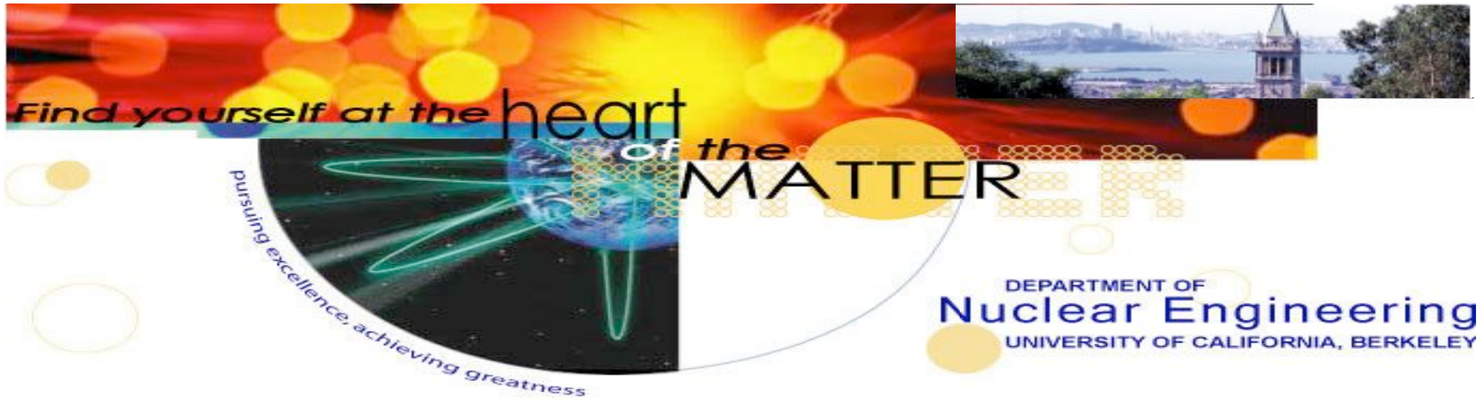

From Atoms to Electricity: An Introduction to Nuclear Power, Its Promise and Challenge

Brian D. Wirth*

Lawrence Berkeley National Laboratory

•bdwirth@nuc.berkeley.edu
•bdwirth@lbl.gov

*Nano*High*

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UC Berkeley NUCLEAR ENGINEERING

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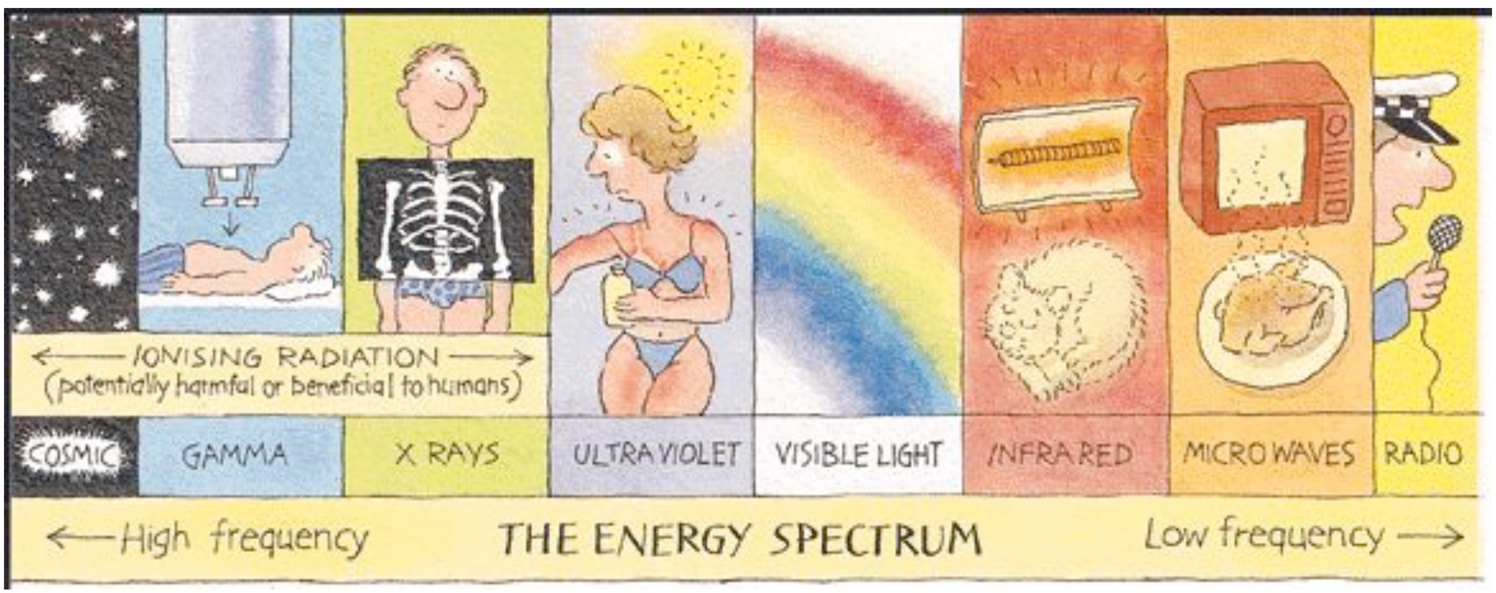
Presentation overview

- **A brief introduction to the radioactivity, the atom, and nuclear fission**
- **Discussion of increasing energy demands with minimal environmental impact (greenhouse gas emissions)**
  - **How will the environment, resources and security issues affect the future evolution of energy technology?**
- **Current nuclear power plants, and performance**
  - **PWR, BWR**
  - **Disposition of spent nuclear fuel, Yucca Mountain Repository**
- **Perspectives for the future**
  - **License applications for new nuclear power plants**
  - **New U.S. Department of Energy program, the Global Nuclear Energy Partnership, seeks to better utilize spent nuclear fuel**
- **Summary**

What is radiation?

- Radiation is energy in the form of particles and electromagnetic rays (waves) traveling through space. Sunshine is one of the most familiar forms of radiation, delivering light, heat and suntans.
- There would be no life on earth without lots of sunlight, but we also know that too much sunlight is not a good thing (sunburns and cancer).
- Sunshine consists of radiation in a range of wavelengths from long wavelength infrared to short wavelength ultraviolet (creates the hazard).
- Beyond ultraviolet are higher energy (shorter wavelength) kinds of radiation, known as ionizing radiation.



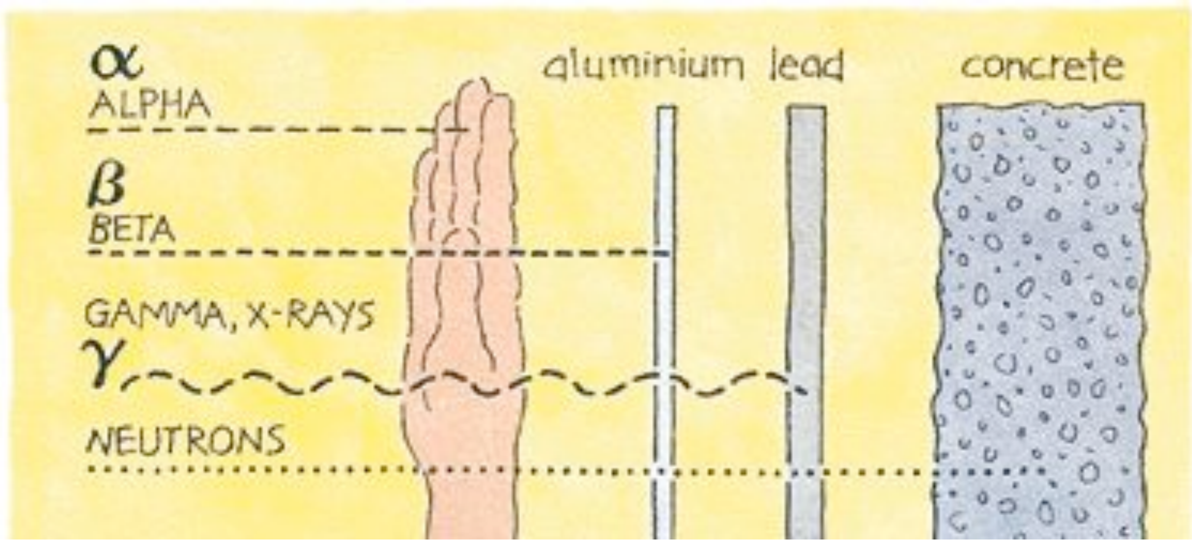
* Source: Uranium Information Center, http://www.uic.com.au/index.htm

Types of radiation

- **Radiation can be electromagnetic rays:**
  - X-rays, γ-rays, cosmic rays, visible light, radio and microwaves

  or particles,
  - α, β, protons, or heavy-ions (charged), and neutrons (neutral)

- **The different types of radiation interact differently with materials (including the body) and have different ranges**

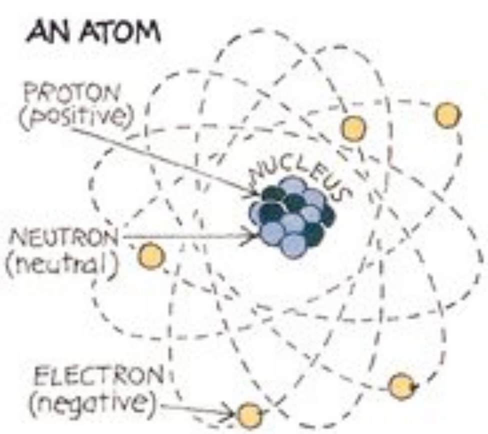


It is important to understand that ionizing radiation (α, β, γ and x-rays) do not cause the body to become radioactive. But, most materials (including tissues in the body) contain natural radioactivity.

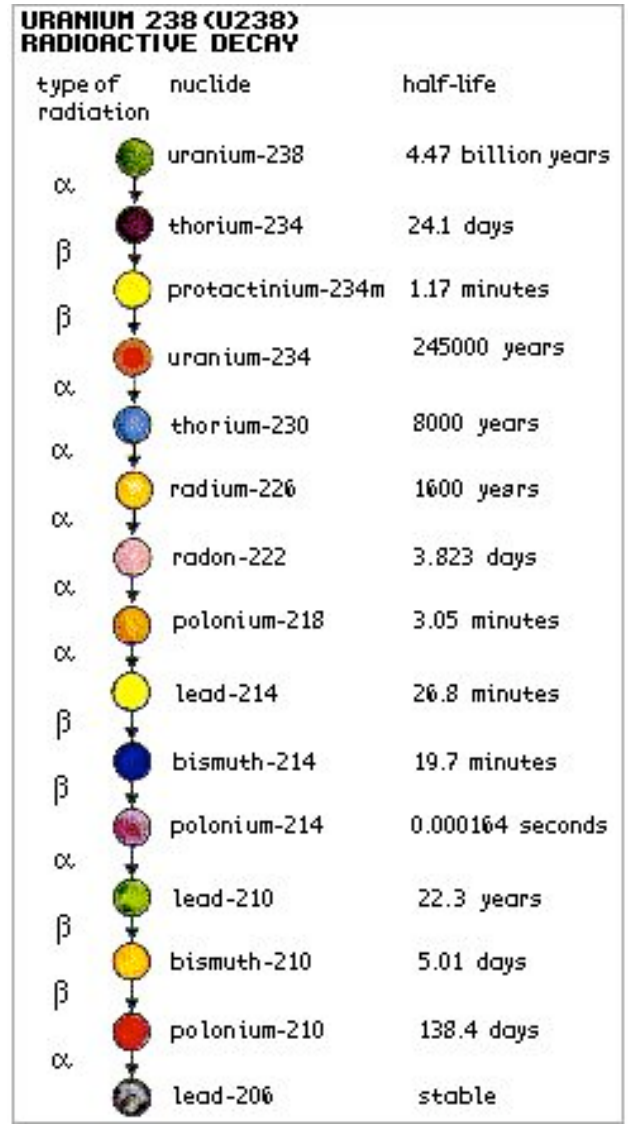
*** Sources: Uranium Information Center, http://www.uic.com.au/index.htm and http://wwww.aboutnuclear.org**

