Nuclear Power Myths and Realities

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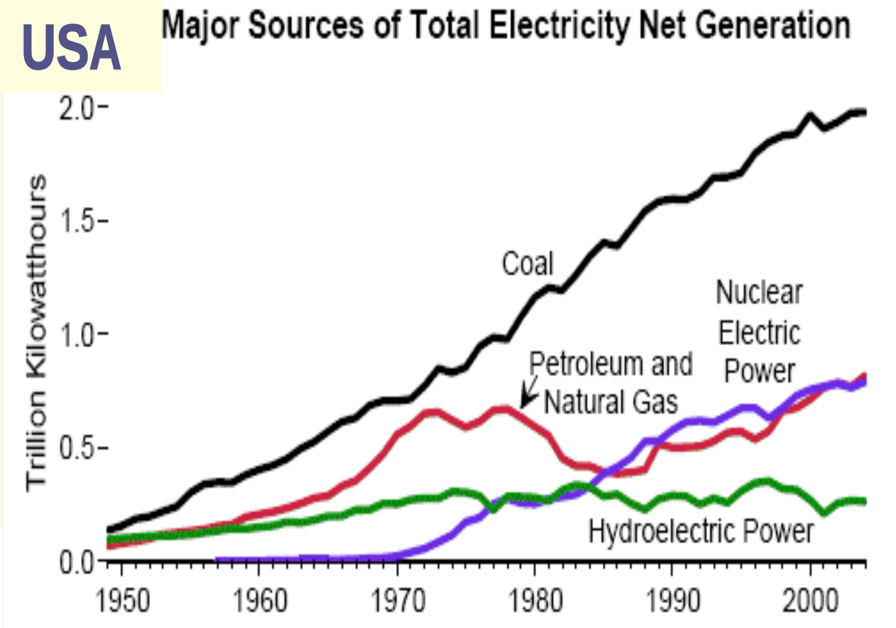
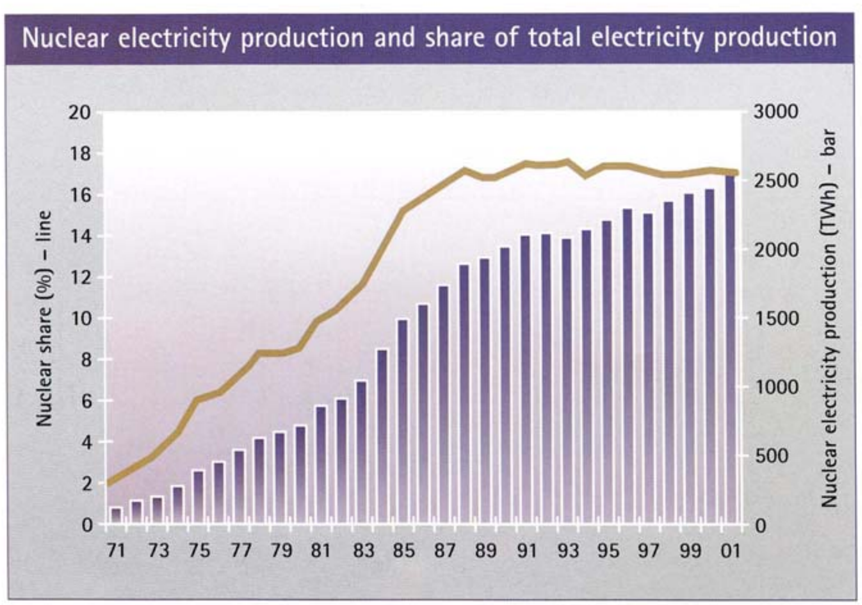
Nuclear Energy Today

