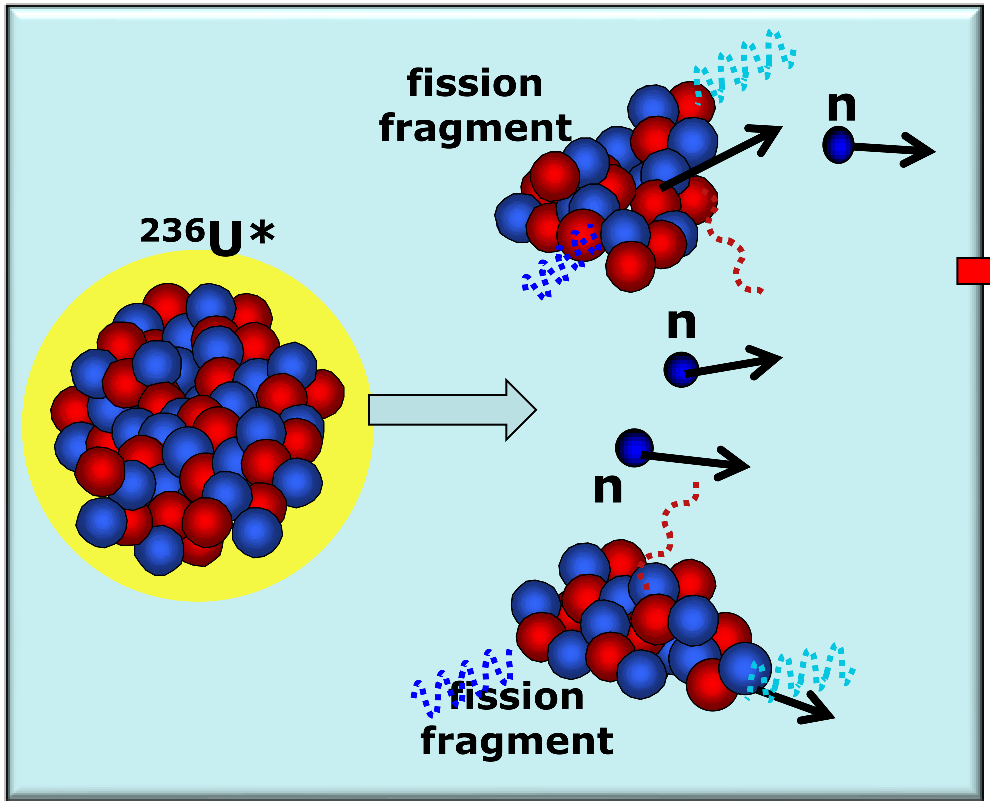
fertile
+ n

fissile → hot enrichm.→weapons

Energy Generation from n_{th}-Induced Fission

$$^{235}U + n_{th} \rightarrow {}^{236}U^{*} \rightarrow 2\,FF + 2(3)n + 200MeV$$

$$Example: \quad {}^{236}U^{*} \rightarrow {}^{147}La + {}^{87}Br^{*} + 2n_{fast}$$



Converts 0.1% of the mass into energy

1g ^{235}U/day = 1MW

10^8 x chemical energies

E_{ff} = 168 MeV
$E_{n\ tot}$ = 5 MeV
E_{γ} = 7 MeV
FF β-decay = 27 MeV
Q_{total} = 207 MeV

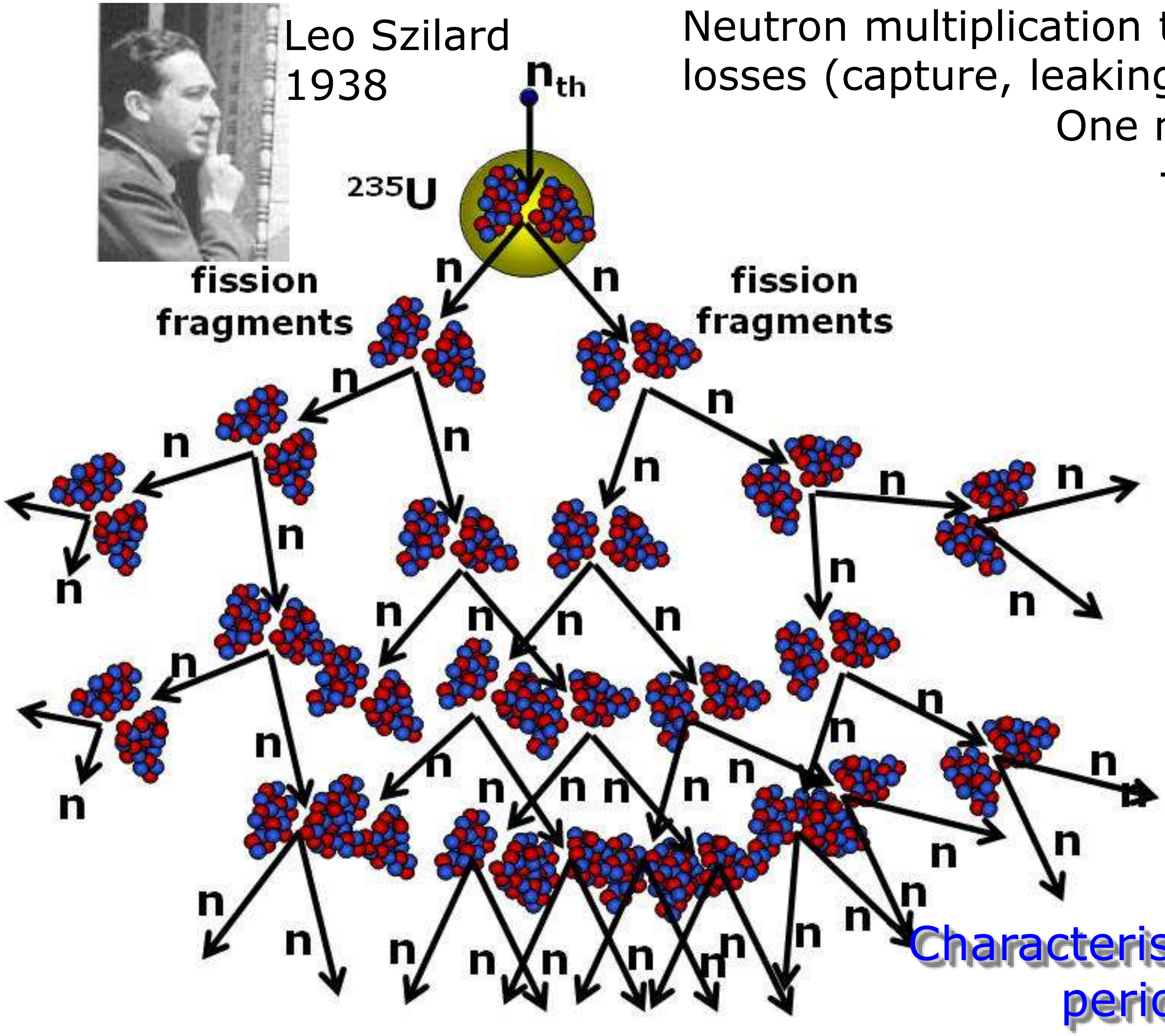
Neutrons per fission:
k = 2.5±0.1
k=1 → critical =chain rxn
k>1 → explosive chain rxn
Fission neutrons are fast:
n-energies $\langle E_n \rangle \approx 2$ MeV

→ Fast n's do not induce ^{235}U fission → need moderation

Most fission neutrons are lost and/or not useful for further fission
Fission fragments = reactor poison, stop chain reaction. ***k < 1 !!!***

Thermal-n Induced Fission Chain Reaction

Leo Szilard
1938



Neutron multiplication through fission *k=2.4*, minus losses (capture, leaking,..), → effective *k < 2.4.*

One n used in fission
→ effective multiplication ***k-1***:

$$\frac{dN_n}{dt} = \frac{1}{\tau}(k-1)\,N_n \rightarrow$$

$$\boxed{N_n(t) = N_n(0)\cdot e^{(k-1)t/\tau}}$$

k >1: avalanche of n
τ = time betw. generations
(τ ~ 40μs in reactors
τ ~ ns in explosives)

$$k_{eff} = k_{prompt} + k_{delayed}$$

Reactor Control

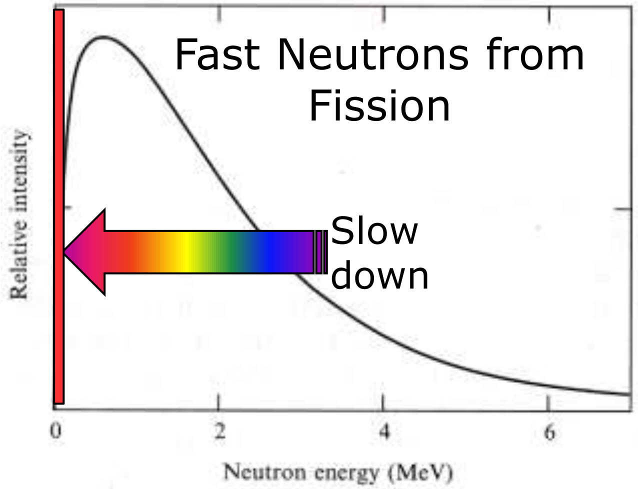
Characteristic period:

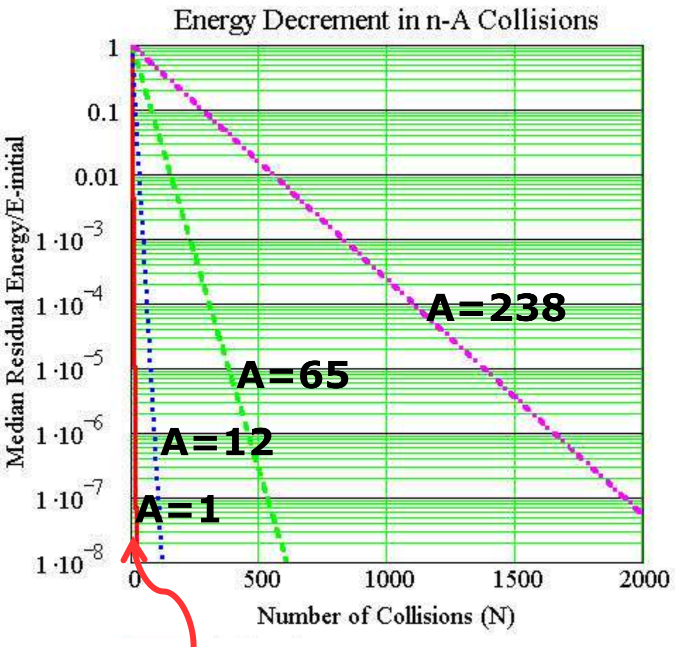
$$\boxed{T = \frac{\tau}{(k_{eff}-1)}}$$

$k_{eff} \approx 1$
e.g., k_{eff}=1.03

Most fission neutrons are lost and/or not useful for further fission
Fission fragments = reactor poison, stop chain reaction. ***k < 1 !!!***

Neutron Moderation





H, D are best moderators

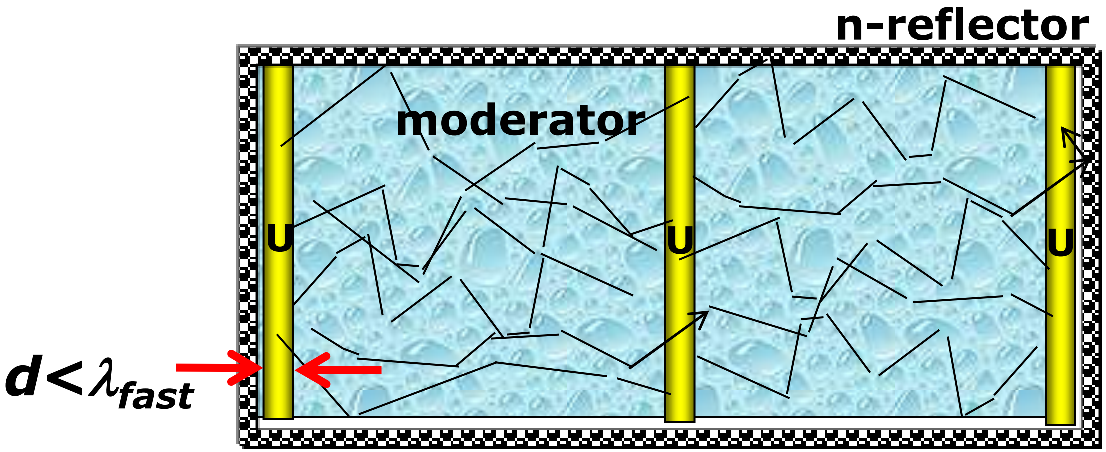
Fission neutrons too energetic, "thermalize" to maximize σ_f for ^{235}U

→ multiple elastic scattering ("moderation") moderator: small σ_{capt} !