Sources of radiation

- Radiation is produced from radioactive decay, changes in energy of an atomic electron or nucleus, atomic motion, or the interaction between radiation (particles or electromagnetic rays) and atoms.
- Sources of radiation include the sun, radioactive materials and thermal radiation
- Radioactivity is the spontaneous emission of radiation emitted by unstable atoms as they transition to a more stable state

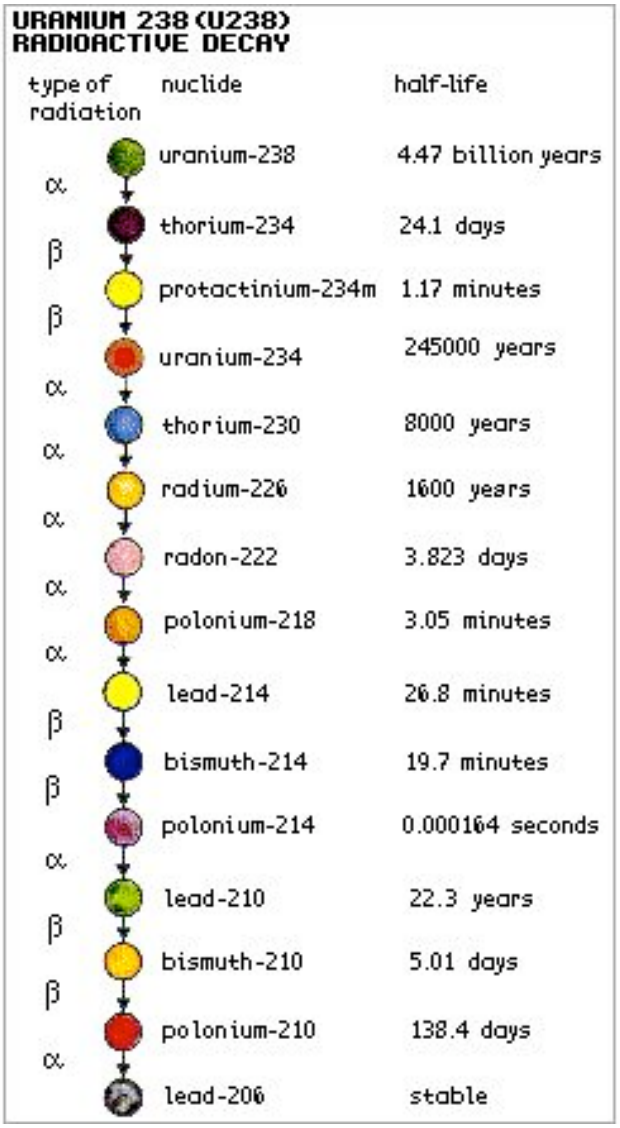


Atoms (elements) characterized by A (atomic number) and Z (# of protons & electrons), the number of neutrons is A-Z



* Sources: Uranium Information Center, http://www.uic.com.au/index.htm and http://wwww.aboutnuclear.org

Nuclear chemistry



Neutron absorption:

$$U_{92}^{238} + n_0^1 \Rightarrow U_{92}^{239}$$

Beta decay:

$$U_{92}^{239} \underset{\nu}{\overset{\beta}{\Rightarrow}} Np_{93}^{239} \underset{\nu}{\overset{\beta}{\Rightarrow}} Pu_{94}^{239}$$

Alpha decay:

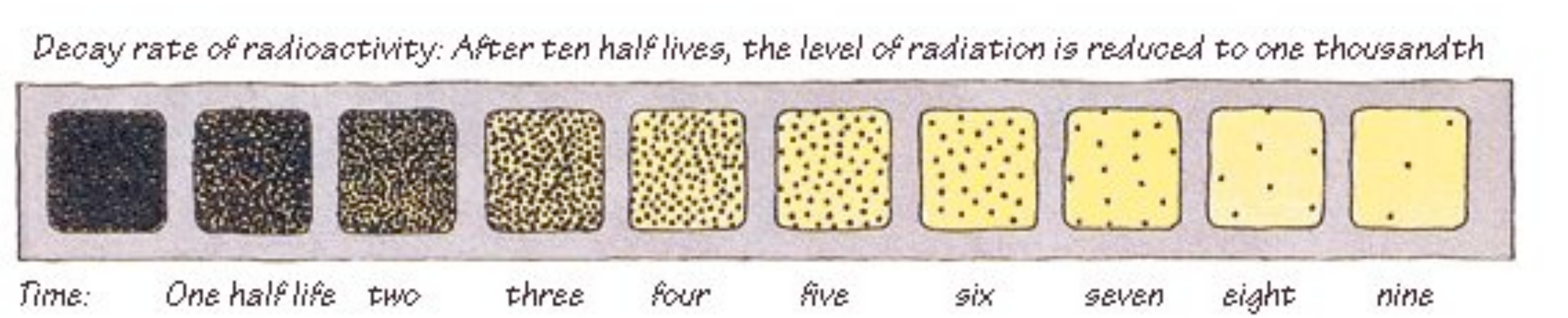
$$U_{92}^{238} \overset{\alpha}{\Rightarrow} Th_{90}^{234}$$

and http://wwww.aboutnuclear.org

Radioactive decay

- Radioactive decay occurs stochastically with a characteristic time, known as a half-life, $\tau_{1/2}$. While we can not predict *when* a given radioactive atom will decay, we can predict the amount of atoms undergo radioactive decay using the half-life.

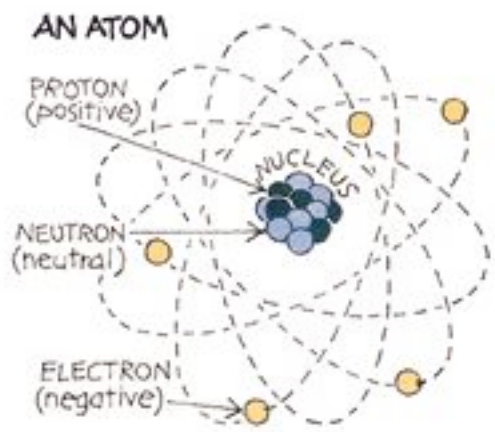
$$N = N_o e^{-\frac{\ln 2}{\tau_{1/2}} t}$$



- The amount of radioactivity is specified in units of Becquerel (Bq) which equals 1 decay per second or Curies (Ci), 1 Ci = 3.7×10^{10} Bq

* Sources: Uranium Information Center, http://www.uic.com.au/index.htm and http://wwww.aboutnuclear.org

The physics of nuclear fission



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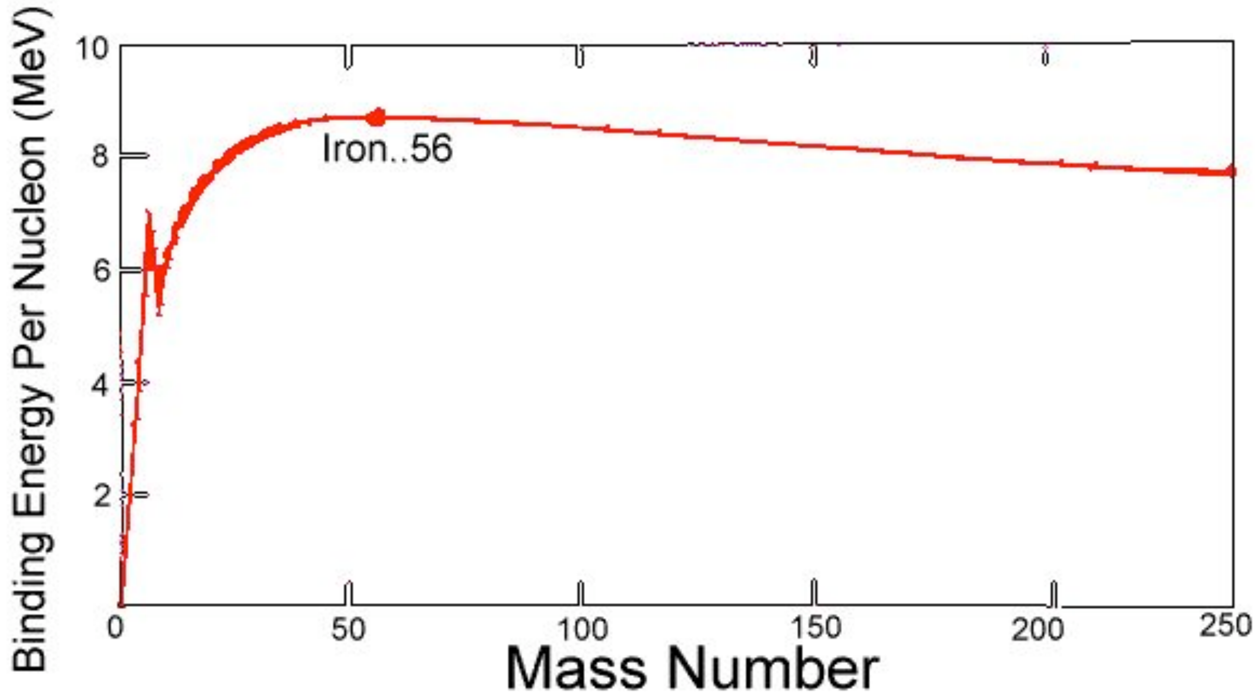


The mass of an atom is smaller than the sum of its parts
The difference is called the "mass defect"
The "binding energy" is the energy required to hold the atom together

$$E = \Delta mc^2$$

If we split or combine atoms, we can release some of the binding energy

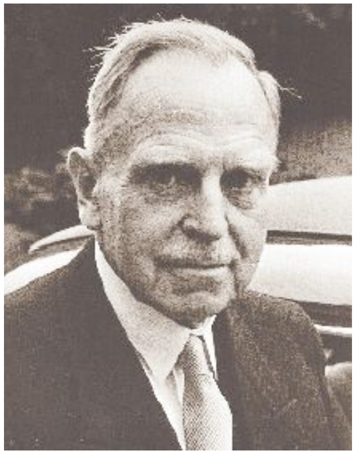
The discovery of nuclear fission

$$^{235}_{92}U + n \rightarrow ^{137}_{55}Cs + ^{97}_{37}Rb + 2n$$

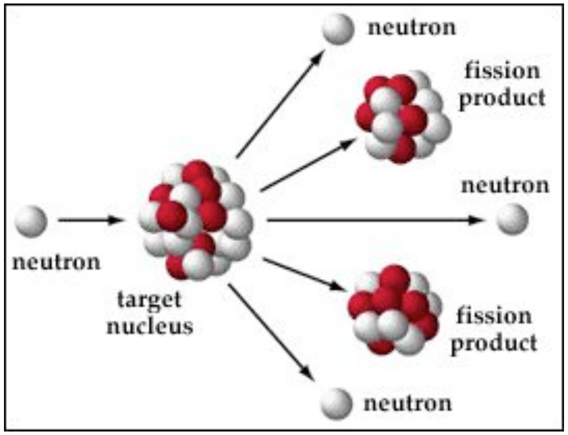
Energy balance:

$$Q = 137(8.5MeV) + 97(8.9MeV) - 235(7.8MeV)$$
$$\cong 200MeV$$

Lise Meitner

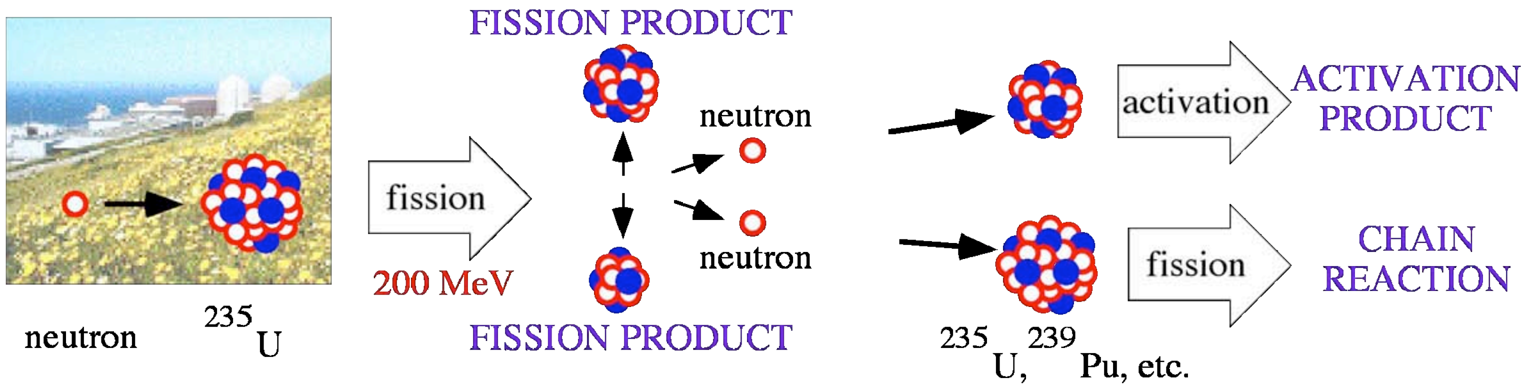


Otto Hahn



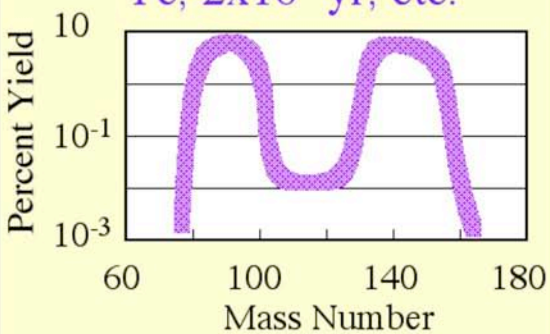
December, 1938 - Meitner and Hahn hypothesize that the strange chemistry of the elements that are formed by neutron irradiation of uranium can be explained by assuming fission of uranium has occurred.

Energy from Nuclear Fission



Fission Fuel Energy Density: 8.2×10^{13} J/kg
Fuel Consumed by 1000-MW$_e$ Plant: 3.2 kg/day
Spent nuclear fuel & waste:

Fission Prod. (3.2 kg/day)
^{90}Sr, 30 yr; ^{137}Cs, 30 yr; ^{99}Tc, 2×10^5 yr; etc.

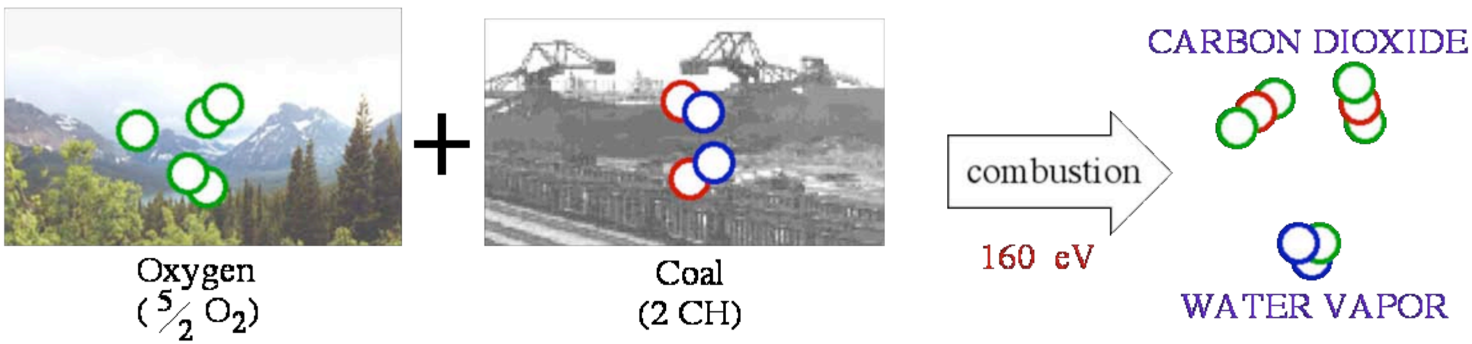


Activation Products
Fuel → Transuranics, longer half lives (^{239}Pu, 24,000 yr; ^{237}Np, 2×10^6 yr; etc.)
Structures → Moderate half lives, low-level waste (^{60}Co, 5 yr)
Coolants → Low (water) to moderate (metals) half lives
Transmutation → Convert from long to short half life

Mining
Radon from mill tails if not capped

Construction materials

Energy from Fossil Fuels: Coal



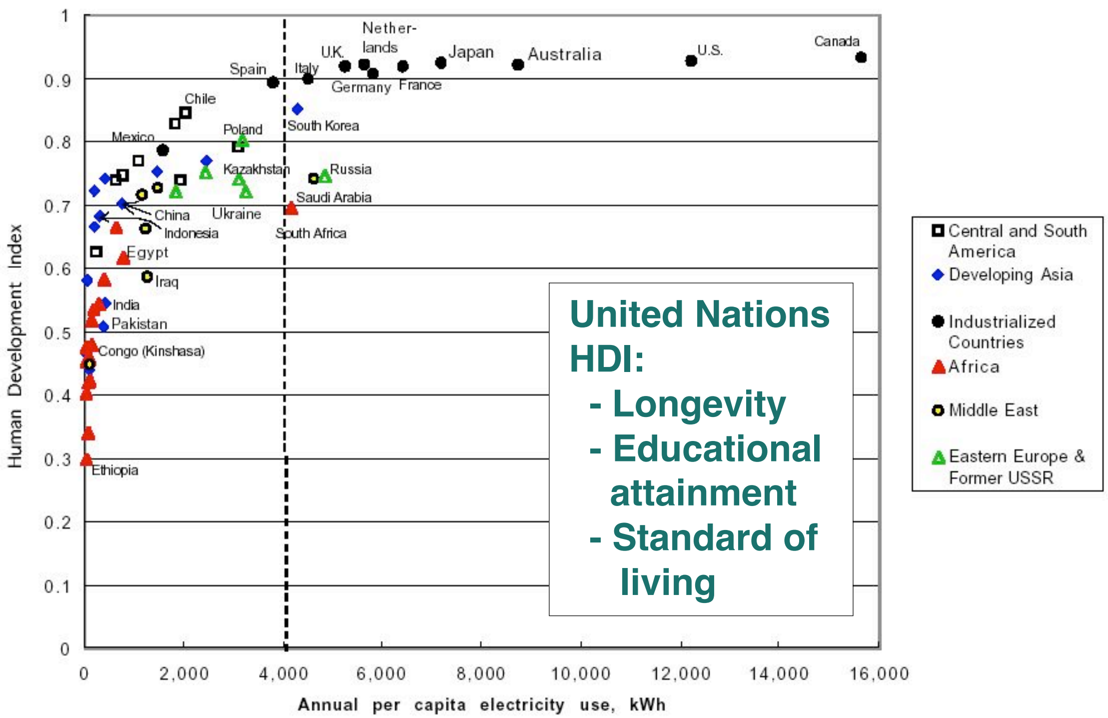
Fossil Fuel (Coal) Energy Density: 2.9×10^7 J/kg
Fuel Consumed by 1000-MW$_e$ Plant: 7,300,000 kg/day
Waste:

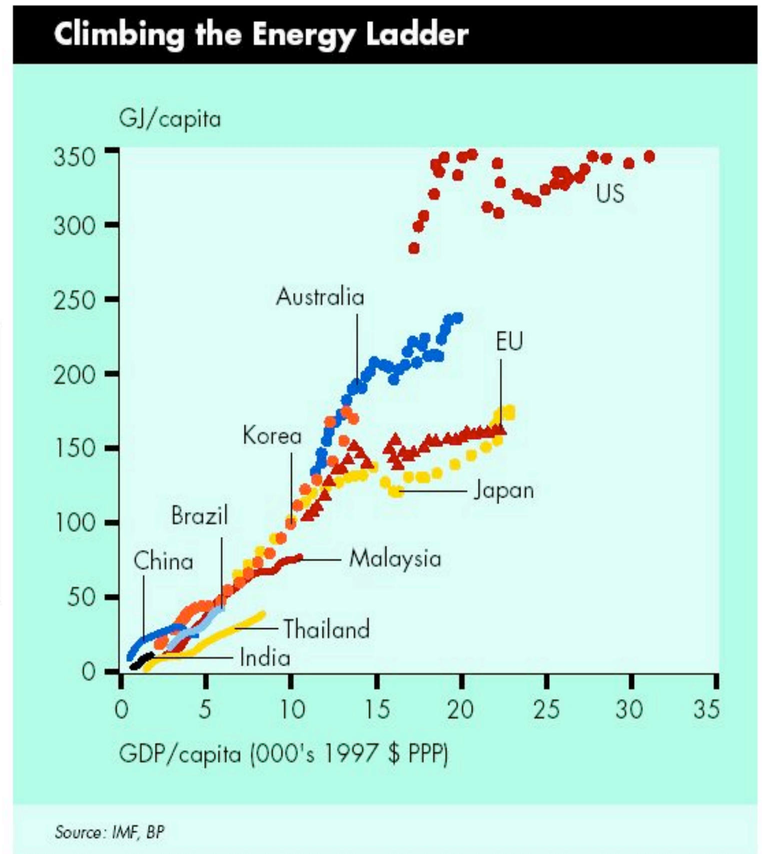
Coal Combustion Products	Mining
NO_x → High temperature combustion	Leachates/ dust from mining
SO_x → Sulfur in coal (0.4% - 5%)	
Ash → (5% - 25% of coal mass)	Construction materials
CO_2 → Global warming	

1999 Global Coal Consumption: 3 billion tons

Importance of energy

- **World electricity consumption is projected to double by 2020. Yet, considering the link between electrical usage and human well-being, the consumption increase could easily be much larger**





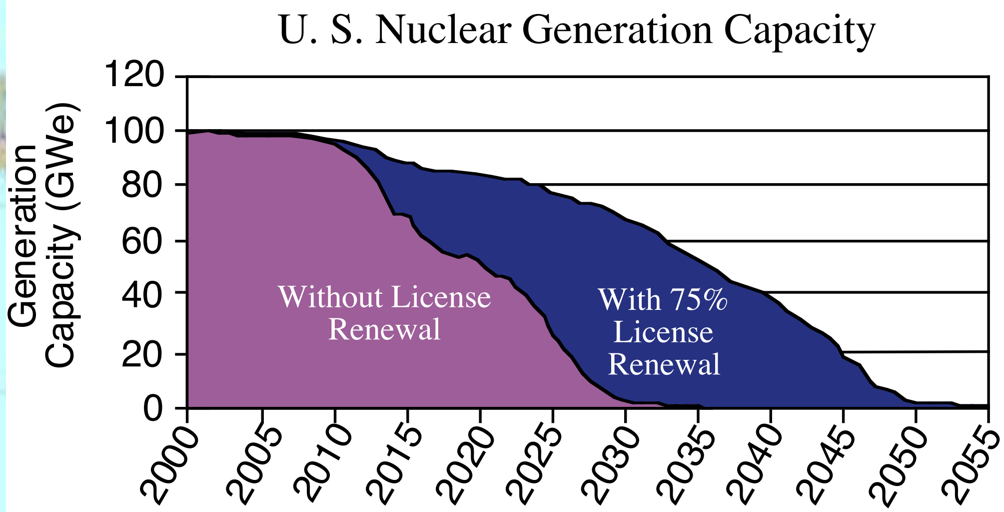
Ref, A.D. Pasternak,
UCRL-ID-140773, 2000.