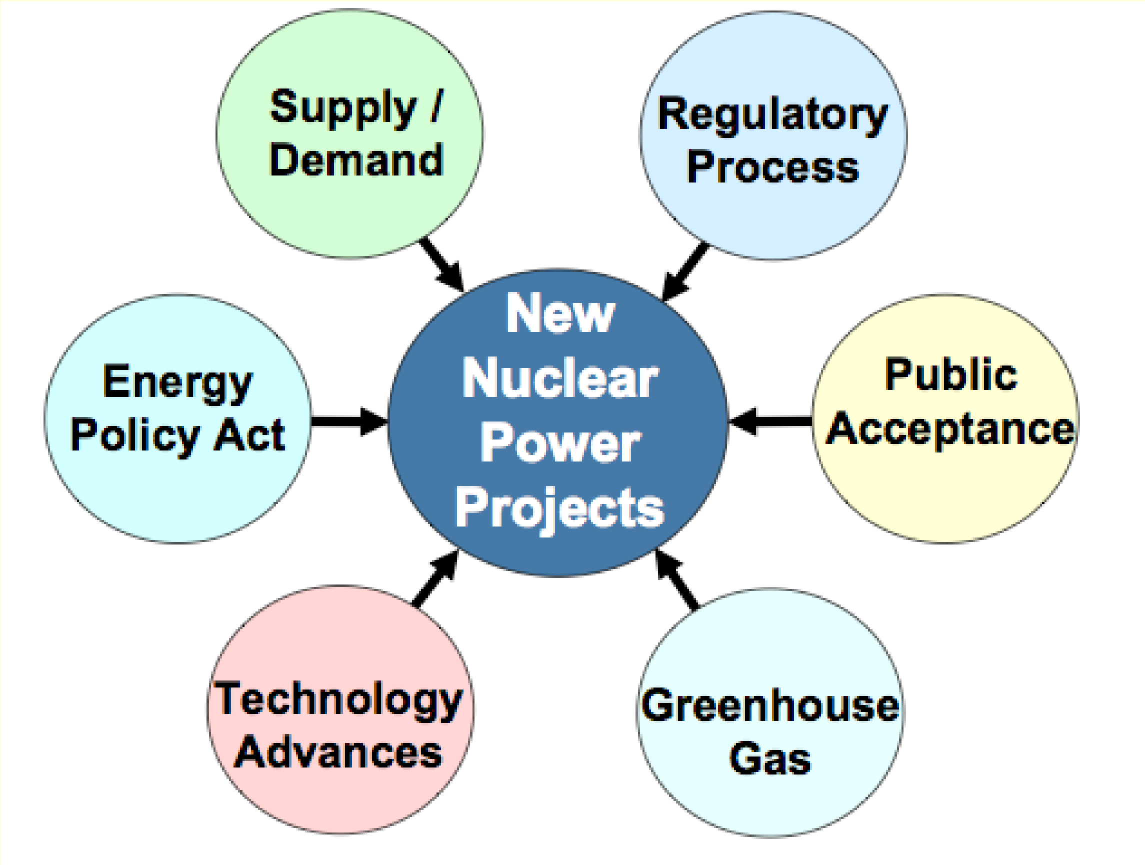
- The largest non-fossil supplier of electricity in the US and worldwide
  - 103 US reactors, 442 World wide
  - US: 99.5 GWe, 20% of production
  - World: 347 GWe, 16% of production
- No order for US nuclear plants since 1975, but in 2005 nuclear production was the highest ever.
  - US plants have run at 90% capacity in 2005, up from 71% in 1990.
  - 3.0 GWe of uprates were permitted in