Need: **2 MeV →0.025 eV/2MeV= 10^{-8}**

Need to "miss" ^{238}U capture resonances ($2eV < E_n < 10keV$)

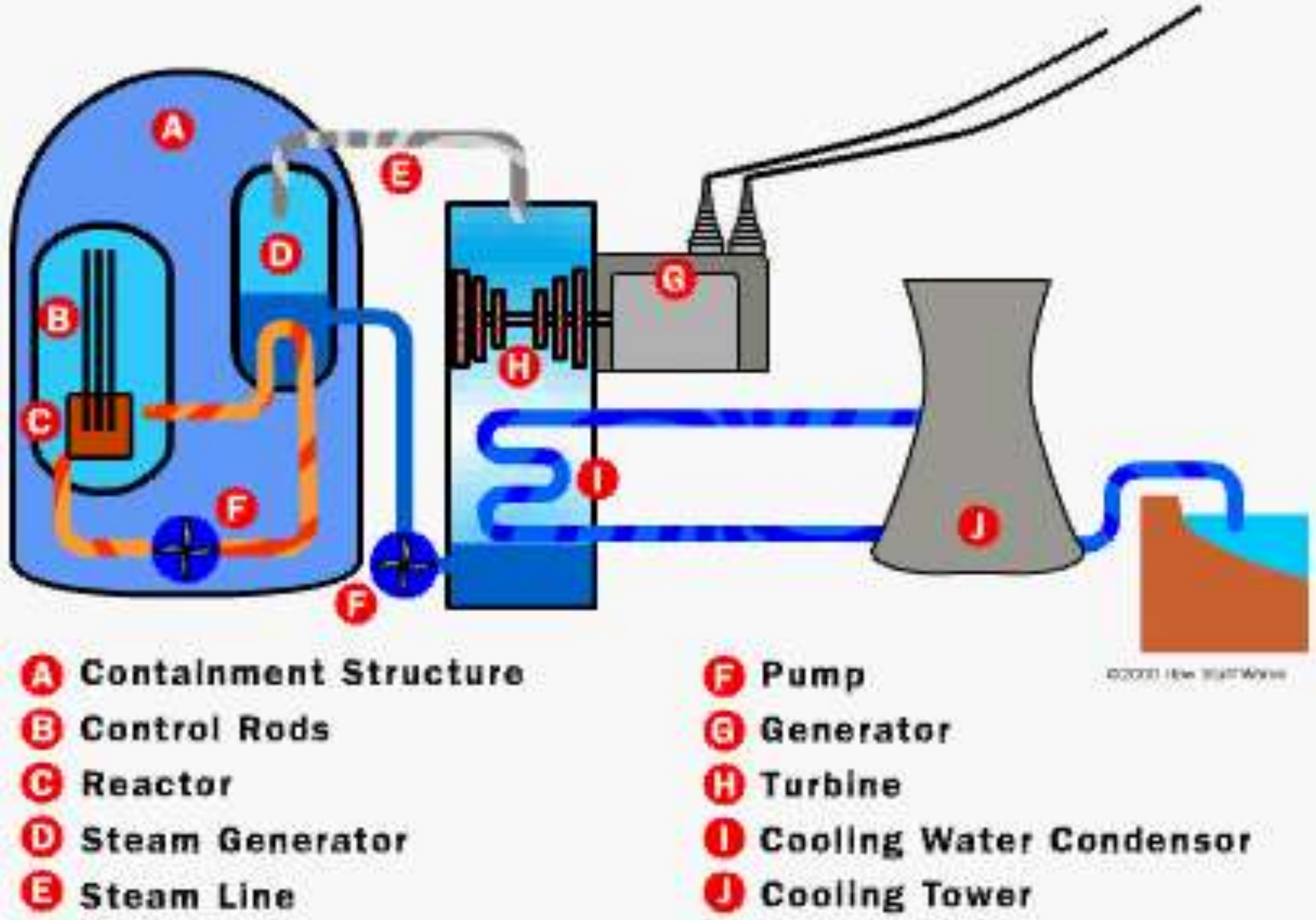
H_2O, D_2O, Be, C(graphite), prevent leakage



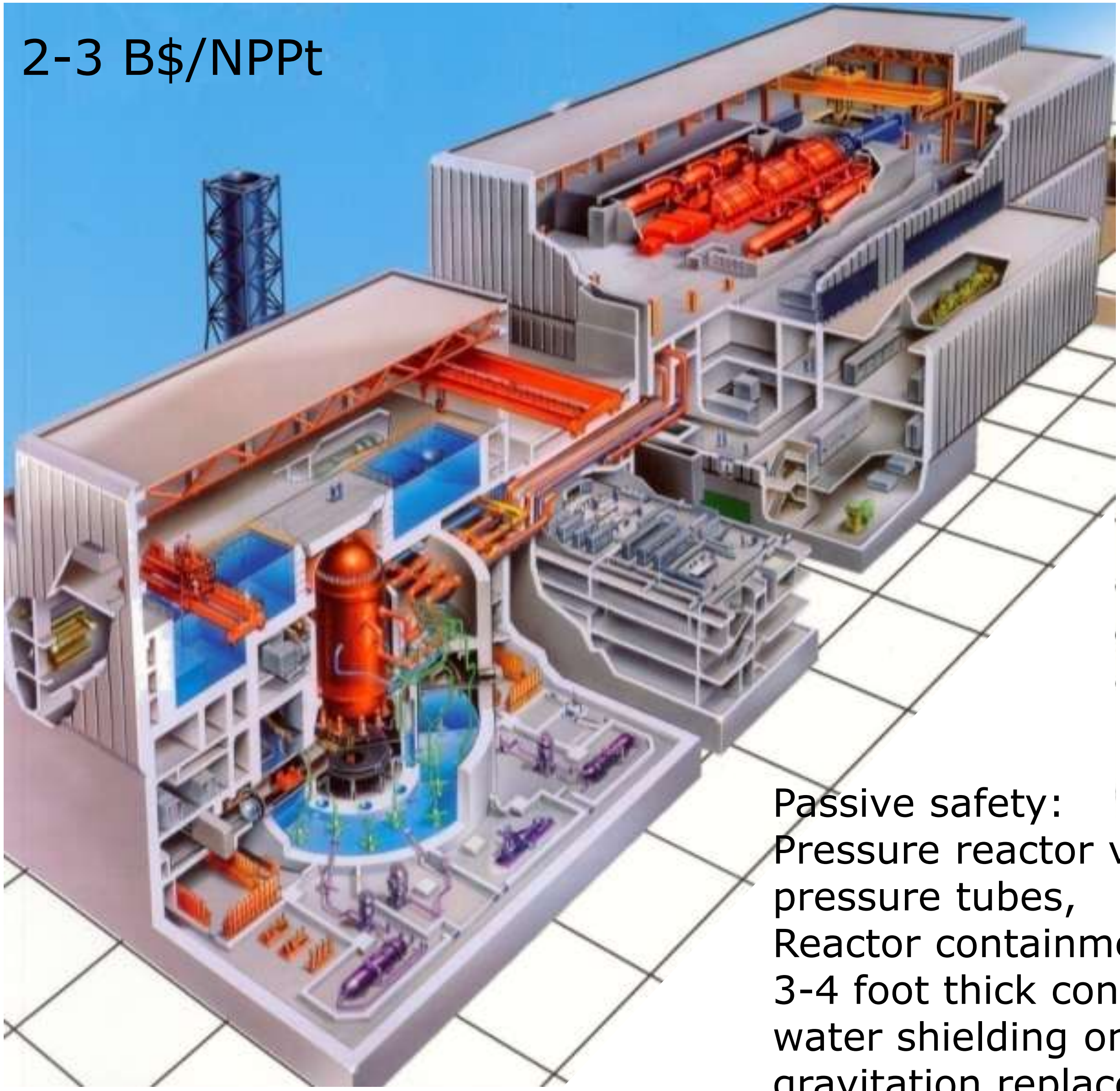
H can capture neutrons:

$H+n_{th}$ → D+2.2 MeV

Principle Boiling Water Reactor



Nuclear Power Plant 1-2GW



2-3 B$/NPPt

Fail-safe operation
Negative Reactivity

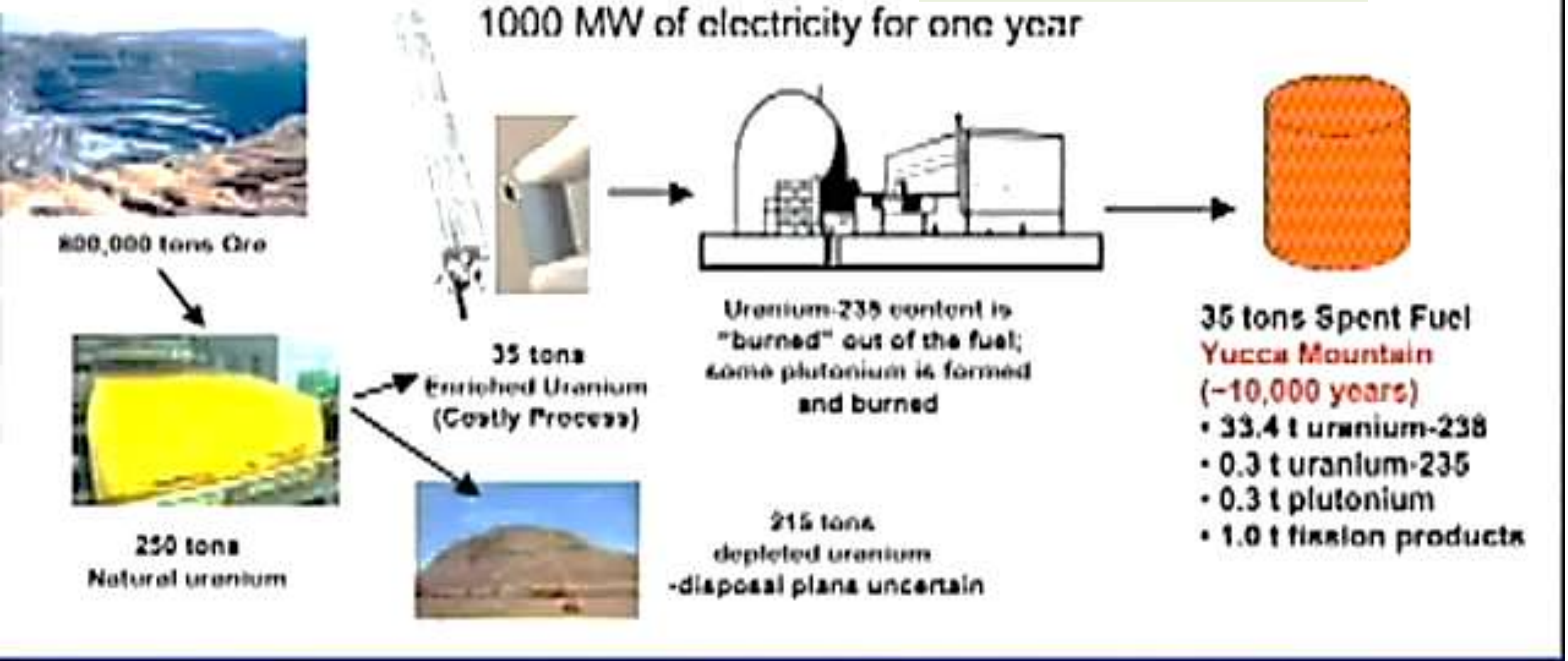
Negative feedback loops:
Reaction subsides when

- coolant gets too hot or disappears (less dense, less moderation)
- fuel gets too hot (*n* capture increases)
- control rods are not moved out

Passive safety:
Pressure reactor vessel ~1′ thick steel, pressure tubes,
Reactor containment building with several 3-4 foot thick concrete walls, concrete + water shielding on top of reactor vessel, gravitation replaces mechanical pumps.