Energy production closely related to quality of life

Current nuclear production & future needs

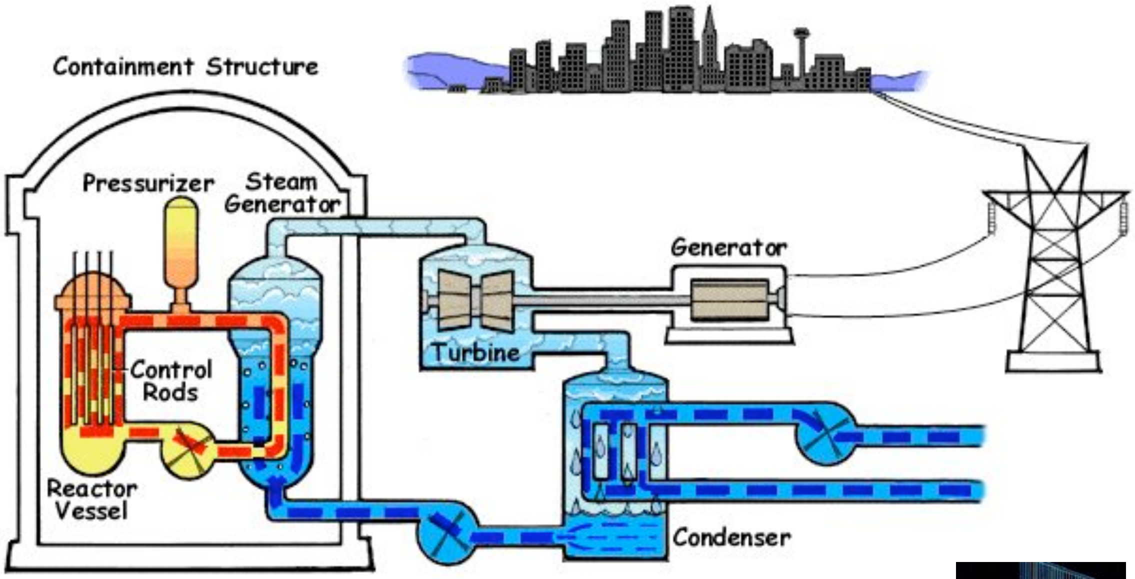
- **104 commercial nuclear power plants produce ~20% of U.S. electricity without contributing to air pollution or greenhouse gases.**
- **U.S. electricity consumption is projected to increase by >30% by 2020.**
- **World electricity consumption is projected to double by 2020.**

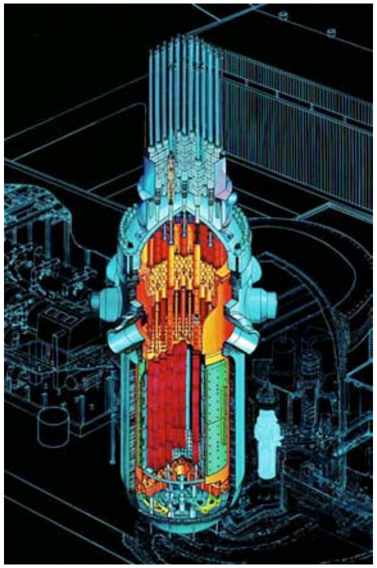
Source,
http://www.insc.anl.gov/pwrmaps/map/world_map.php

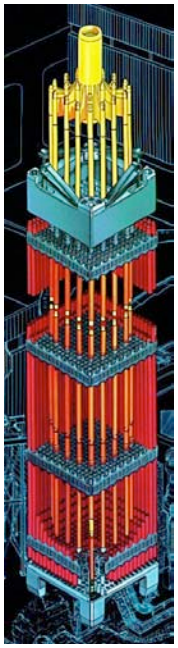


source, U.S. DOE
NEPO website

*Pressurized water reactor (PWR)**



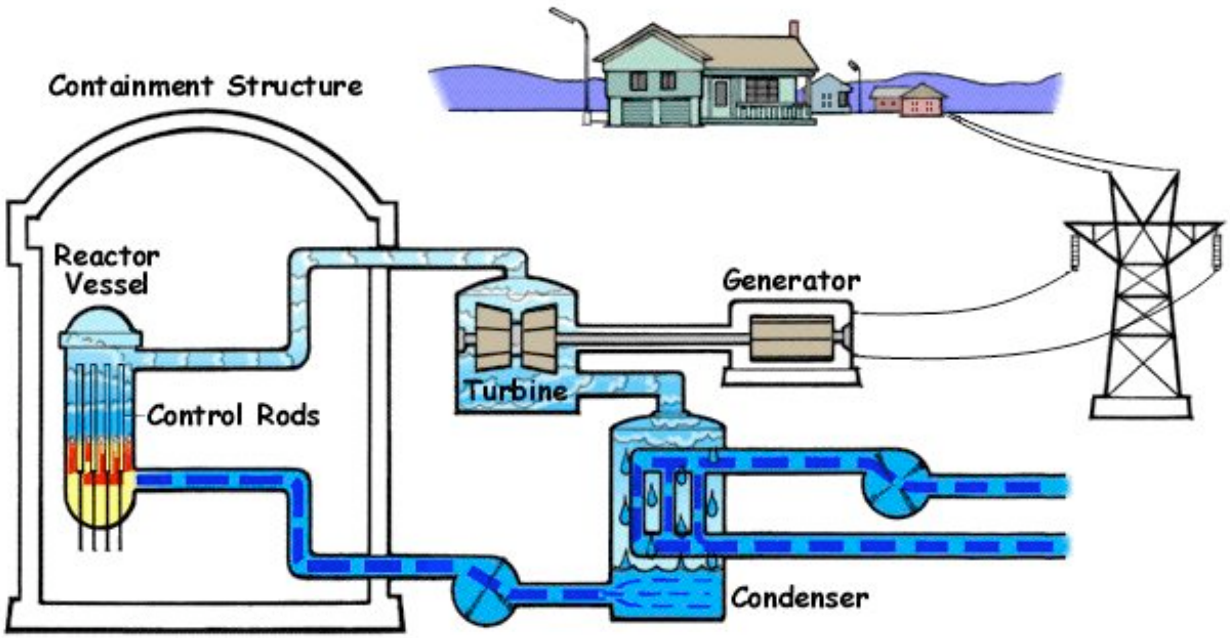




- Core contained in *RPV* at a pressure of about 15 MPa. RPV is ~20 m high, 4 m in diameter and ~220 mm thick.
- Core consists of about *190 fuel assemblies*, each about 4 m tall and containing about 250 - 300 *fuel rods.*
- The *primary* circuit circulates water from the core to the *steam generator*, used to boil the water in the *secondary* circuit at 7 MPa and 280°C.
- The chemical composition of the water is controlled by addition of selected chemicals (*water chemistry)* - used for reactivity control, generally add boron (~1000 ppm at start of core life), also control chemistry to reduce corrosion

* http://www.nucleartourist.com/type/pwr.htm

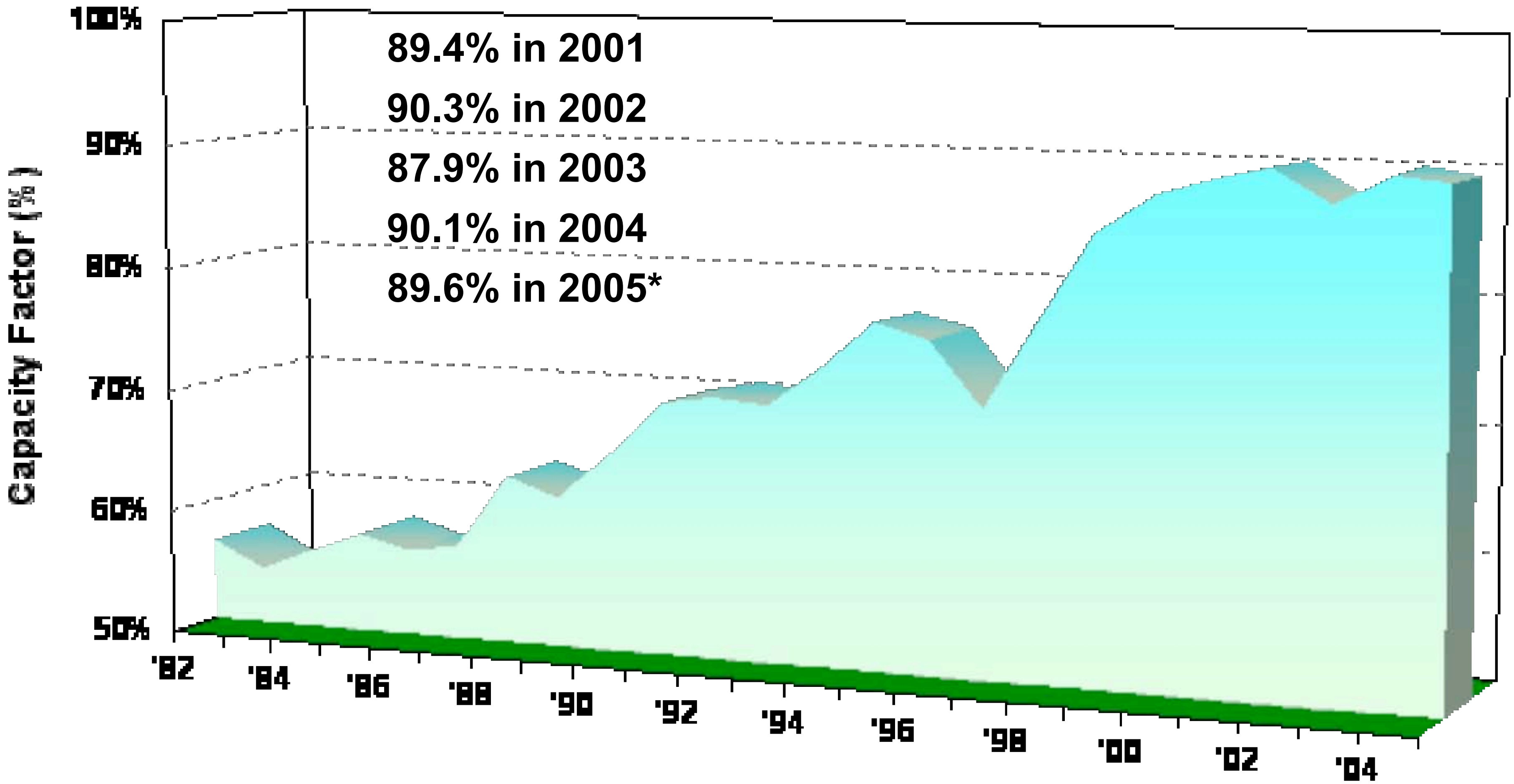
Boiling water reactor (BWR)*



- BWR RPV is ~22 m high, 6 m in diameter and ~150 mm thick. The core consists of about *700 fuel assemblies*, each containing about 63 *fuel rods* encased in a square channel. The core is ~5 m diameter and 4 m high.
- Water is boiled in the core at a pressure of about 7 MPa and about 280°C
- Low-pressure reject steam is converted to liquid in the condenser
- Water is returned to the core via a feedwater pump with intermediate purification
- The chemical composition of the water is controlled by addition of selected chemicals - no reactivity control, generally H_2 added to reduce corrosion due to radiolysis