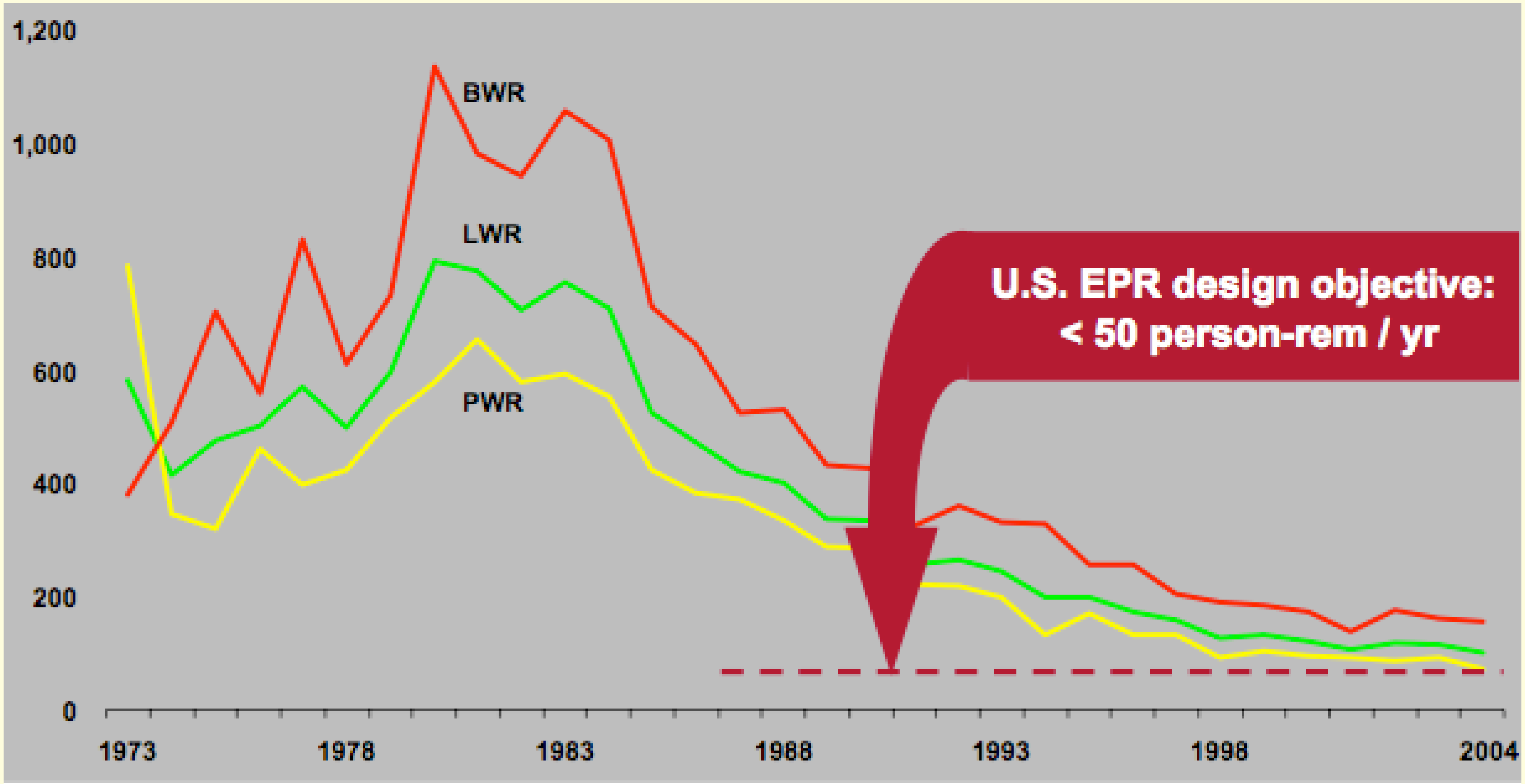
- 44 reactor licenses extended, from 40 to 60 years.
- Applications for an additional 3 GWe are pending
- US utilities recently declared plans for license applications for 30 new light water reactors (LWRs)
- China, India, Russia and South Korea have declared plans to add about 110 new reactors by 2025

Why New Nuclear Orders?



Source: Joe Turnage, Constellation

Dose to workers at US plants and AREVA goal for US-EPR



Source: Nuclear Regulatory Commission Occupational Radiation Exposure at Commercial Nuclear Power Reactors and Other Facilities 2004

Nuclear Energy - Myths and Realities

- Nuclear Power has been in decline since the TMI accident in 1979. In fact US nuclear plants are producing 50% more energy than they did in 1980. Nuclear orders appear imminent as plans for 31 new reactors have been announced.
- Nuclear power is dangerous: radiation emissions and potential accidents are intolerable. In fact there have not been accidents in the US that harmed the public, and only one accident world-wide for a design and operating procedures that would not have been allowed in the US.
- Nuclear power is too expensive. While expensive to build, it is very inexpensive to run, and can run continuously. That is why when other fuels get expensive it will be only logical to turn to nuclear for more energy.
- Nuclear power generates intolerable amounts of wastes. Per unit energy, the volume of the fuel and the plant is the smallest of any other power source.
- Nuclear power will lead to nuclear weapons proliferation. The fuel used in nuclear power plants is not suitable for bombs as it enters or leaves the reactor. There are lower cost options to weapon materials than nuclear power.
- Nuclear power is useful for electricity generation, but cannot help meet the transportation energy sector needs. Nuclear (heat and hydrogen) can in the near future lower the carbon intensity of heavy and unconventional oil extraction and refining. It can recharge car batteries or fuel cells in the future