Nuclear Fuel Storage & Transport

Uranium Fuel Cycle US Now



1000 MW of electricity for one year

800,000 tons Ore

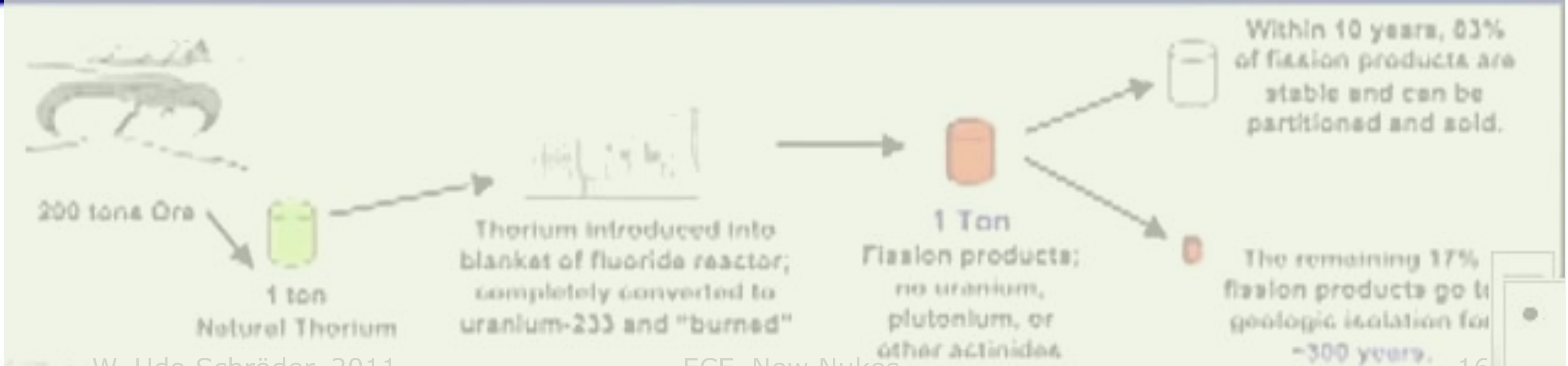
250 tons
Natural uranium

35 tons
Enriched Uranium
(Costly Process)

Uranium-235 content is "burned" out of the fuel; some plutonium is formed and burned

215 tons
depleted uranium
-disposal plans uncertain

35 tons Spent Fuel
Yucca Mountain
(~10,000 years)
- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium
- 1.0 t fission products



200 tons Ore

1 ton
Natural Thorium

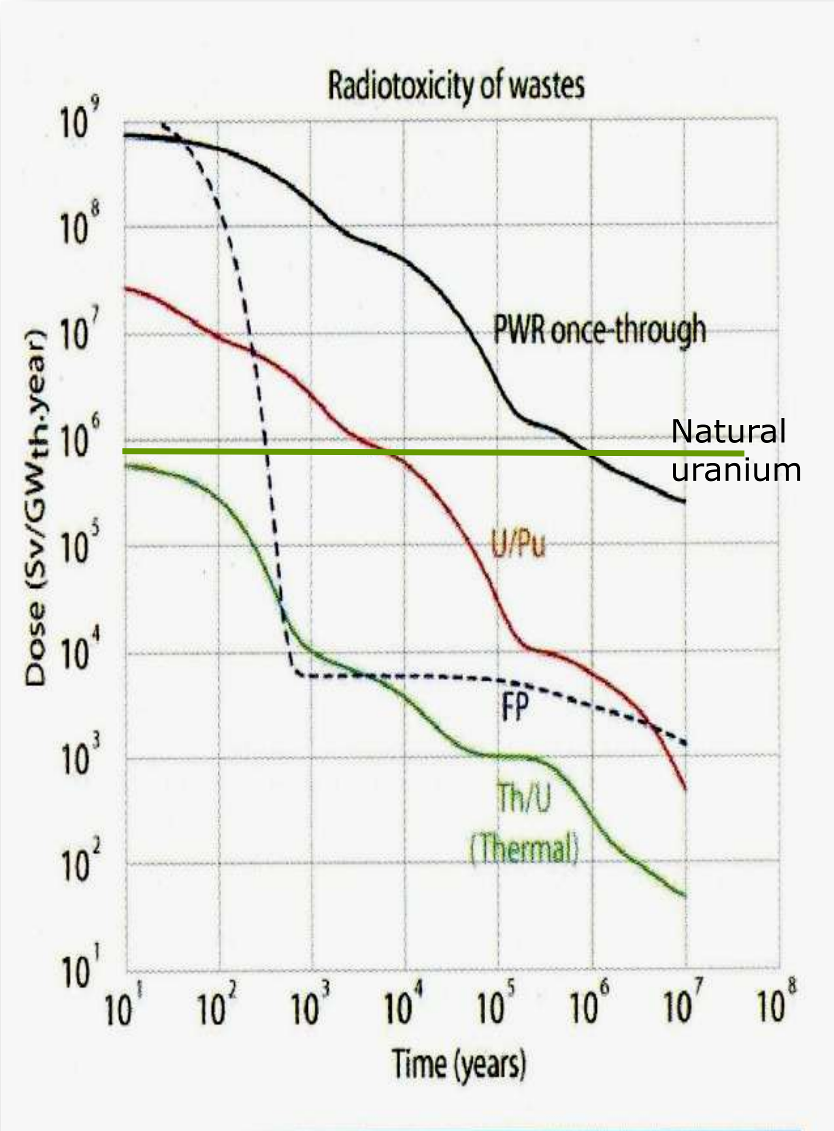
Thorium introduced into blanket of fluoride reactor; completely converted to uranium-233 and "burned"

1 Ton
Fission products; no uranium, plutonium, or other actinides

Within 10 years, 83% of fission products are stable and can be partitioned and sold.

The remaining 17% fission products go t geologic isolation fo ~300 years.

Radiotoxicity of Spent Nuclear Fuel



Radio toxicity vs. time after shutdown, of spent fuel from

•pressurized water uranium reactor (PWR),

- U/Pu breeder, and
- Th/U fuel cycle.

FP indicates the faster decay of fission products.

Multiple reprocessing, less residuals.

Reprocessing involves robotics because of *Tl* gamma radiation → not for extremists' garage!

(David, Nifenecker, 2007)

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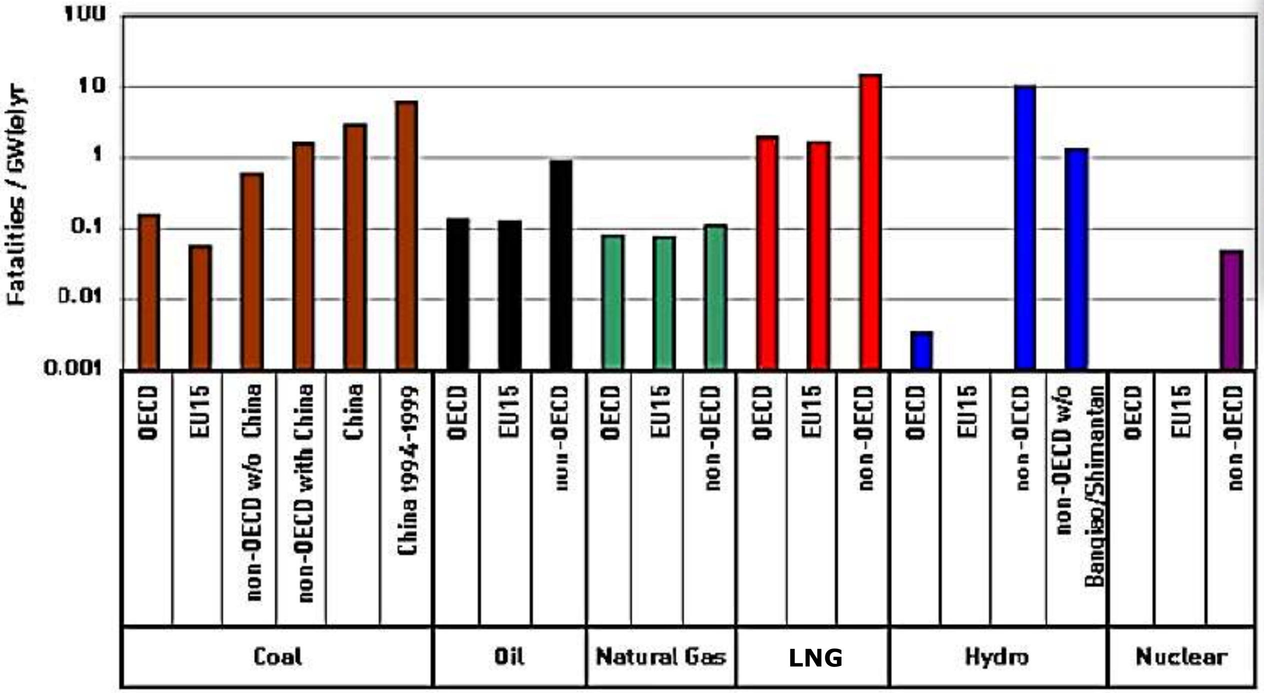
Strategic Issues

Status

1. Operational reactor safety .... √
2. Resource limits of nuclear fuel (^{235}U/Pu, Th,…) … √
3. Safe capture, storage and sequestration of radiotoxic nuclear waste .... √
4. Proliferation resistance (nations, individuals) …… (√)
5. Economy (Capital plus fuel costs) .... √
6. R&D requirements .... √
7. Capability for rapid deployment .... (√)
8. Public perception .... (√)

Fatalities in Energy Production (1969-2000)