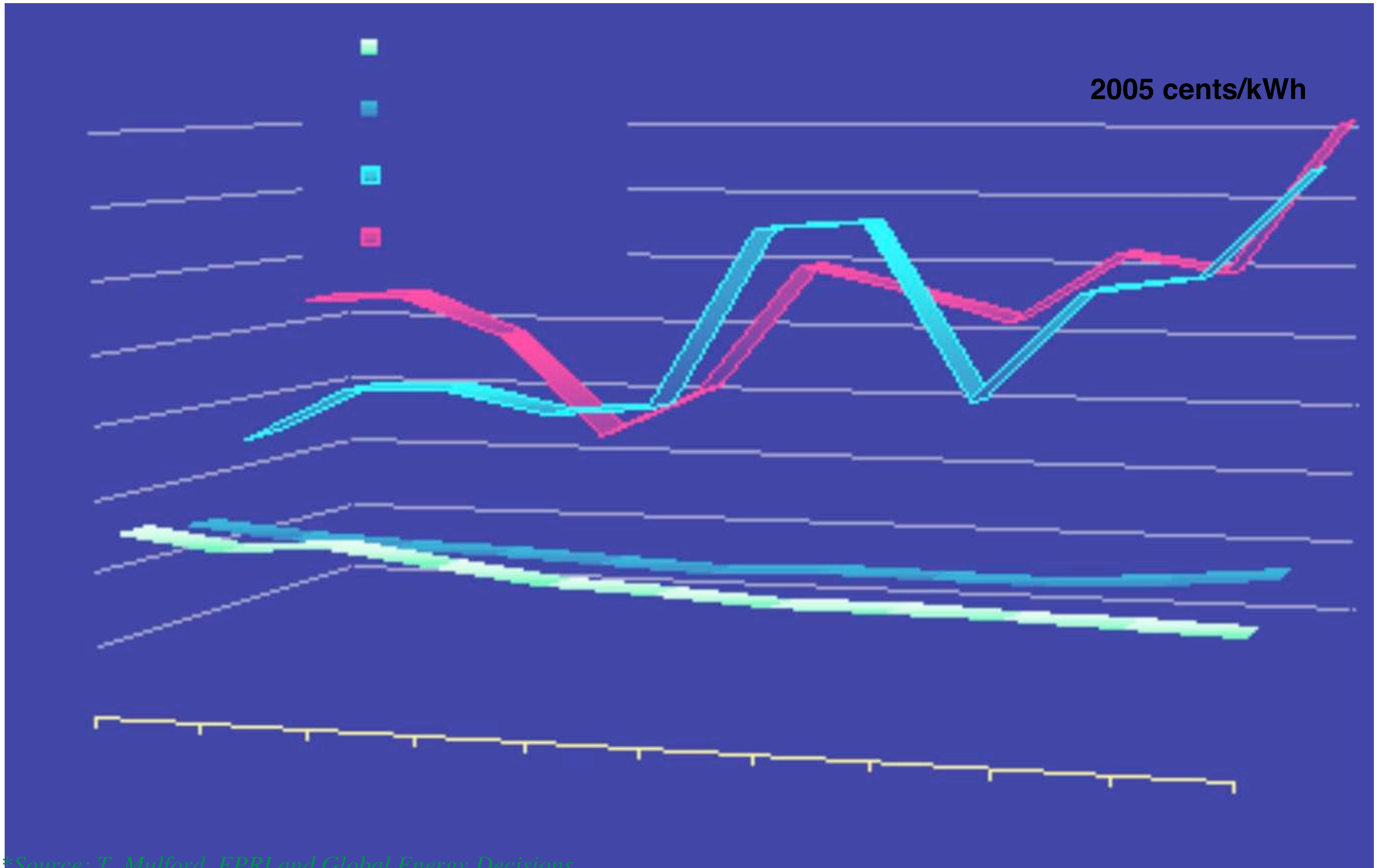
* http://www.nucleartourist.com/type/bwr.htm

Nuclear industry performance*



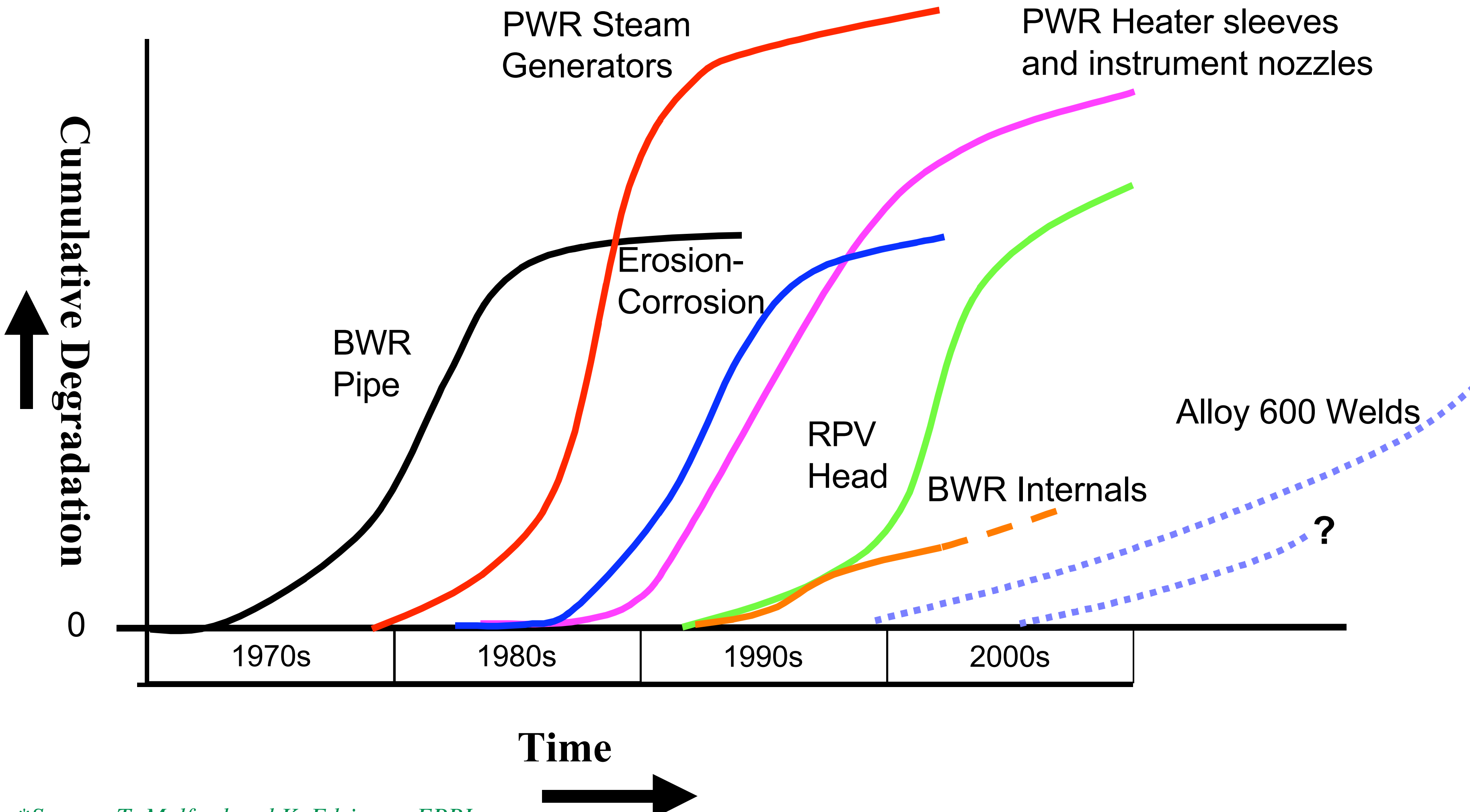
*Source: T. Mulford, EPRI and Energy Information Administration

US electricity production costs*



*Source: T. Mulford, EPRI and Global Energy Decisions

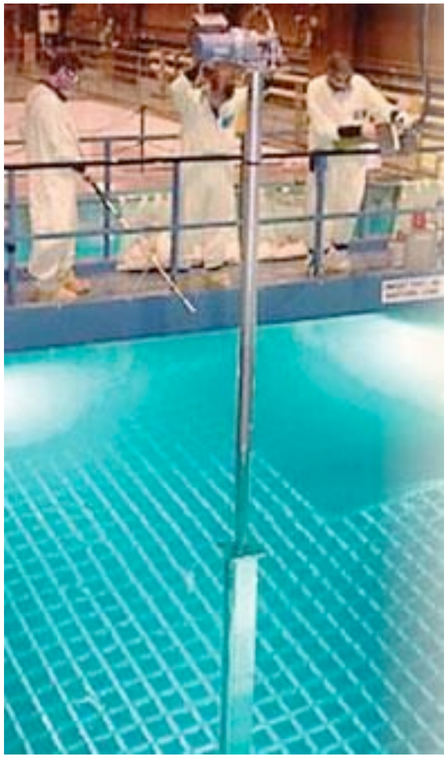
*Materials challenges have been, are and will remain challenging now and into the future of nuclear power**

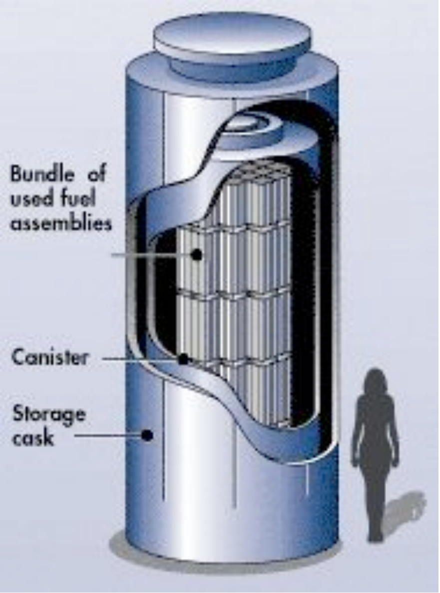


**Source: T. Mulford and K. Edsinger, EPRI*

Spent nuclear fuel today

- **Spent fuel stored in storage pool, then moved to dry cask storage awaiting transfer to the Yucca Mountain Repository**