Nuclear Energy Economics

Key Factors

- Plant cost is about 70% of cost of electricity
- Depends on duration of construction and effective Interest rate on capital.
- Nuclear fuel is only 15% of cost of electricity

Industry Solutions

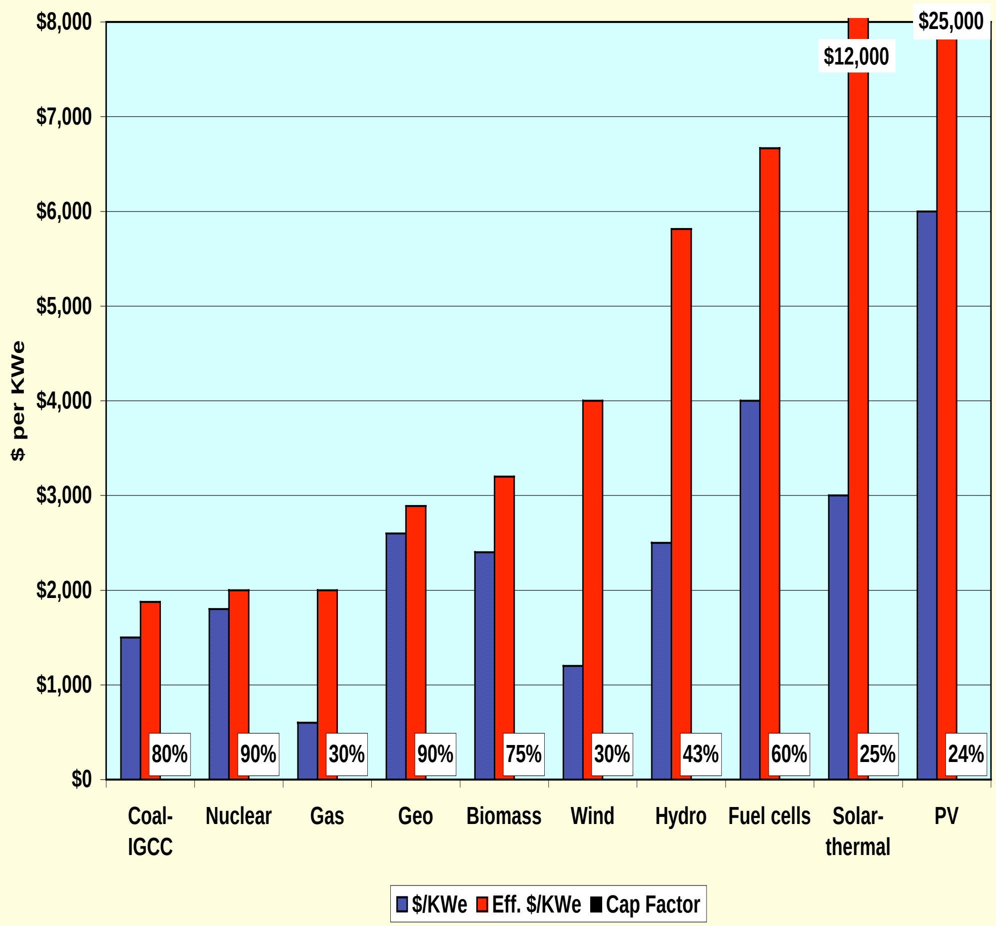
- **Simplification**: W-AP1000 uses 2 not 4 loops & GE-ESBWR eliminates pumps
- **Standardization**: fixed design for multiple units
- **Large Capacity**: Several models at 1500 MWe
- **Construction time** 5 yrs, as in Japan and France

Government Solutions - Energy Act 2005

- Production credits up to 6000 MWe
- Regulatory reform, and Insurance for delays
- Loan guarantees for non-emission