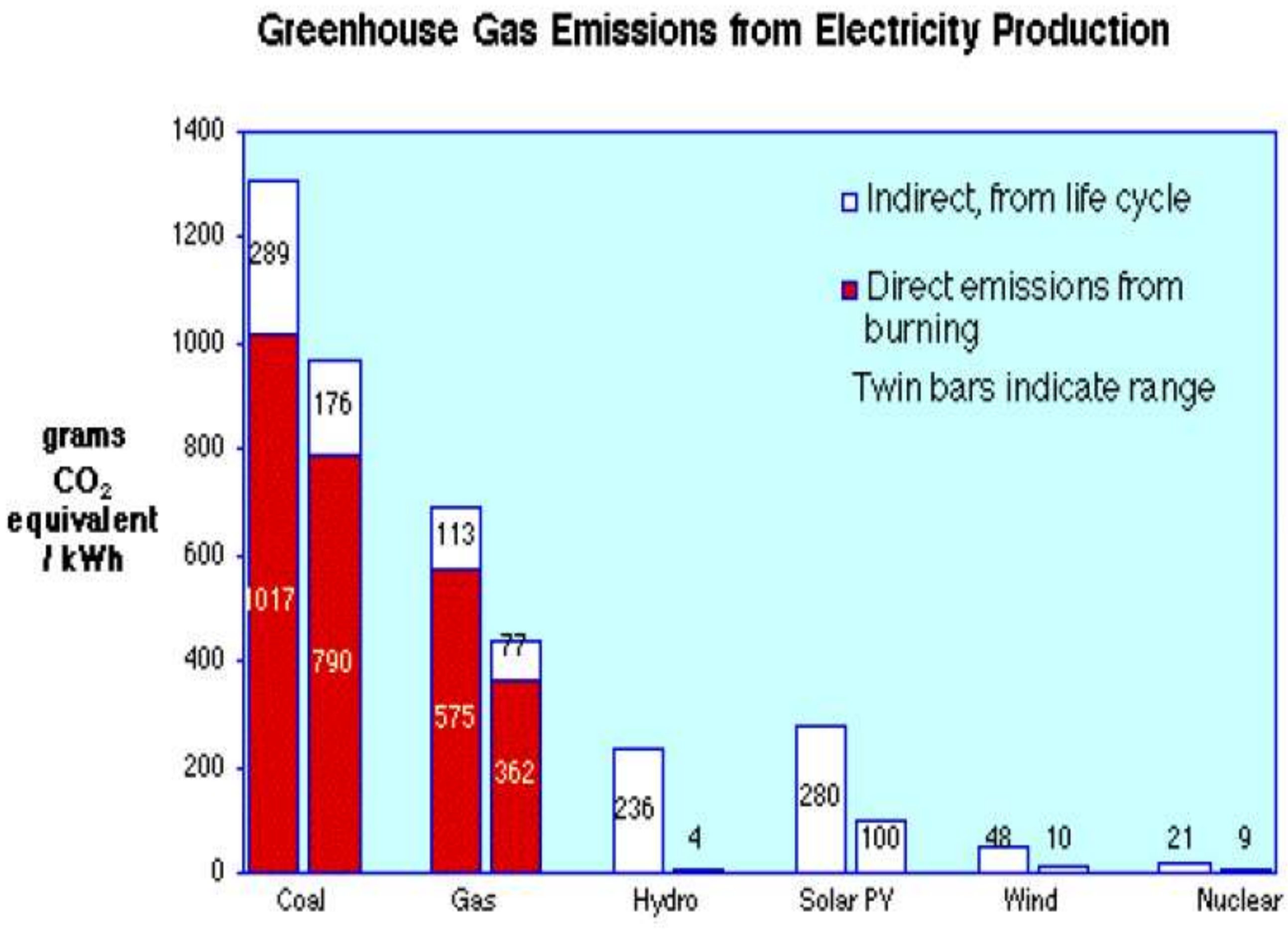
Chernobyl/ Ukraine 1986: 45 Ŧ

Paul Sherrer-Institute/Switzerland.
Omitted: large hydro disasters Shimantan and Banqiao (China 1976: 26,000†).

2006 U.S. coal mines : 42† (equivalent 1 Chernobyl nuclear accident/a)

Every primary energy technology has potentials & hazards.
→ Safety record of nuclear energy

Pollution Footprints of Energy Technologies



Source: IAEA 2000

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 Actind,
localized + decays)

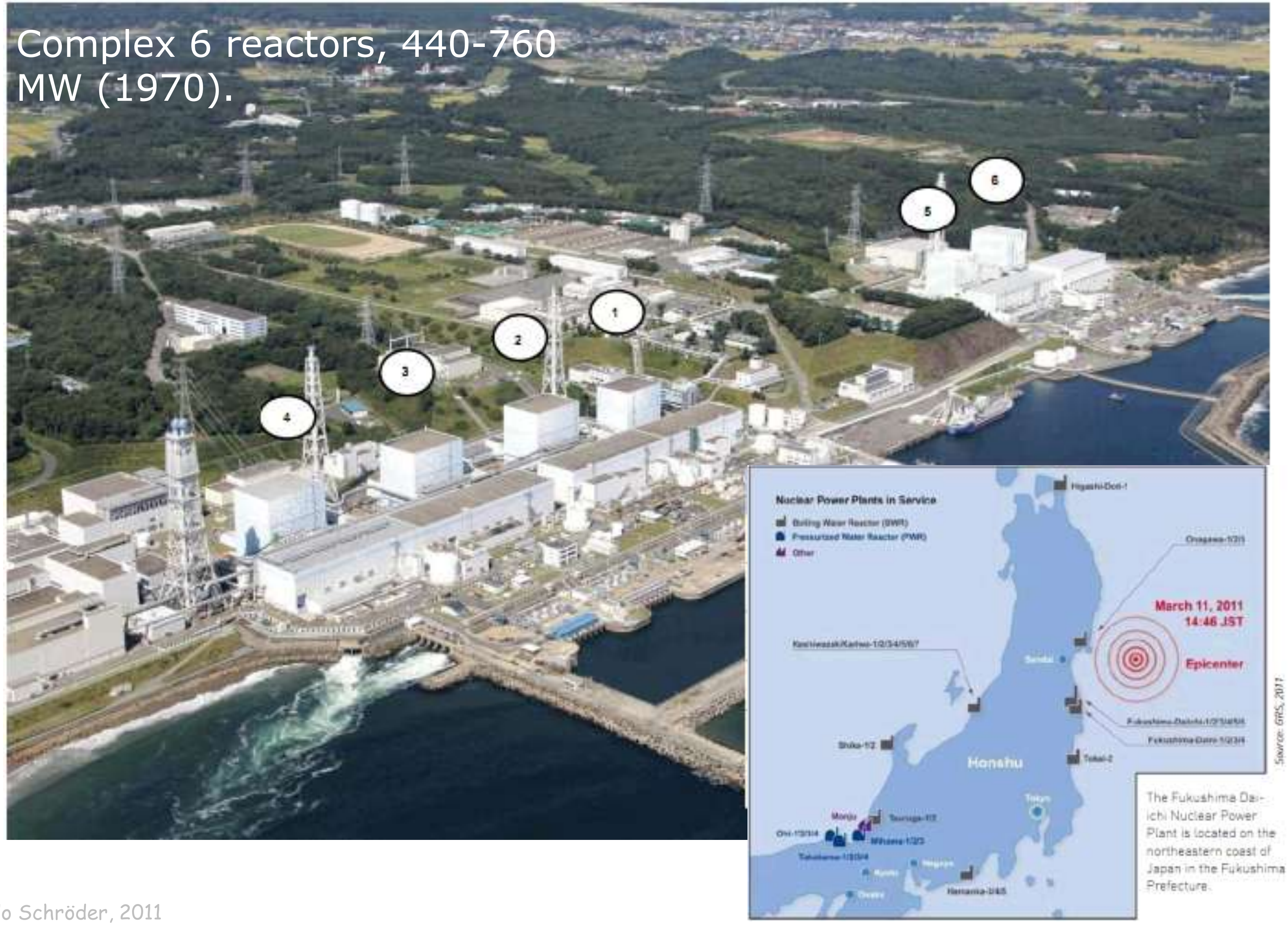
High power density →
small environmental footprint → Nuclear

The following few slides provide an overview of the Fukushima event (March 11, 2011) in Japan, where earthquake and subsequent tsunami disabled several nuclear power plants, leading to a release of significant amounts of radioactivity into the environment.

Lessons taken from this event will have consequences for the design criteria imposed on future nuclear power stations, as indicated by reports of government commissions and independent expert conferences.

Fukuchima-Daiichi NPP

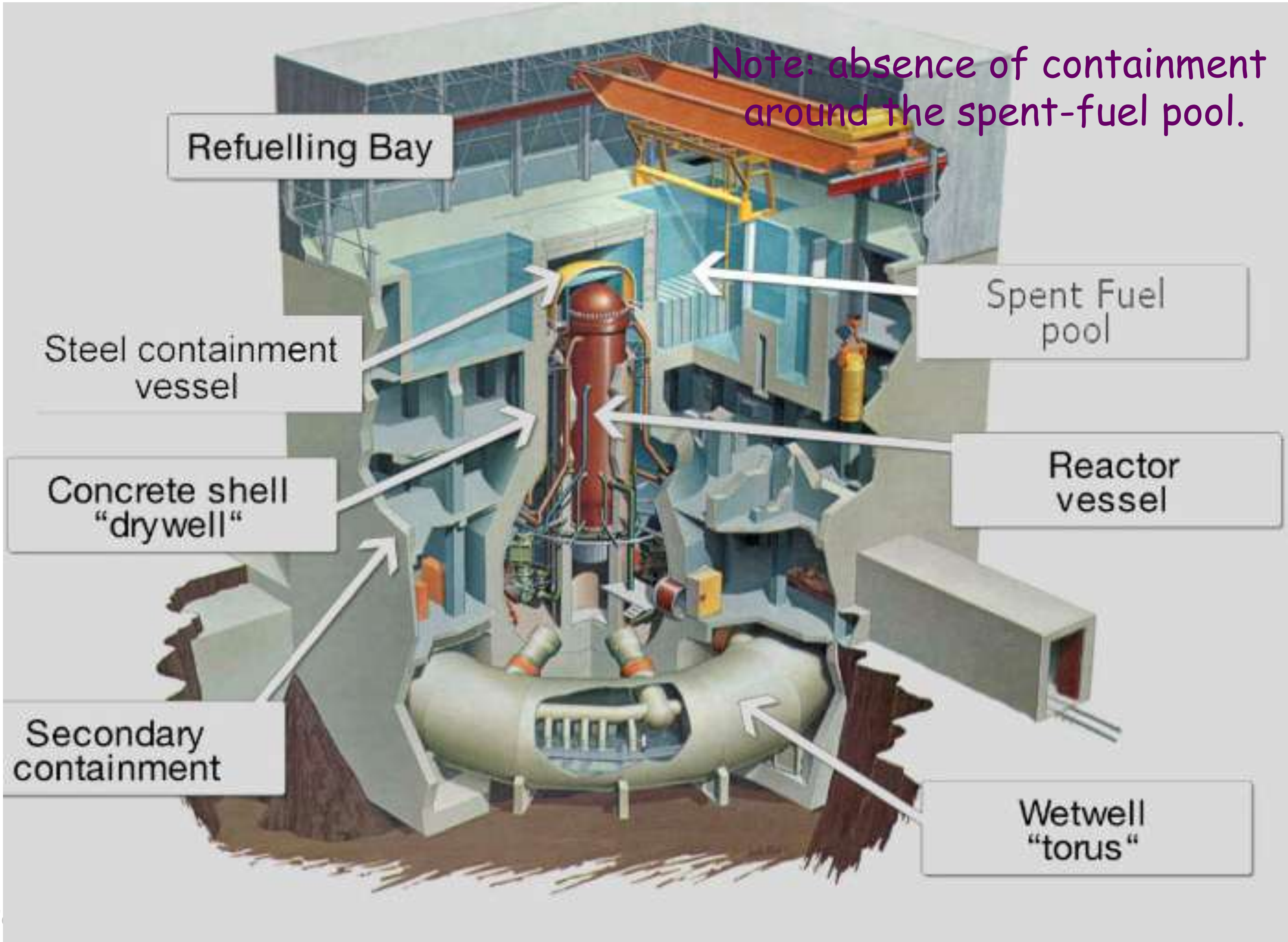
Complex 6 reactors, 440-760 MW (1970).