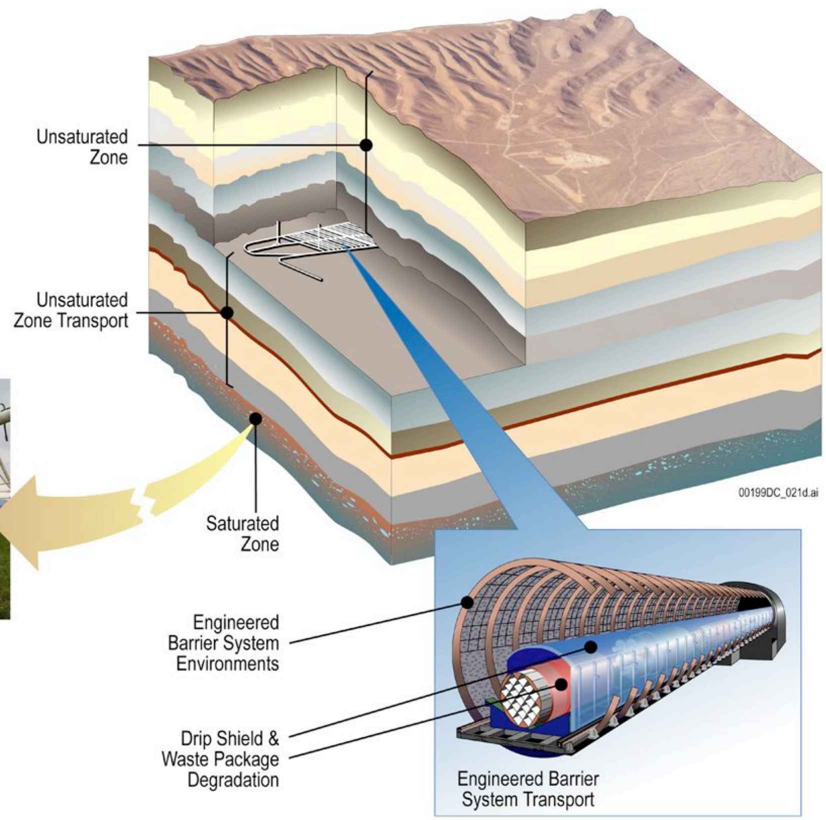




Overview of Yucca Mountain Repository

- **Unsaturated Zone (UZ) ~600 meters thick**
  - **Repository in this zone (unique to Yucca Mountain)**
- **Engineered Barrier System**
  - **Tunnel, “drip shield”, container, cladding, waste itself**
- **Saturated Zone (SZ)**
  - **Groundwater transport 18+ km downstream**
- **Biosphere**
  - **Where the contaminants come into contact with humans and other biota**

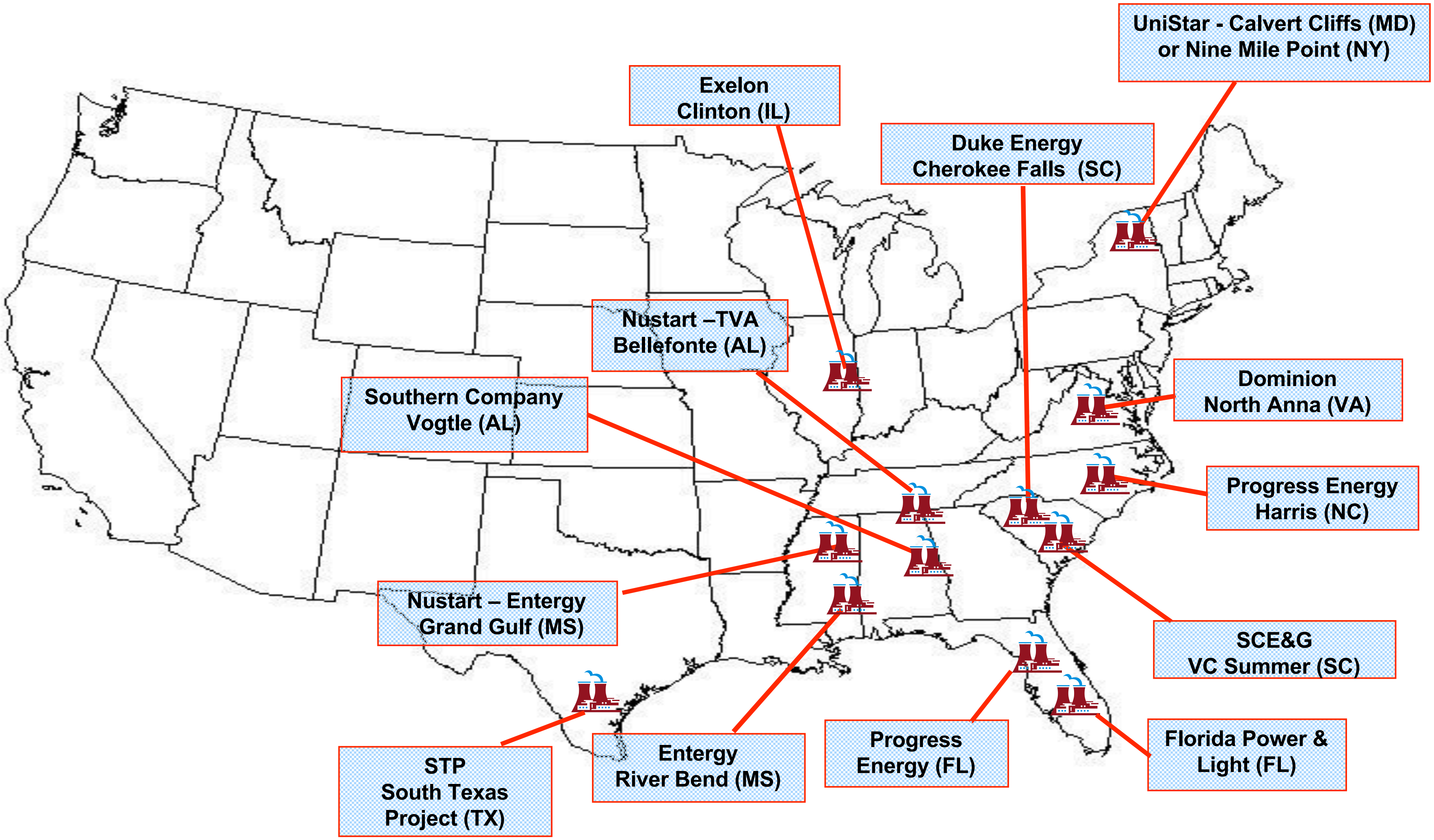
Biosphere



Importance of nuclear power into the future

- **Significant projected increase in electricity (energy) consumption over the next two decades**
- **At the same time, awareness that the concentration of greenhouse gases in the atmosphere is increasing at historic rates**
- **Possible emergence of a hydrogen-based transportation economy and increased demand for electrical-based desalination of water resources**
- **All combine to produce very large demands on "clean" electrical generation**
- **Solar, wind, geothermal and hydroelectric are all important "clean" energy producers, but they may not economically meet the entire energy demands. Likely near term reliance on natural gas but not entirely "clean" or cost competitive.**
- **Nuclear power is the safe, clean alternative - requires an improved treatment of spent nuclear fuel utilization & disposal, inherently safe fission reactor designs, and "lots of science advances", including advanced materials**

US utility announcements*

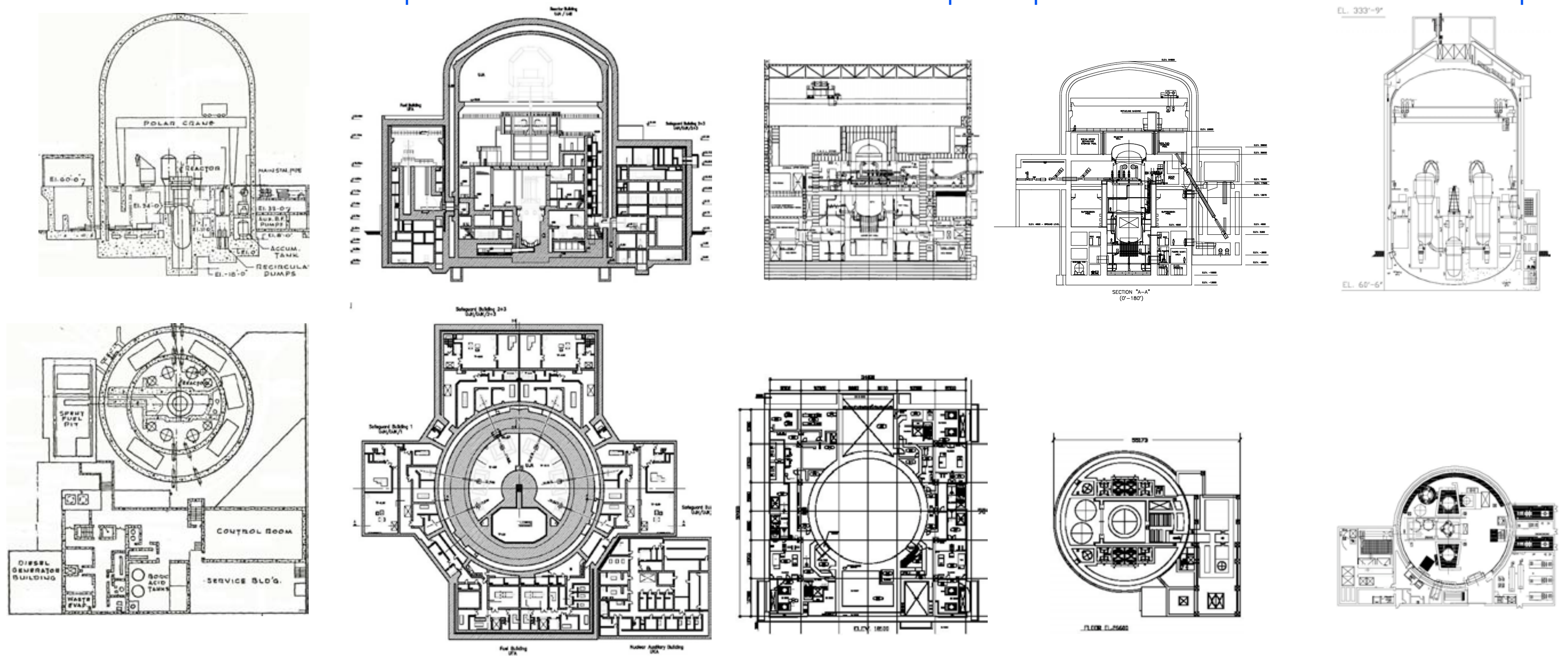


19 total combined operating license (COL) applications for 26 total reactors (≈60% advanced PWR, ≈25% advanced BWR)

*Source: T. Mulford, EPRI

Reduced capital costs expected for next reactors due to passive safety systems

Gen II | **Gen III - Active** | **Gen III+ - Passive**

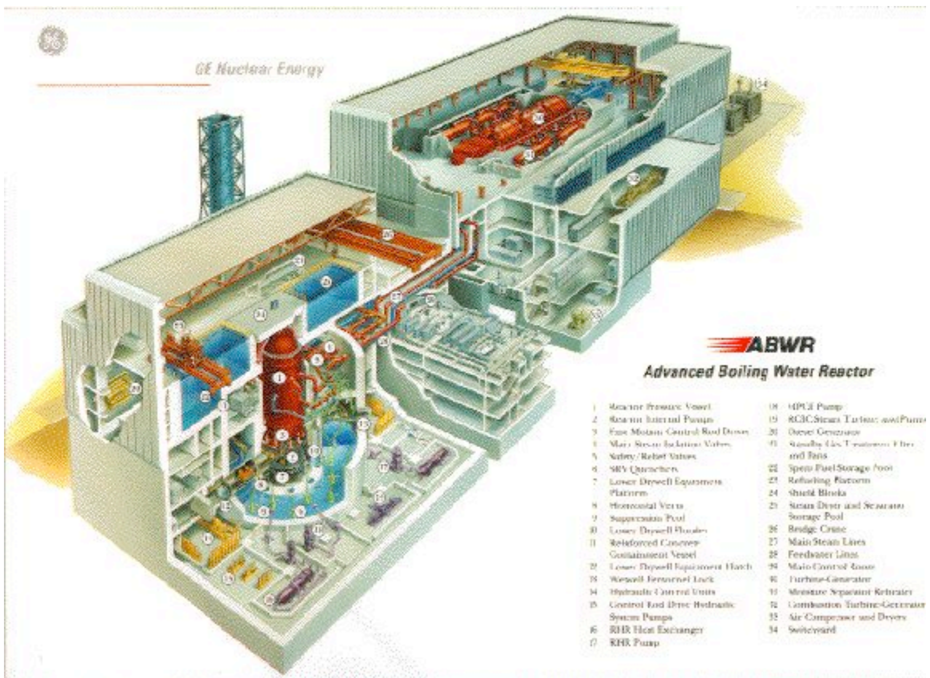


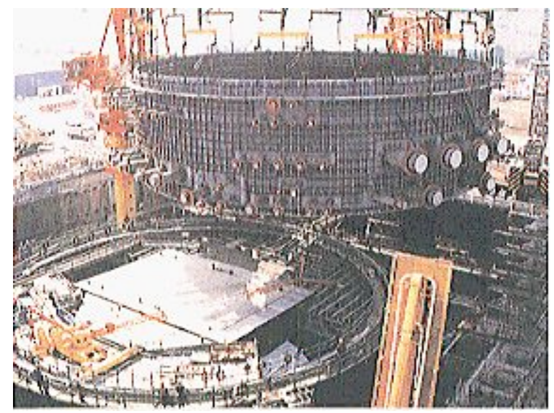
1970's PWR	EPR	ABWR	ESBWR	AP-1000
1000 MWe	1600 MWe	1380 MWe	1500 MWe	1090 MWe
40 MT_{steel}/MW	49 MT_{steel}/MW	51 MT_{steel}/MW	37 MT_{steel}/MW	