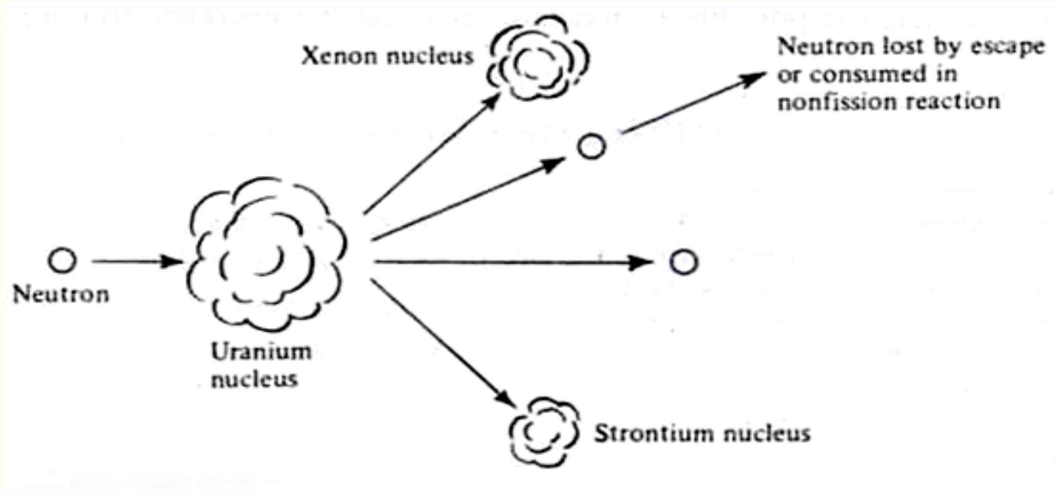
Innovative Technology Solutions

- Increase reactor power density
  - New fuel design
  - Improved coolant properties - nanofluids
- Increase power conversion efficiency
  - High Temperature Gas Cooled Reactors



Nuclear as a base loaded electricity source beats all other sources but coal.
Gas is only competitive below $5/MBTU. Question is how far off are Carbon taxes?

A Typical Fission Reaction



$$_{92}U^{235} + {}_{0}n^{1} \longrightarrow {}_{54}Xe^{140} + {}_{38}Sr^{94} + 2\,{}_{0}n^{1} + Q\ (200\ \text{MeV})$$

$$Q = [\,(M^{235} + M^{1}) - (M^{140} + M^{94} + 2M^{1})\,]\,c^{2}$$

Fission of 1.05 g of U^{235} generates 1 MWd of thermal energy, or 8,000 kWhr of electricity. Average house consumes 2400 kWhr per year, which generates 0.3 g of fission products per year embedded in 9 g of U (or spent fuel) per year.

Note that more than 300 fission products are possible

Fission products and some neutron capture products are radioactive, which makes spent fuel both highly radioactive and a heat source for a long time after its extraction from the reactor.

Nuclear Fuel Cycle - Resources

- Uranium-235 is the only naturally occurring isotope that can be used as fuel in thermal reactors, such as today's reactors. U-235 is present (at 0.71%) in U in terrestrial locations and ocean waters. Plutonium-239 and U-233 can also be used, but need to be manufactured by capturing one neutron in U-238 and Th-232 respectively

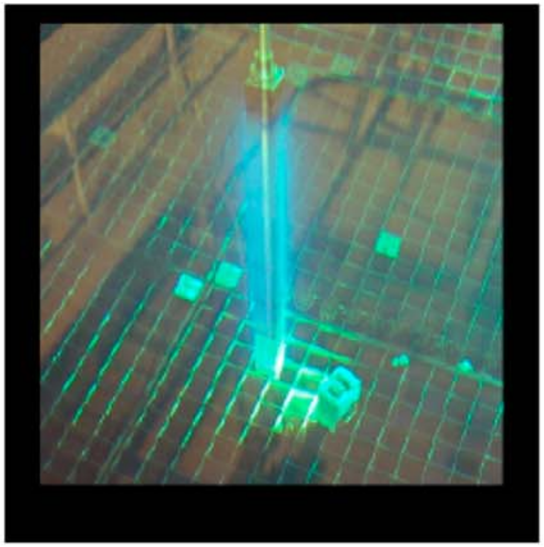
- Uranium: Mostly U238
  - World use in 2004 was about 0.07 million tons (MT) of U ore.
  - Large deposits in Australia, Canada, Kazakhstan, Namibia, US, others
  - Current U spot price is about $150/kg, in 2004 only $40/kg.
  - IAEA estimates 2.5 million tons (MT) of U in conventional sources at costs below $80/kg. That might lead to 25-100 MT at $300/kg.
  - Lower grade uranium from unconventional sources, e.g. sandstone and phosphate may add another 100 MT at higher prices.
  - Sea water has another 5,000 MT at costs higher than $500/kg.