Source: GRS, 2011

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)



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

What Went Wrong, Hydrogen Explosion

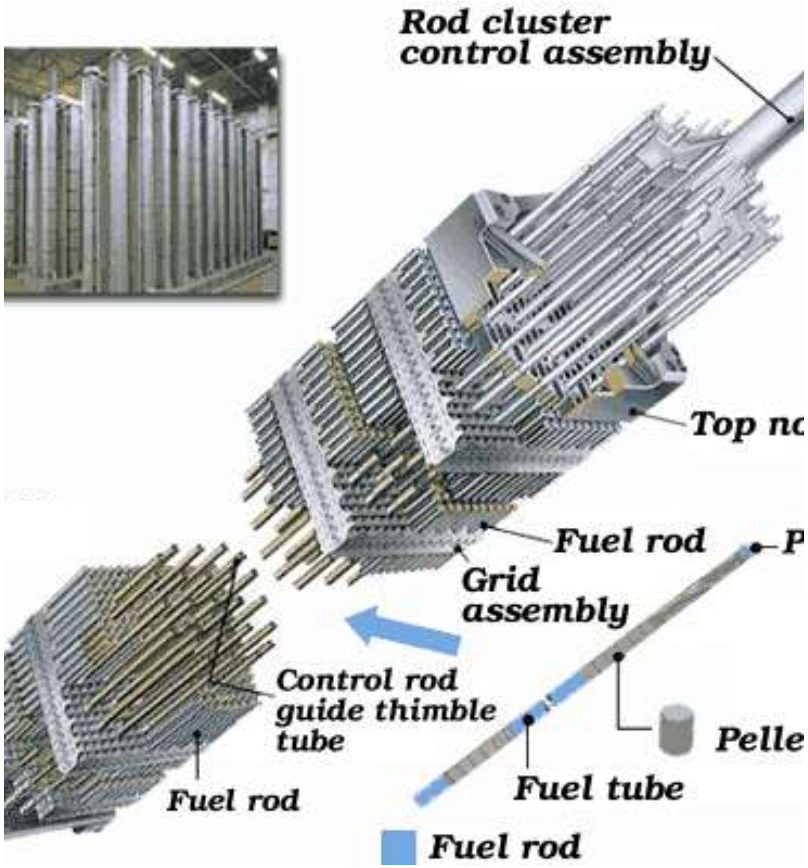
Nuclear fuel rods clad in Zr alloys (little corrosion, low capture cross section).

But: reactivity against water

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

- Operators vented H into the maintenance hall of 1,2,3 → H_2/O_2 mix detonated. Direct venting of H2 into atmosphere would have been preferred design option.
- More modern reactors have a catalyst-based recombinator hydrogen and oxygen into water at room temperature before explosivity limit is reached.

While a similar event would not have happened with the modern U.S. stations, there is an obvious need for more comprehensive risk/benefit analyses for all stations.



Return of the People

There have been no fatalities in the Fukushima event caused by radioactivity.

News › World › Asia

Some Japanese Children To Wear Radiation Detectors

by LUCY CRAFT

Listen to the Story
Morning Edition [1 min 21 sec]

June 15, 2011

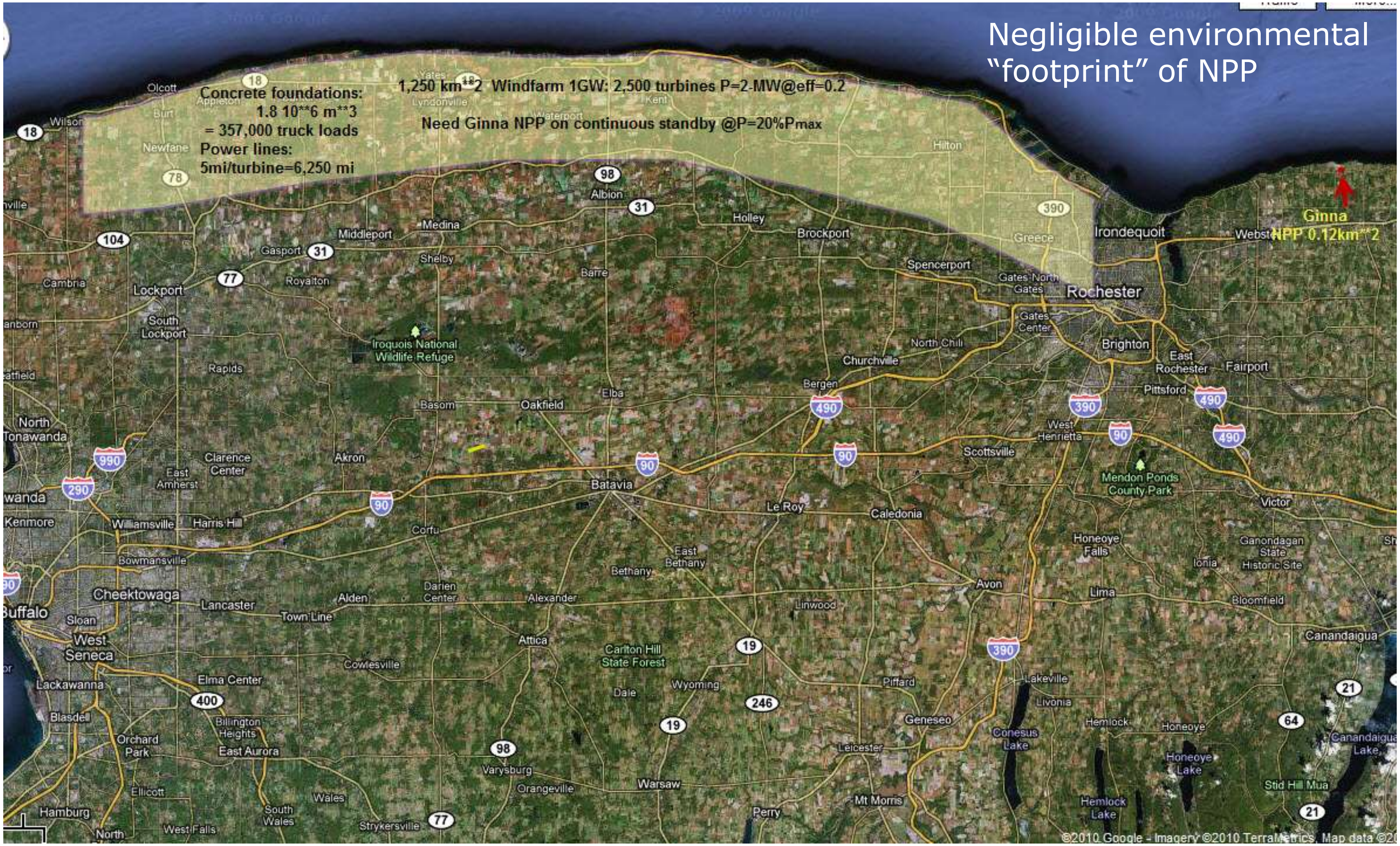
Authorities in the Japanese city of Fukushima will give radiation detectors to 34,000 children between the ages of four and 15. They will wear the devices for three months, and readings will be taken on a monthly basis. The move is aimed at reassuring parents near the failed nuclear reactor that radiation levels are safe.

Close vicinity of the Fukushima NPP is polluted by radioactivity released in the H_2 explosions.
Clean-up of affected areas may take years and $$.

Fortunately, polluted area is small.

For comparison, look at environmental footprint of renewable energy technologies, e.g., wind farms.

Wind Farm “Energy Sprawl”



Negligible environmental “footprint” of NPP

Concrete foundations:
1.8 10**6 m**3
= 357,000 truck loads
Power lines:
5mi/turbine=6,250 mi

1,250 km**2 Windfarm 1GW: 2,500 turbines P=2-MW@eff=0.2

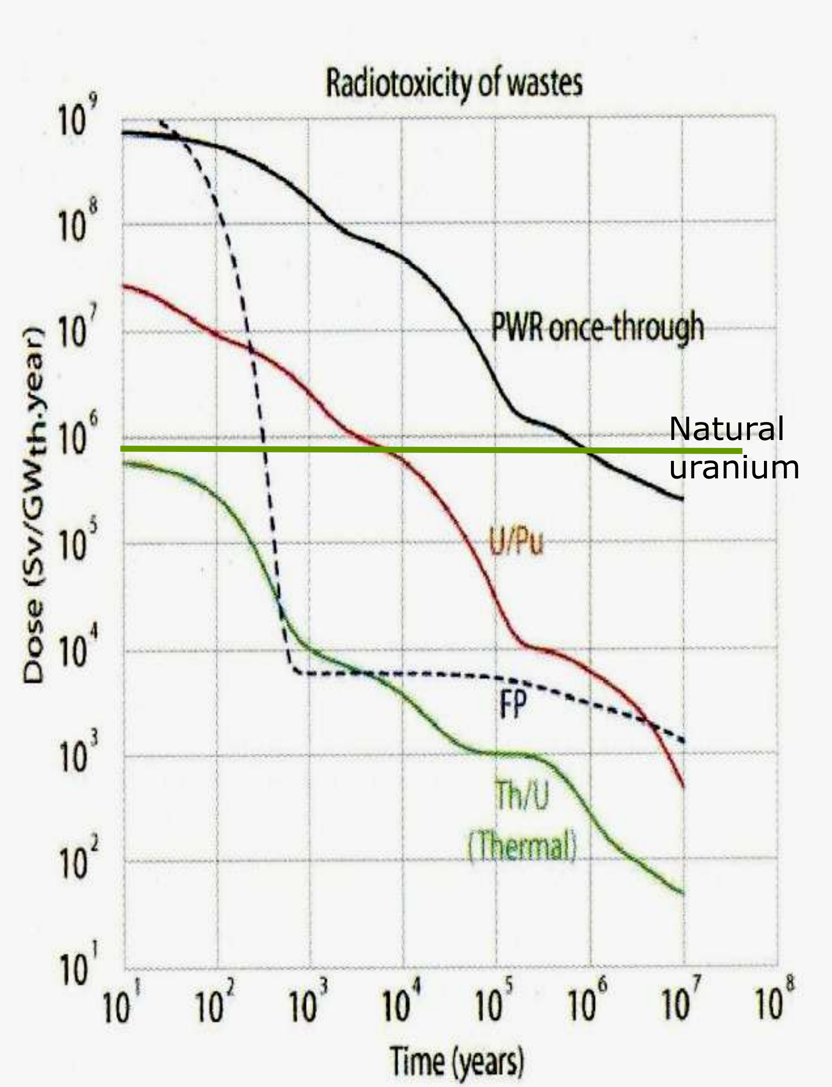
Need Ginna NPP on continuous standby @P=20%Pmax

Ginna
NPP 0.12km**2

©2010 Google - Imagery ©2010 TerraMetrics, Map data ©20

Requires large area (coastal strip 67 mi x 8 mi for P≈1GW+ NPP on standby ($P/P_{max}=0.2$)) → Permanently uninhabitable.

Issue: Radiotoxicity of Spent Nuclear Fuel



(David, Nifenecker, 2007)

Radio toxicity vs. time after shutdown, of spent fuel from

•pressurized water uranium reactor,

- U/Pu breeder, and
- Th/U fuel cycle.

FP indicates the faster decay of fission products.

Multiple reprocessing, less residual waste.

Transmute/incinerate transactinides and FF solves waste issue

Store very small amounts of HL waste for ~100 years
small geological depository, problem disappears in time.

Successful long-term test depository in Carlsbad maintained by U.S. armed forces.

Issue: Nuclear Fuel Resources

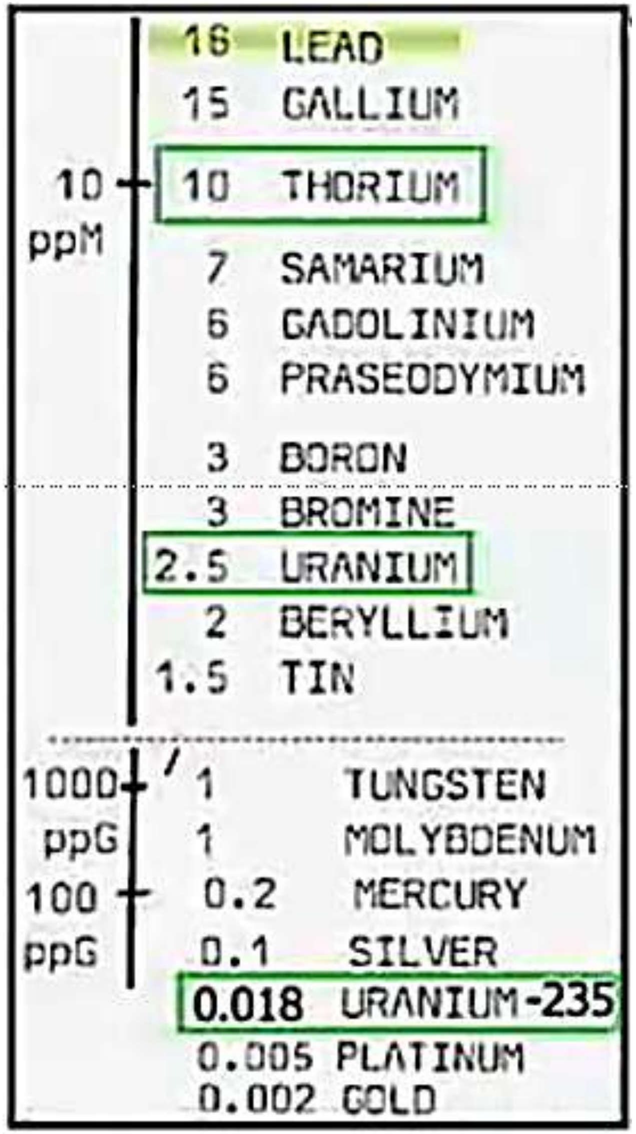
World (US)
443 (103) reactors
365 (100) GW

U use: 67 kt/a
World reserves: 5 Mt known (15 est.)
Once-through cycle:200 years

Reprocessing: $\sim 10^3$ years
US:174 t weapons grade U for fuel mix

Th use: little so far
World reserves >15 Mt $\sim 10^3$ a with reprocessing.