Scaled Comparison

The ABWR has demonstrated rapid construction

- **Advanced Boiling Water Reactor - an “Evolutionary” design developed by:**
  - **General Electric, San Jose, California**
  - **Hitachi/Toshiba, Japan**
- **1350-MWe capacity**
- **2 units constructed in Japan, 2 under construction in Taiwan**

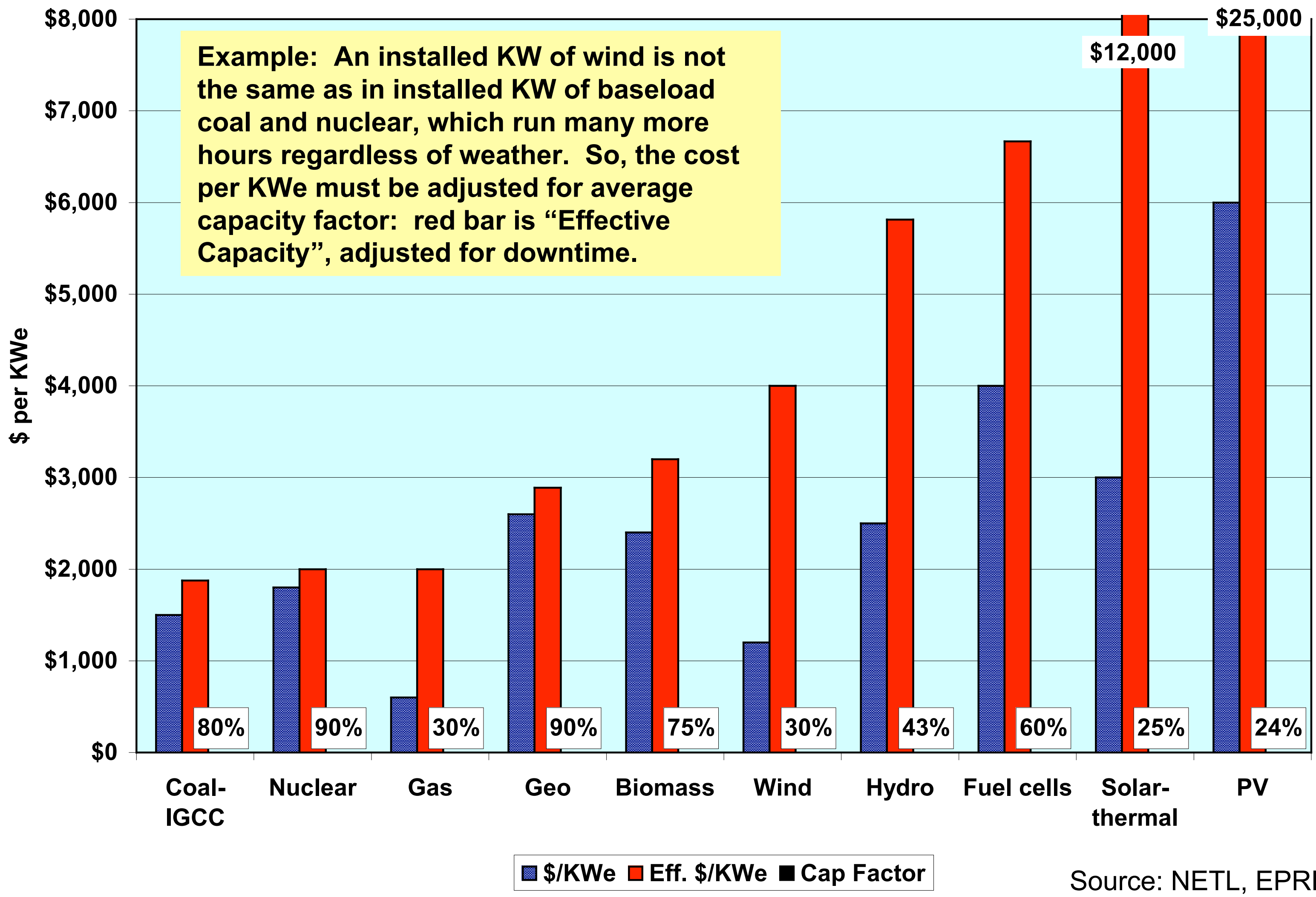




Modular assembly reduced construction time to 52 months

Real power generation costs are impacted by capacity factor

Fuel costs, weather affect downtime of some sources, which impacts investment.



Source: NETL, EPRI

Context for future nuclear power: A new view is emerging for global non-proliferation policy

***President G.W. Bush, National Defense College, Feb. 11, 2004*:**

- **"The world must create a safe, orderly system to field civilian nuclear plants without adding to the danger of weapons proliferation. <u>The world's leading nuclear exporters should ensure the states have reliable access at reasonable cost to fuel for civilian reactors, so long as those states renounce enrichment and reprocessing.</u> Enrichment and reprocessing are not necessary for nations seeking to harness nuclear energy for peaceful purposes. The 40 nations of the Nuclear Suppliers Group should refuse to sell enrichment and reprocessing equipment and technologies to any state that does not already possess full-scale, functioning enrichment and reprocessing plants."**

***Mohamed El Baradei, "Towards a Safer World," The Economist (October 18, 2003)*:**

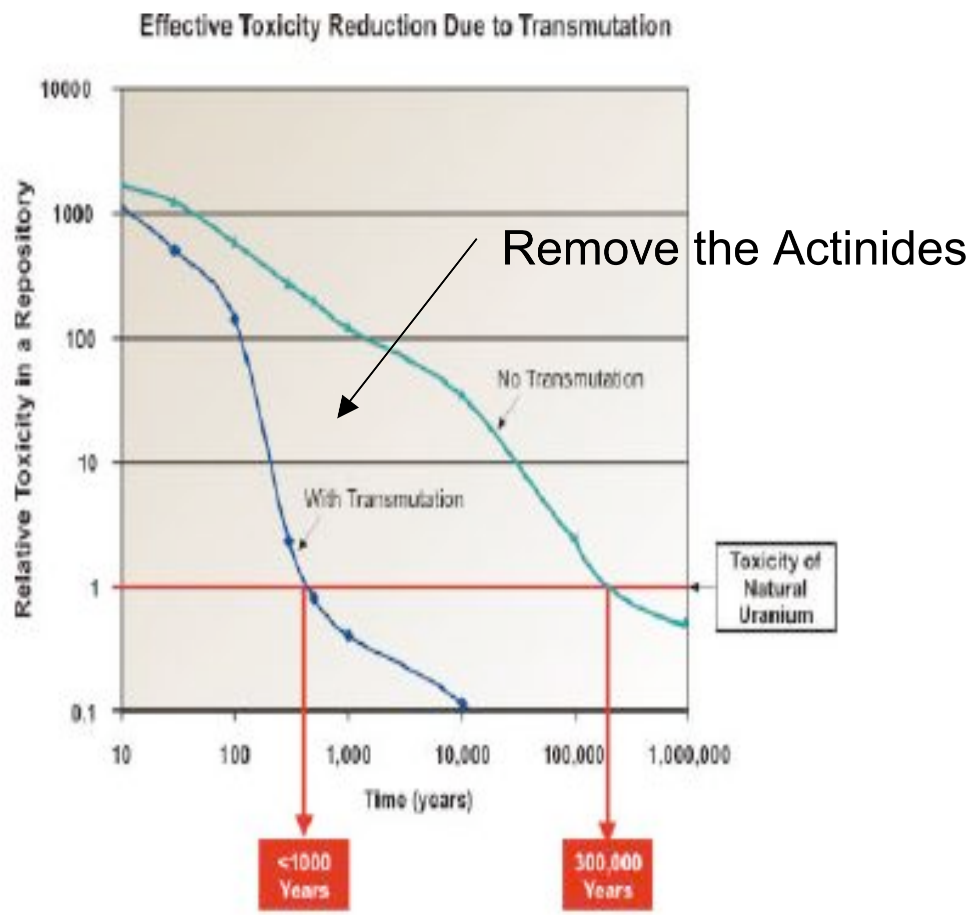
- **"It is time to limit the processing of weapon-usable material (separated plutonium and high-enriched uranium) in civilian nuclear programmes, as well as the production of new material through reprocessing and enrichment, by agreeing to restrict these operations exclusively to facilities under multinational control. These limitations would need to be accompanied by proper rules of transparency and, above all, by an assurance that legitimate would-be users could get their supplies.... [Also] <u>we should consider multinational approaches to the management and disposal of spent fuel and radioactive waste."</u>**

***New York Times editorial, January 4, 2004*:**

- **"There is no legitimate reason for countries to develop [enrichment and reprocessing] if they can be sure of reliable outside fuel supplies. Reactor fuel production should be limited to the few advanced countries that already have fully transparent nuclear technology industries. <u>Other countries should have a guaranteed right to purchase all the reactor fuel they need, provided they accept intrusive inspections and return nuclear byproducts."</u>**