- Thorium is three times as abundant as uranium

Nuclear Fuel Cycle - Economics

- Nuclear fuel cycle makes up only about 15% of the cost of electricity from nuclear energy, or about 6 $/MWhr, out of a total electricity cost of 40 $/MWhr

- This covers the following steps
  - Uranium ore extraction and conversion to U_3O_8, at $48/kg
  - Enrichment in U235, typically by centrifugal forces spinning gaseous UF_6, to about 4% (Japan Rakashu plant in side pictures)
  - Manufacturing of UO_2 pellets, and placing them in Zr tubes (cladding) thus producing fuel rods. The rods (or pins) are arranged in square lattices called assemblies.
  - Removal of spent fuel assemblies to temporary storage in fuel pools, then to interim dry storage
  - 1 $/MWhr for spent fuel disposal fees



http://www.nucleartourist.com/

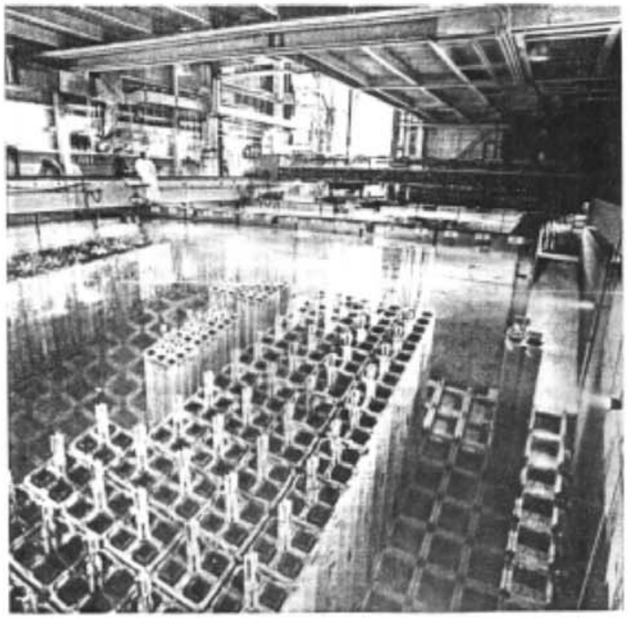


Figure 2.2: Concrete storage casks at a U.S. nuclear power plant

FIGURE II-A-1. G. E. Morris Operation — Fuel Pool.* Water Depth is 8.7 m (28.5 ft).

After 10 or more years, radiation and decay heat levels are low enough that the fuel assemblies may be stored in large casks cooled by air on the outside. Such casks hold 24 to 40 fuel assemblies.

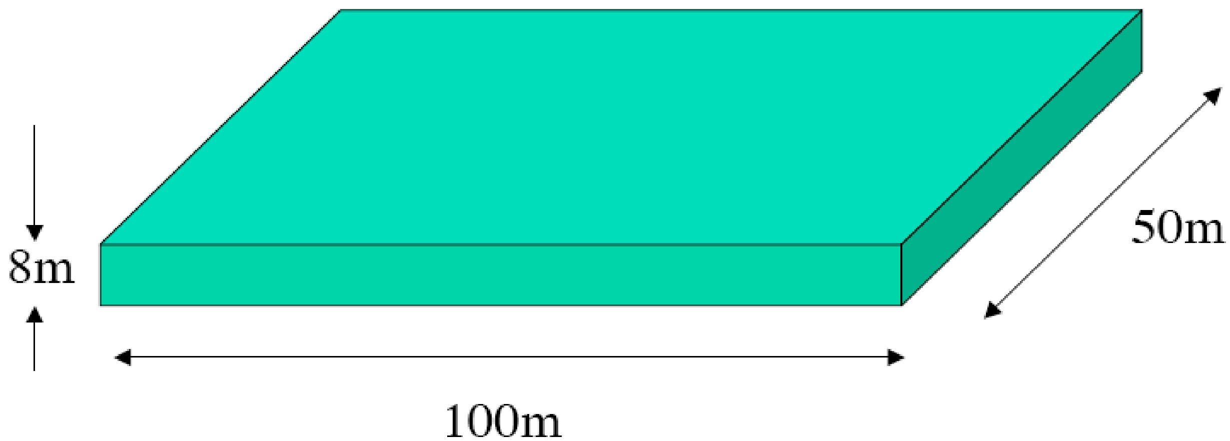
The casks have double metal ring seals and are bolted to ensure no radioactive release will be ale to occur Helium is used inside the cask to promote heat removal from the fuel assemblies to the cask wall. Air on the outside removes the heat.