Gen IV breeder reactors, Thorium reactors, molten salt reactors

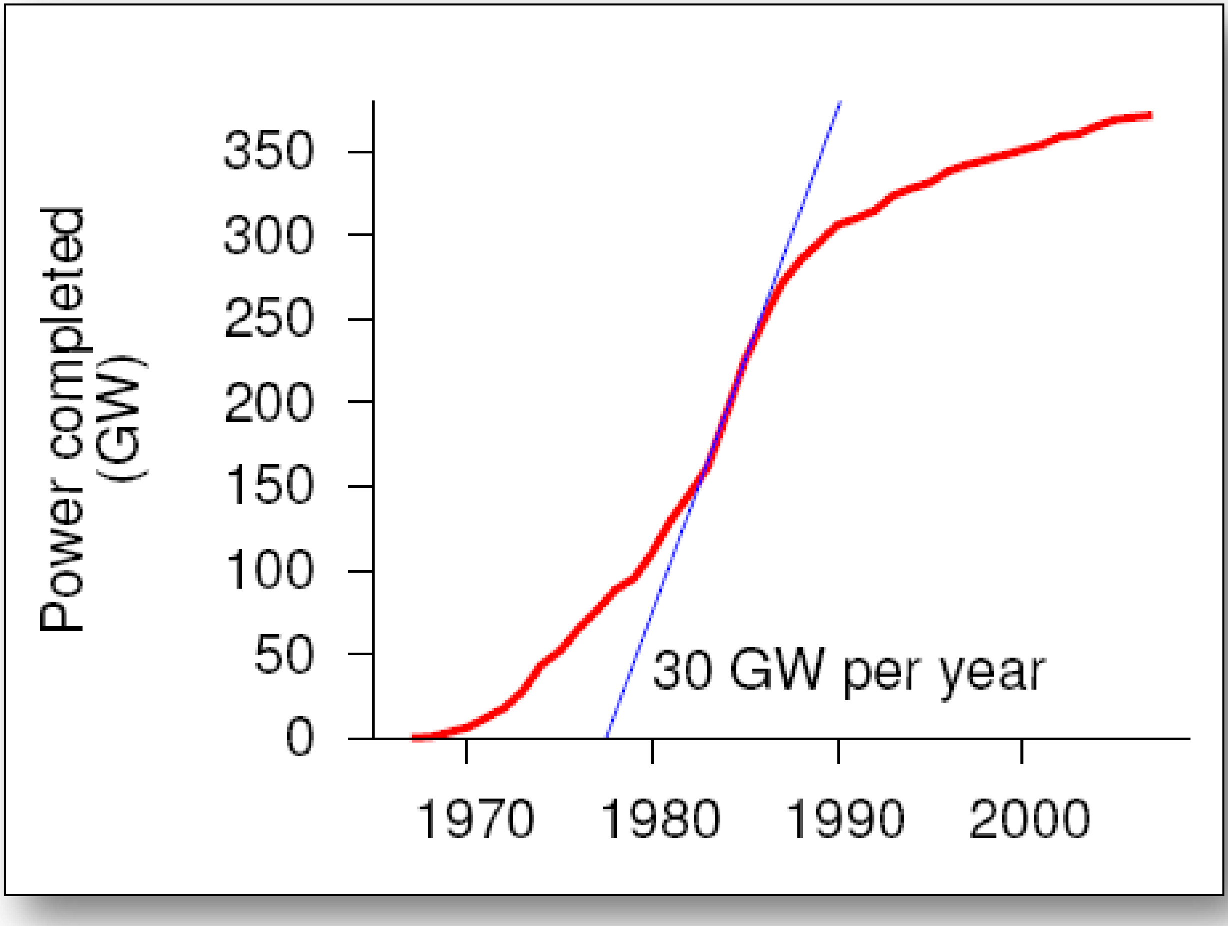


16	LEAD
15	GALLIUM
10	THORIUM
7	SAMARIUM
6	GADOLINIUM
6	PRASEODYMIUM
3	BORON
3	BROMINE
2.5	URANIUM
2	BERYLLIUM
1.5	TIN
1	TUNGSTEN
1	MOLYBDENUM
0.2	MERCURY
0.1	SILVER
0.018	URANIUM-235
0.005	PLATINUM
0.002	GOLD

Issue: Deployment Potential

Can we double nuclear capacity over 25 years?

100 GW/25y=4 GW/a = (2-3)NPPT/a → requires $(8-10)B/a = 12,000 construction workers continuously. + 2500 operators/a



Past performance: Construction dates of reactors still operating (GW_e vs. year).

1985: France built (completed) 2.5 GW/a

Construction time now 2 years/NPPT Japan, Korea, China

Operator manpower

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

Issue: Economics/Capital Requirements

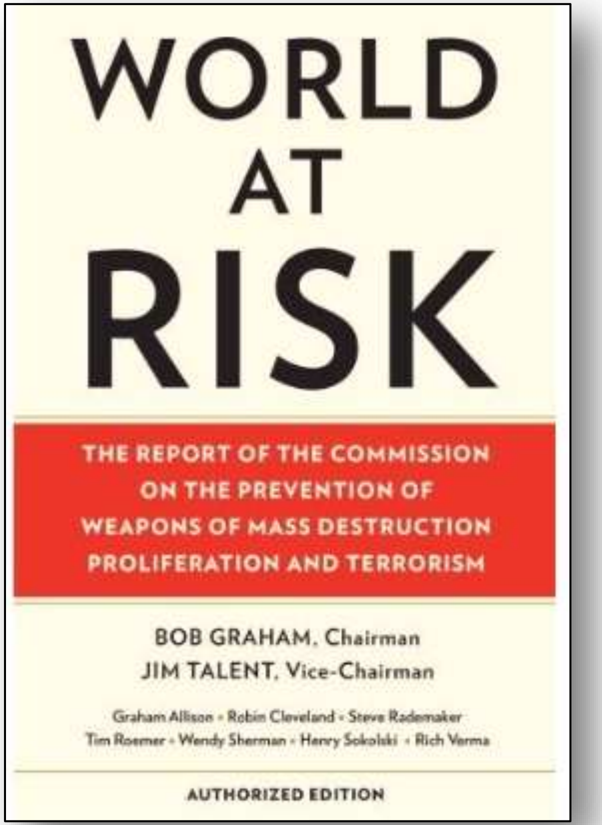
Can we afford to invest long-term $10 B/a into nuclear energy infrastructure? (Can we afford not to??)

→ Economic necessity, global growth high-tech industry

→ No strategic problem, except political and regulatory Economics of scale for standardized, modular NPPT

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

Strategic Issue: 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 nation states.
Illicit trade in weapons-grade ^{235}U or ^{239}Pu.

Weaponized ^{235}U or ^{239}Pu: > 95% enriched
Need ~ (10-20) kg for one bomb.

Reactor materials: low-enriched mix of isotopes

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

" 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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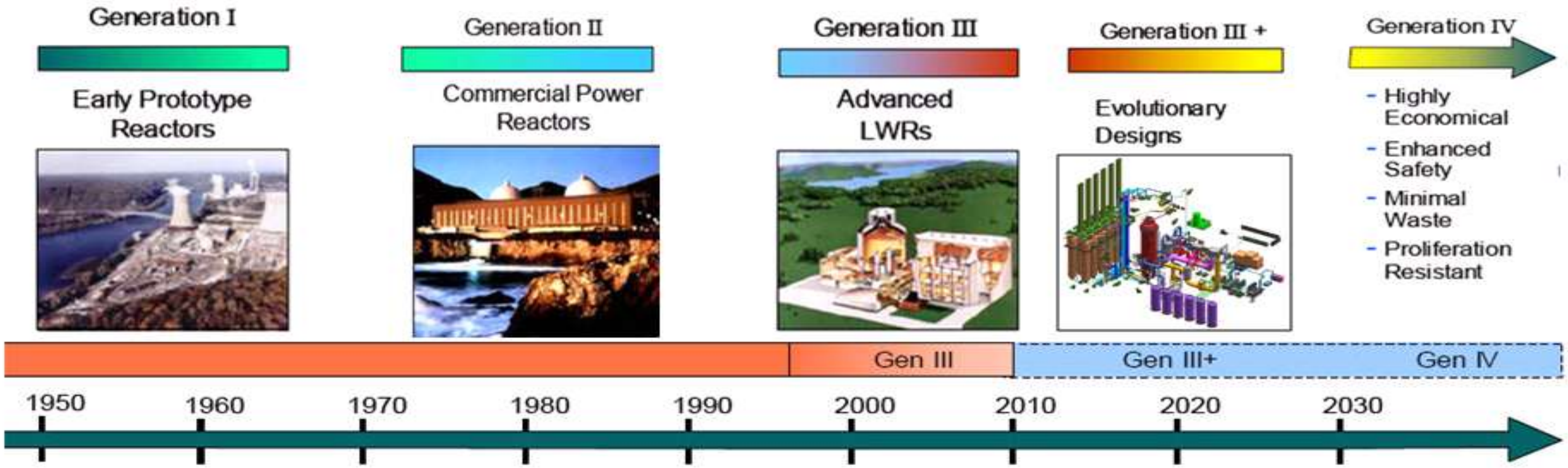
Timeline of Advanced Reactors/Fuel Cycles



GNEP framework (now includes U.S., U.K.) → 2030: Gen IV designs studied, modelled, tested:

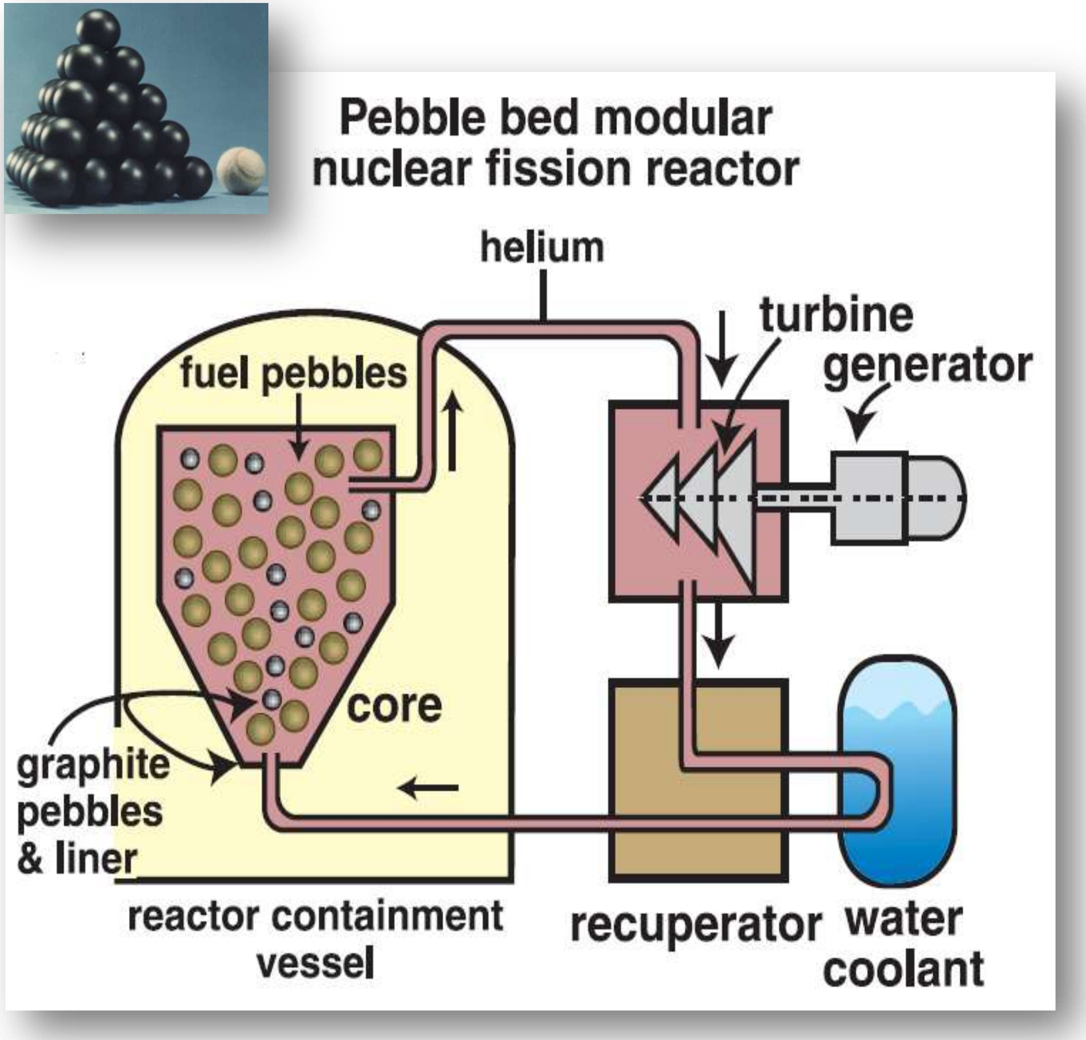
- Very high-temperature reactors (VHTR)
- Sodium-cooled fast reactors (SFR)
- Reactors cooled by supercritical water (SCWR)
- Lead-cooled fast reactors (LFR)
- Gas-cooled fast reactors (GFR)
- Molten-salt reactors (MSR, LIFTR)

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

Already testing Gen IV: France, Japan, S-Africa, China, India

Advanced Reactors: Pebble-Bed HTR

S-Africa, China: Modular (@250MW)



He (inert gas) cooled
T ~ 950^0C
C-moderator/reflector

Continuous throughput replacement of "pebble" fuel elements

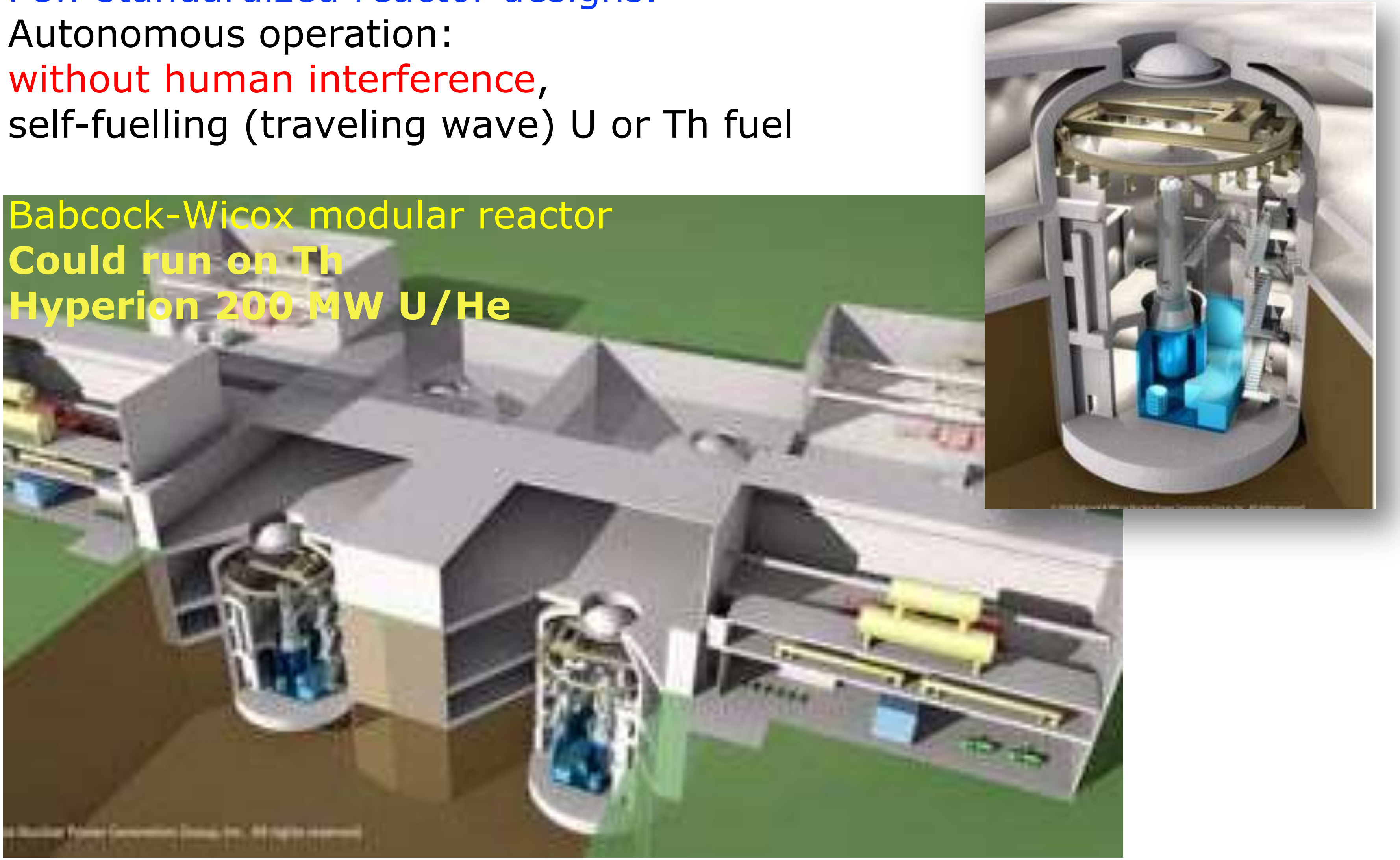
Strongly negative reactivity

Core has high surface/volume ratio, low power density.

Fail-safe operation.

Small Modular Reactors

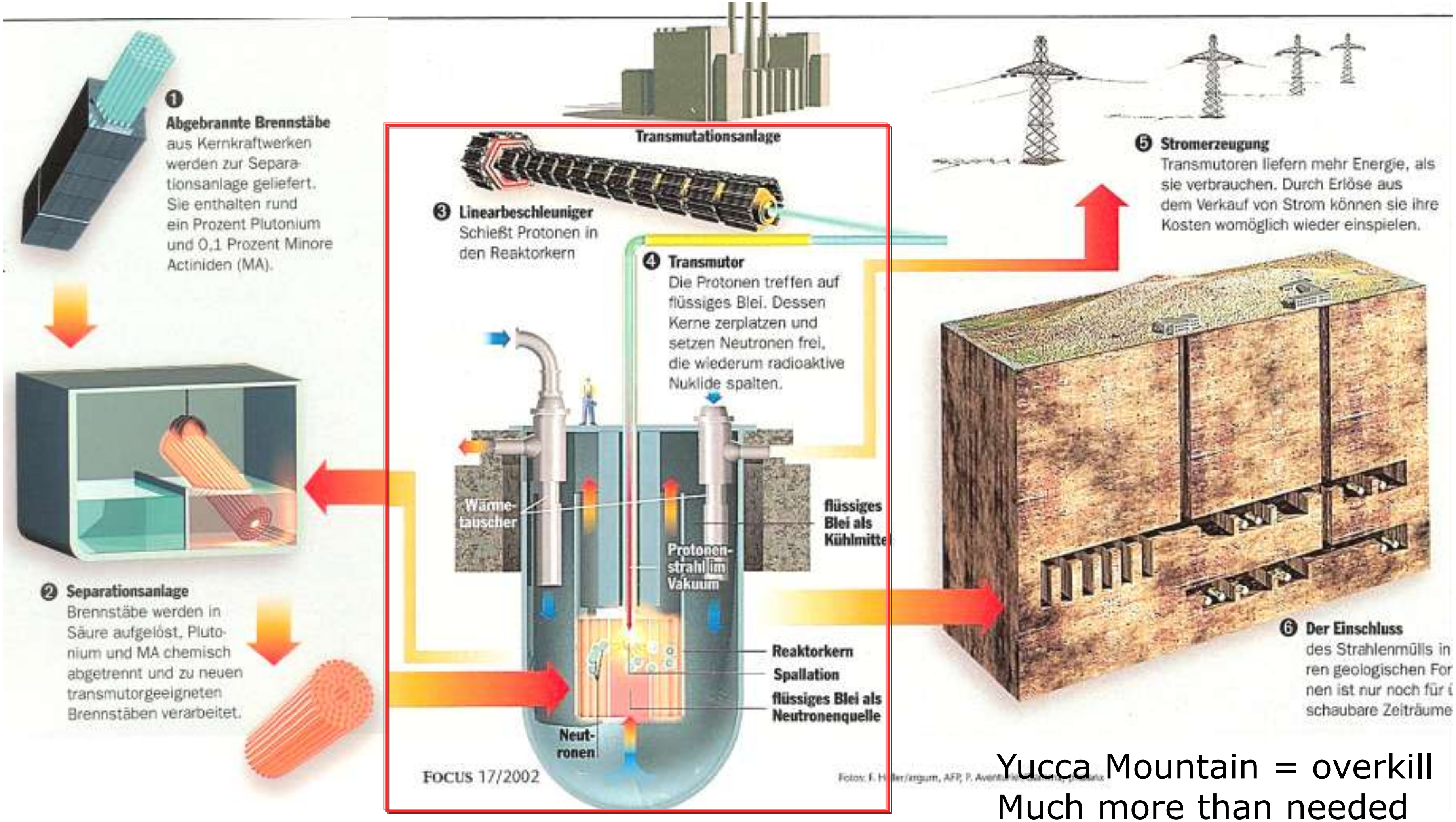
Prefabricated (GE A-1000 conventional PWR comes in 300 parts)
Few standardized reactor designs.
Autonomous operation:
without human interference,
self-fuelling (traveling wave) U or Th fuel



Babcock-Wicox modular reactor
Could run on Th
Hyperion 200 MW U/He

Transmutation/Breeding in ADS

Spallation: n multiplication → incineration of waste generates E
Advanced (ADS) reactor development under GNEP program



❶ **Abgebrannte Brennstäbe** aus Kernkraftwerken werden zur Separationsanlage geliefert. Sie enthalten rund ein Prozent Plutonium und 0,1 Prozent Minore Actiniden (MA).

❷ **Separationsanlage** Brennstäbe werden in Säure aufgelöst, Plutonium und MA chemisch abgetrennt und zu neuen transmutorgeeigneten Brennstäben verarbeitet.

❸ **Linearbeschleuniger** Schießt Protonen in den Reaktorkern

❹ **Transmutor** Die Protonen treffen auf flüssiges Blei. Dessen Kerne zerplatzen und setzen Neutronen frei, die wiederum radioaktive Nuklide spalten.

❺ **Stromerzeugung** Transmutoren liefern mehr Energie, als sie verbrauchen. Durch Erlöse aus dem Verkauf von Strom können sie ihre Kosten womöglich wieder einspielen.