*“DOE announces new nuclear initiative”**

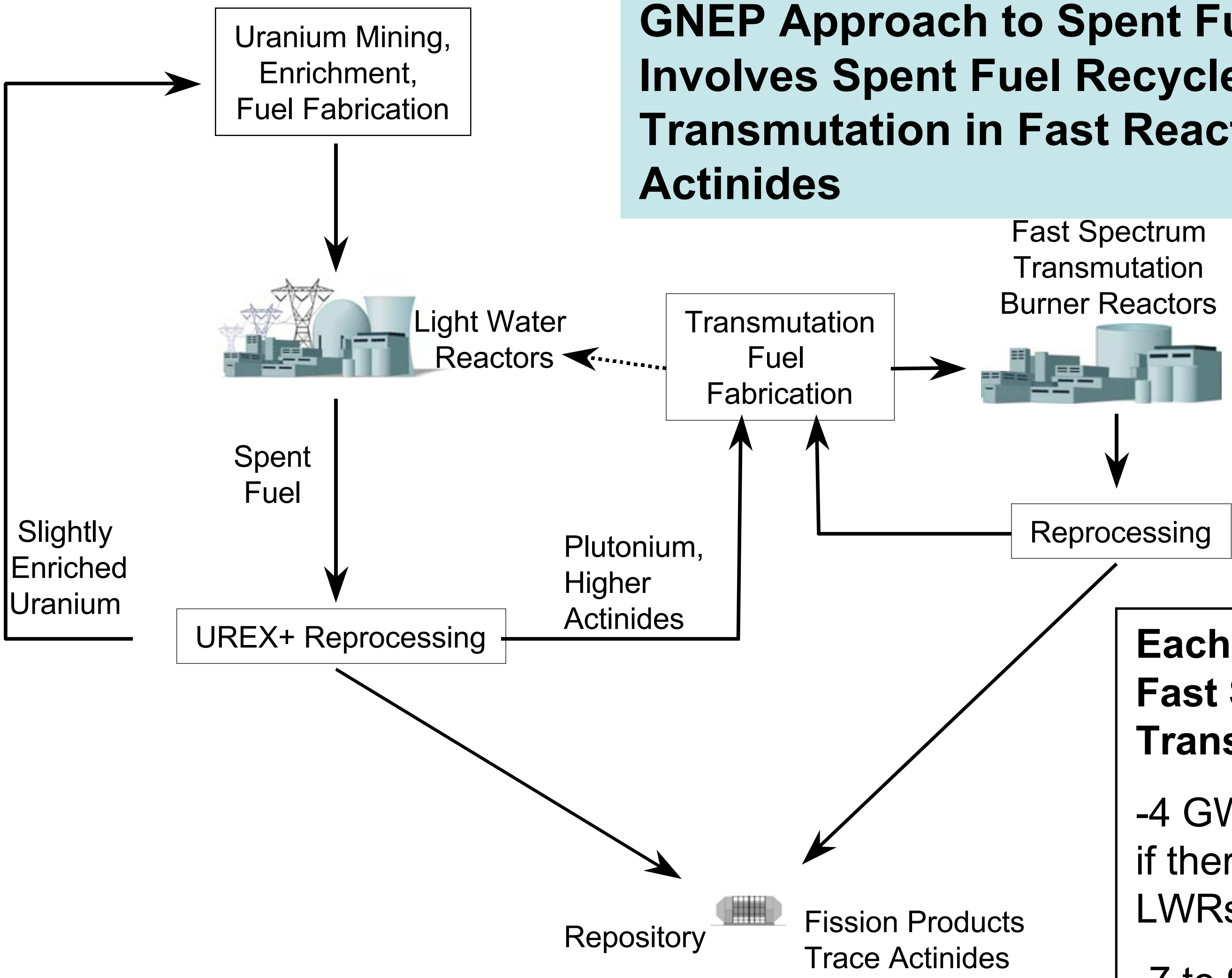
- **FY07 Request of $250M for GNEP: Global Nuclear Energy Partnership**
- **Enable expansion of nuclear energy worldwide by demonstrating and deploying new technologies to recycle nuclear fuel, minimize waste, improve nuclear material management.**
- **7 elements of GNEP**
  - **–New generation of nuclear power in the US**
  - **–New nuclear recycling technologies**
  - **–Manage and store spent nuclear fuel in the US**
  - **–Design advanced burner reactors for recycling nuclear fuel**
  - **–Establish international fuel services program**
  - **–Develop small scale reactors for developing countries**
  - **–Improve safeguards to enhance proliferation resistance and safety**



*Secretary of Energy Samuel Bodman, 6 Feb 2006 press release

GNEP spent fuel management

GNEP Approach to Spent Fuel Management Involves Spent Fuel Recycle and Transmutation in Fast Reactors to Eliminate Actinides



Closed Fuel Cycle

Each GW-thermal of Fast Spectrum Transmuters support:

-4 GW-thermal of LWRs if there is no recycle in LWRs

-7 to 9 GW-thermal of LWRs if there is recycle in LWRs

Extreme environments in Advanced Nuclear Energy Systems

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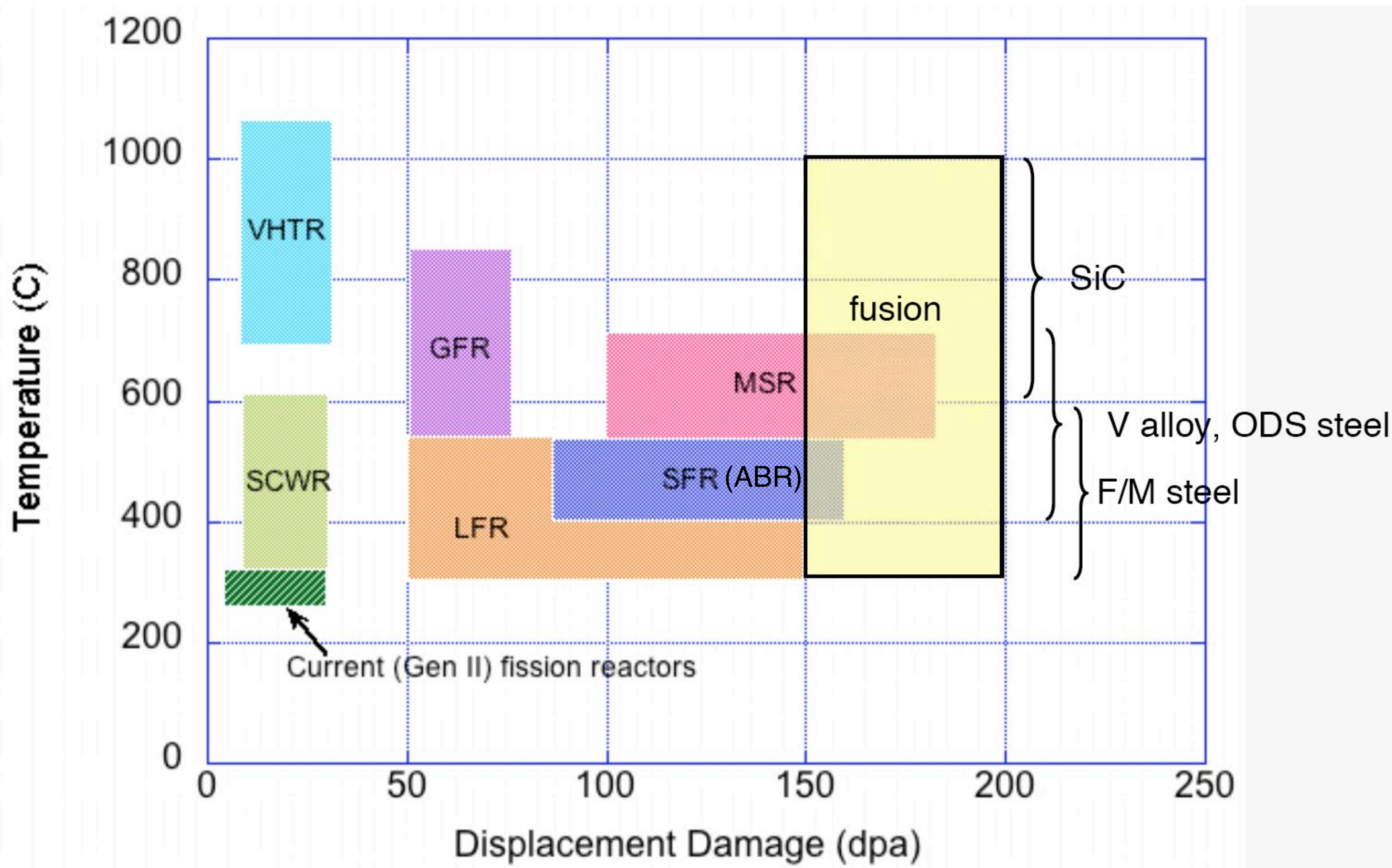


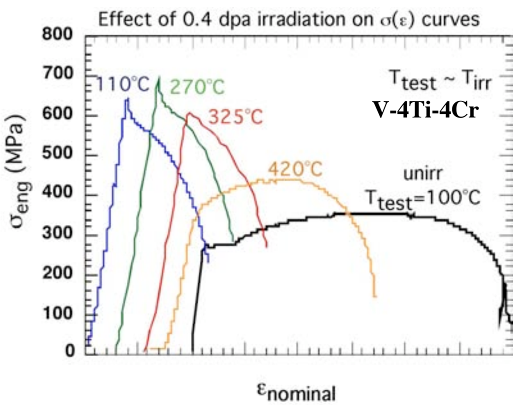
Very High Temperature Reactor
Super-Critical Water Reactor
Gas-cooled Fast Reactor

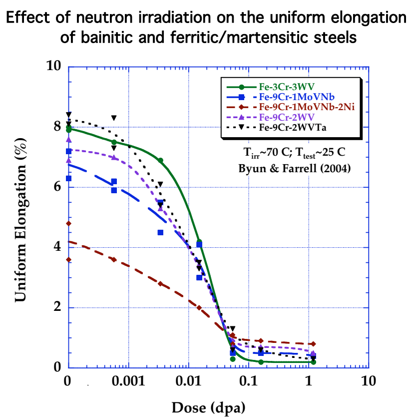
Lead-cooled Fast Reactor
Sodium-cooled Fast Reactor
Molten Salt Reactor

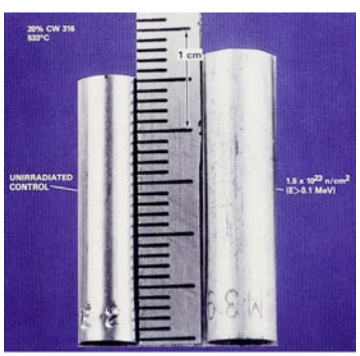
* S.J. Zinkle, ORNL

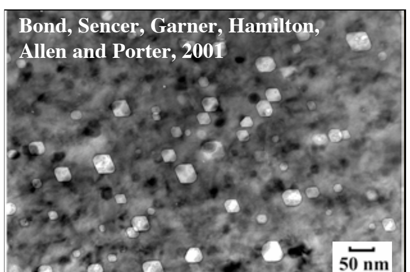
Structural Materials Challenges: Radiation Effects

- Exposure to neutrons degrades the mechanical performance of structural materials and impacts the economics and safety of current & future fission power plants:
  - Irradiation hardening and embrittlement/decreased uniform elongation (< 0.4 T_m)
  - Irradiation (<0.45 T_m) and thermal (>~0.45 T_m) creep
  - Volumetric swelling (0.3 - 0.6 T_m)
  - High temperature He embrittlement (> 0.5 T_m); Specific to fusion & spallation accelerators









304 Stainless steel irradiated in EBR-II, 380°C, ~22 dpa, 1% swelling

Variables

- Material (steels, Vanadium and Ni-based alloys, Refractory metals & alloys, SiC) and composition
- Initial microstructure (cold-worked, annealed)
- Irradiation temperature
- Chemical environment & thermal-mechanical loading
- Neutron flux, fluence and energy spectrum
  - materials test reactor irradiations typically at accelerations of 10^2 - 10^4

Synergistic Interactions

Summary

- **Nuclear energy systems consume very small quantities of natural resources without contributing to greenhouse gas emissions**
  - Backend of the fuel cycle remains a problem, but potential opportunity

- **Operating experience from current generation of nuclear plants provides substantial lessons for the future and knowledge-base to support the safe expansion of nuclear power**

- **Recent activity in nuclear energy has been substantial**
  - **Waste repository site selected, and new EPA license standard in United States**
  - **Over 50% of U.S. reactors to receive 20-year license renewals by 2007**
  - **New reactor designs with lower capital cost**
  - **3 U.S. sites have submitted applications for combined Construction and Operating Licenses, with more than 20 applications in the queue**
  - **Introduction of the GNEP by the U.S. DOE**

- ***What's really important for large-scale expansion of nuclear power into developing countries in the coming century?***
  - address global climate change
  - reduce the public health and environmental impacts of fossil energy use
  - get non-proliferation and nuclear security right