Pressure inside the cask and temperature on the outside are monitored.

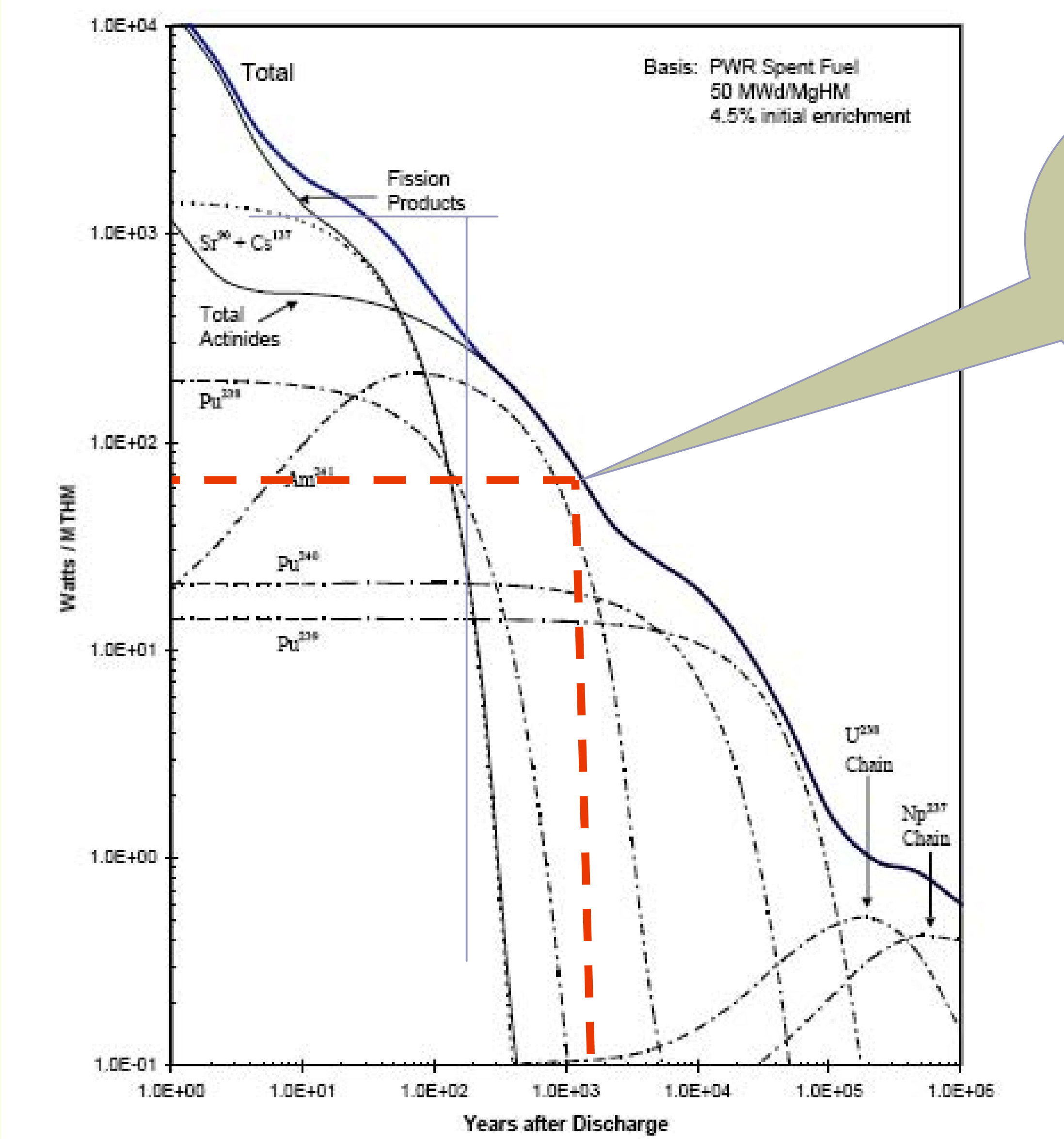
How large is the waste volume?