❻ **Der Einschluss** des Strahlenmülls in ren geologischen For nen ist nur noch für schaubare Zeiträume

FOCUS 17/2002

Fotos: F. H[illegible]ler/argum, AFP, P. Aventu[illegible]

Yucca Mountain = overkill
Much more than needed
with reprocessing

Fuel Breeding ^{239}Pu/^{233}U Breeding

Technologically understood, several working research/test reactors

Fast (neutron spectrum) U reactor: *n*-capture without fission

Prevent additional n capture

$+n\uparrow$ $\qquad$ $+n\uparrow$

U – Pu Cycle

$$^{238}U + n \rightarrow {}^{239}_{92}U \xrightarrow[t_{1/2}=23\,\mathrm{min}]{\beta^-} {}^{239}_{93}Np \xrightarrow[2.4d]{\beta^-} {}^{239}_{94}Pu\left(2.4\cdot 10^4\,a\right)$$

Continued n capture/β decay $\quad {}^{239}_{94}Pu + n \rightarrow {}^{240}_{94}Pu \,|\, {}^{240}_{94}Pu + n \rightarrow {}^{241}_{94}Pu$

Isotope mix: Not useful for nuclear fuel/weapons → extensive isotope separation

Need many neutrons: source is unimportant !
(Use waste or heavy materials like Pb, Bi,….)

^{232}Th/^{233}U Fuel Breeding

Technologically understood, several working research/test reactors

Fast (neutron spectrum) U reactor: *n*-capture without fission

Isotope mix: Not useful for nuclear fuel/weapons → extensive isotope separation

Prevent additional n capture

$$^{234}_{91}Pa \xrightarrow[6h]{\beta^-} {}^{234}_{92}U\left(2.5\cdot 10^5 a\right)$$

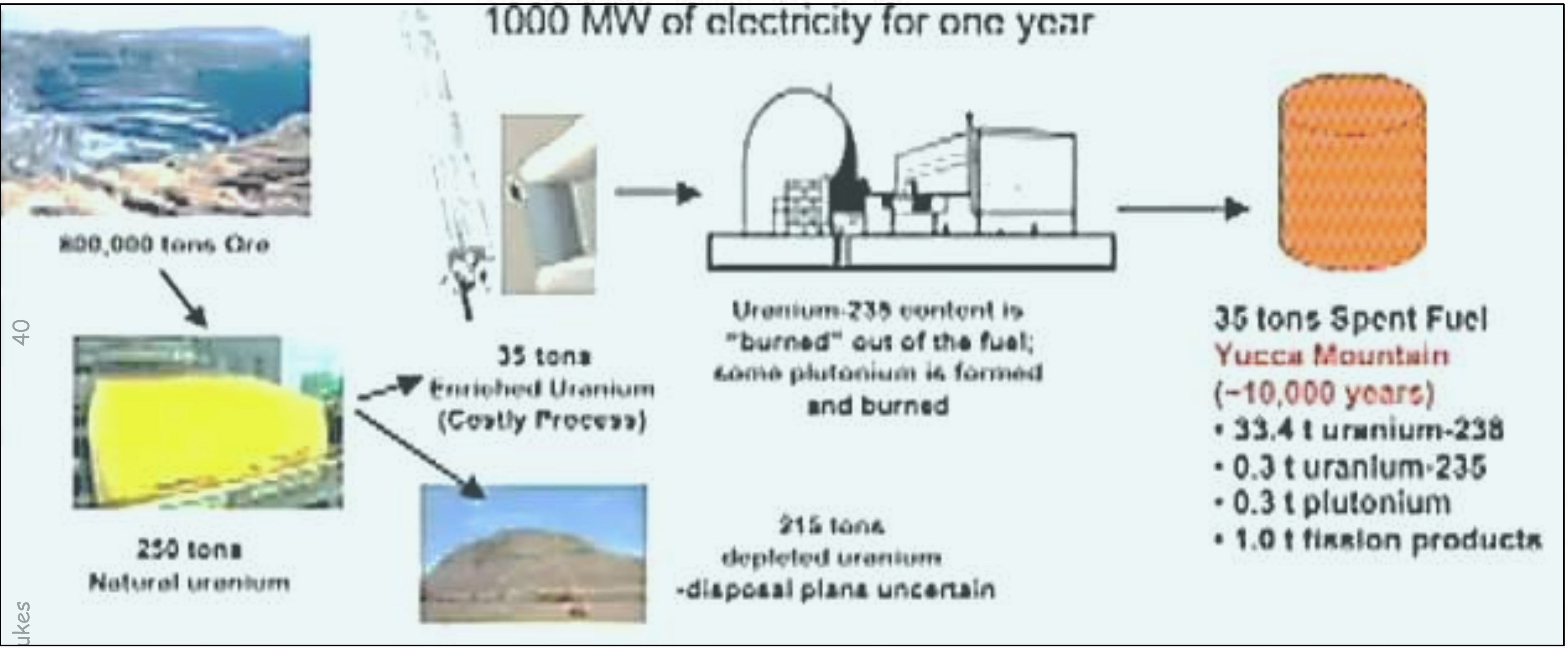
$+n\uparrow$ $\qquad$ $+n\uparrow$

Th – U Cycle

$$^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th \xrightarrow[t_{1/2}=22\,\mathrm{min}]{\beta^-} {}^{233}_{91}Pa \xrightarrow[27d]{\beta^-} {}^{233}_{92}U\left(1.6\cdot 10^5 a\right)$$

India builds Th reactor fleet → large Th resources, small waste problem. (Mumbay test reactor). Also France, Russia

Uranium Fuel Cycle vs. Thorium



1000 MW of electricity for one year

800,000 tons Ore

250 tons
Natural uranium

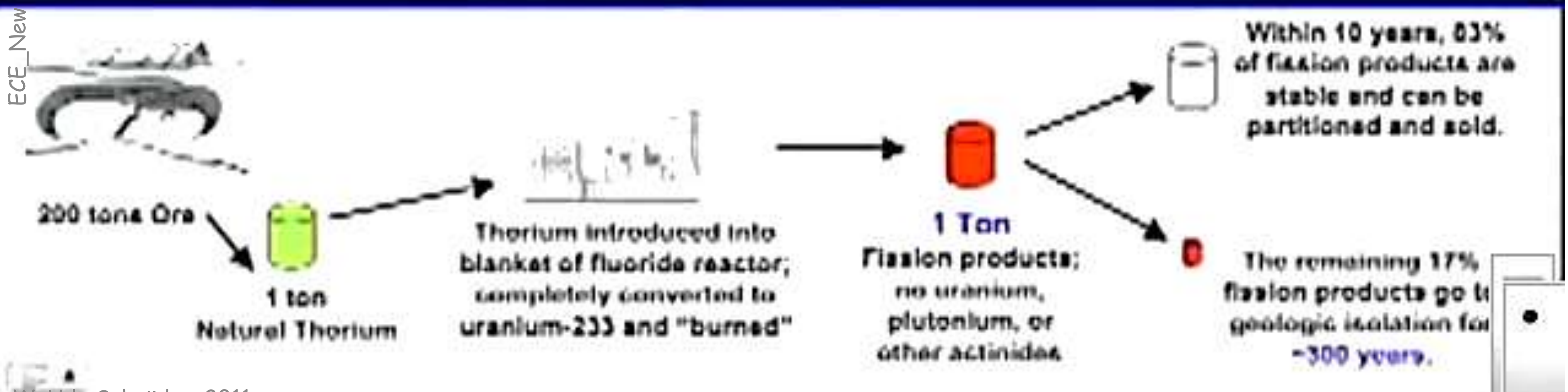
35 tons
Enriched Uranium
(Costly Process)

215 tons
depleted uranium
-disposal plans uncertain

Uranium-235 content is "burned" out of the fuel; some plutonium is formed and burned

35 tons Spent Fuel
Yucca Mountain
(~10,000 years)

- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium
- 1.0 t fission products



200 tons Ore

1 ton
Natural Thorium

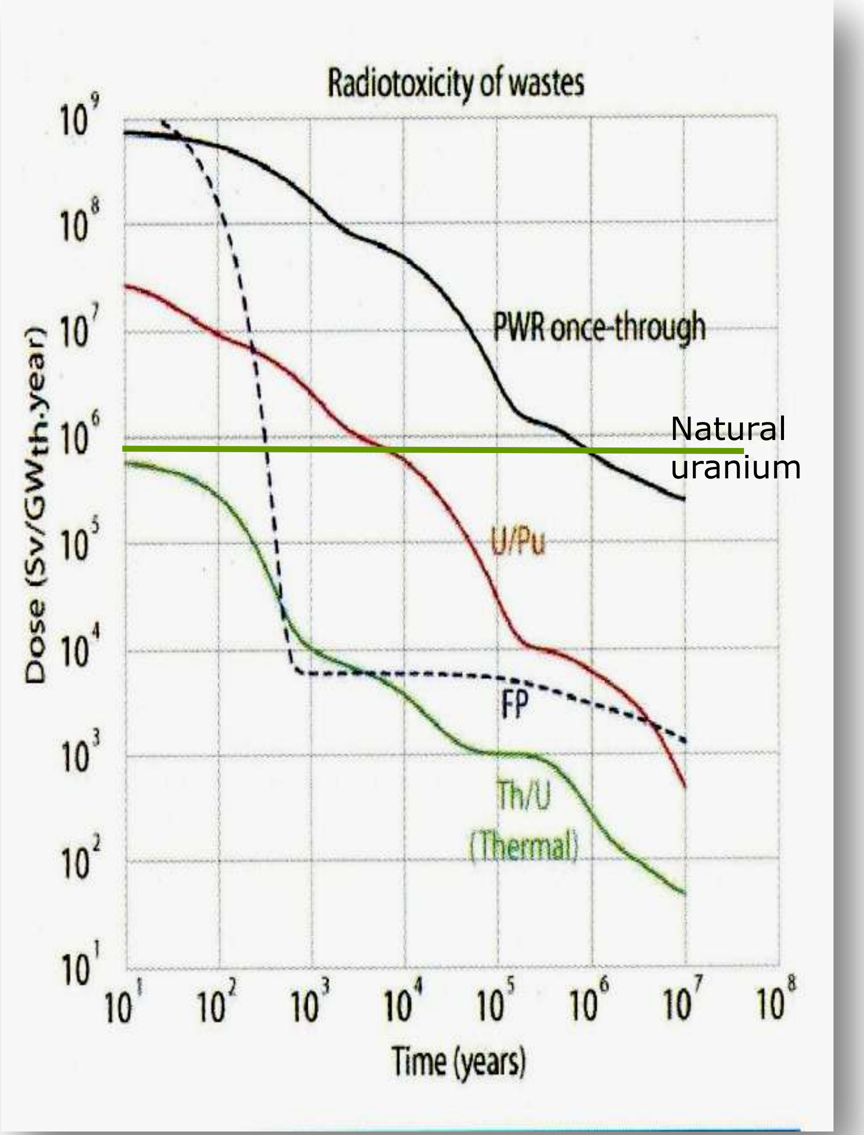
Thorium introduced into blanket of fluoride reactor; completely converted to uranium-233 and "burned"

1 Ton
Fission products;
no uranium,
plutonium, or
other actinides

Within 10 years, 83% of fission products are stable and can be partitioned and sold.

The remaining 17% fission products go t
geologic isolation fo
~300 years.

Radiotoxicity of Spent Nuclear Fuel



Radio toxicity vs. time after shutdown, of spent fuel from

•pressurized water uranium reactor (PWR),

- U/Pu breeder, and
- Th/U fuel cycle.

FP indicates the faster decay of fission products.

Multiple reprocessing, less residual waste.

Transmute/incinerate transactinides and FF solves waste issue

Store small amounts of HL waste for ~100 years small geological depository

(David, Nifenecker, 2007)

Conclusion: Nuclear Power in a Sustainable Future

Promising and potent: Advanced nuclear power, redirection of electricity generation mainly to nuclear. Develop synfuels from coal/nat. gas.
Need massive renewal of energy infrastructure

Develop and Employ Advanced Nuclear Power in the US:

- 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 chemistry of molten salt mixtures, molten salt test 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 !**

End