How much spent fuel will be generated by the current U.S. fleet of ~100 nuclear reactors over their operating lifetime?

10 (m^3/reactor-year) x 40 (years) x 100 reactors ~ 40,000 m^3



Decay behavior of spent fuel -- thermal power



About 70 watts of heat (a light bulb) per spent fuel assembly after 1000 years

Disposition alternatives for high-level waste

- Central surface or near-surface engineered storage (do nothing for 100 years)
- Geologic repositories (such as Yucca Mountain below)
- Deep borehole disposal
- Sub-seabed disposal
- Ice-sheet disposal
- Extra-terrestrial disposal
- Partitioning and use of useful isotopes, but transmutation of troublesome ones

Should Pu be stored or burned?

- ☆ Roughly 2000 (8000) tons of spent fuel are discharged in the US (world) per year. About 50,000 (130,000) tons have been discharged in the US (world)
- ☆ Mostly uranium (about 95%, at 0.5 to 0.8% ^{235}U) with:

  1% plutonium, 0.1% minor actinides, 3-5 % fission products.
- ☆ In the US, and some other countries like Sweden and Finland, spent fuel is currently stored at the reactor sites, but destined for a repository.
- ☆ In France, Japan and other countries, spent fuel is reprocessed with fission products and minor actinides emplaced in glass; one recycle of Pu in LWRs as mixed oxide (MOX) is planned, then fuel is stored until it is needed for future fast reactors.
- ☆ Pu and higher actinides are accumulating, whether in spent fuel storage or processed output storage.
- ☆ Add to that discarded weapons Pu, about 10% of civilian Pu to date, or 150 tons, with more potentially coming
- ☆ Options to burn (transmute) Pu and higher actinides are being considered.

  - Mixed Oxides in LWR - Adv. Fuels LWR

  - Fast reactor - Accelerator Driven Systems

The CONFU Fuel Assembly to fit in ordinary PWRs

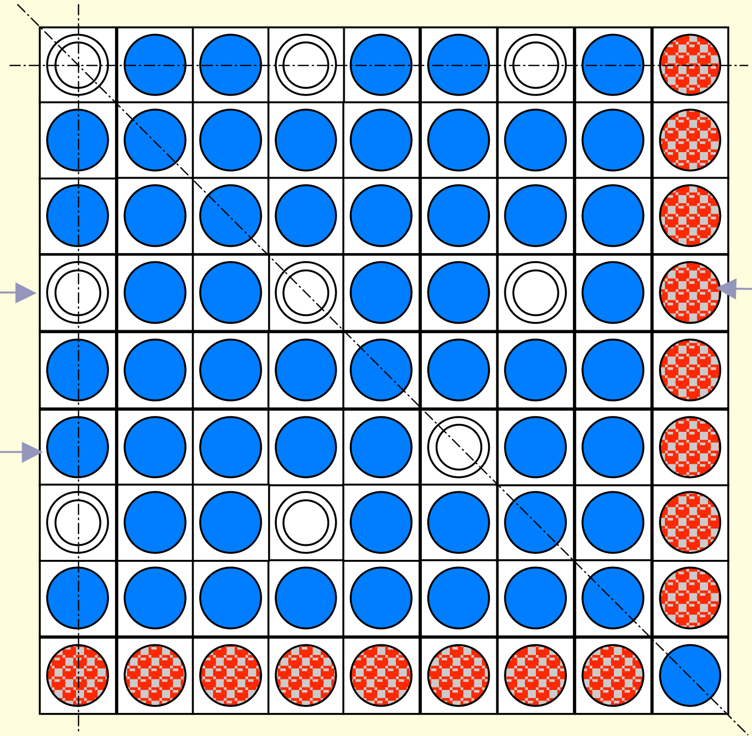
The COmbined Non-Fertile and Uranium Fuel Assembly

Guide Tubes

UO_2 Pins

4.2% Enrichment

Total 355 kg of U/assembly



Fertile Free Pins:

70 v/o – Host Material ($MgAl_2O_4$)

18 v/o –Stablizer (YSZ oxide)

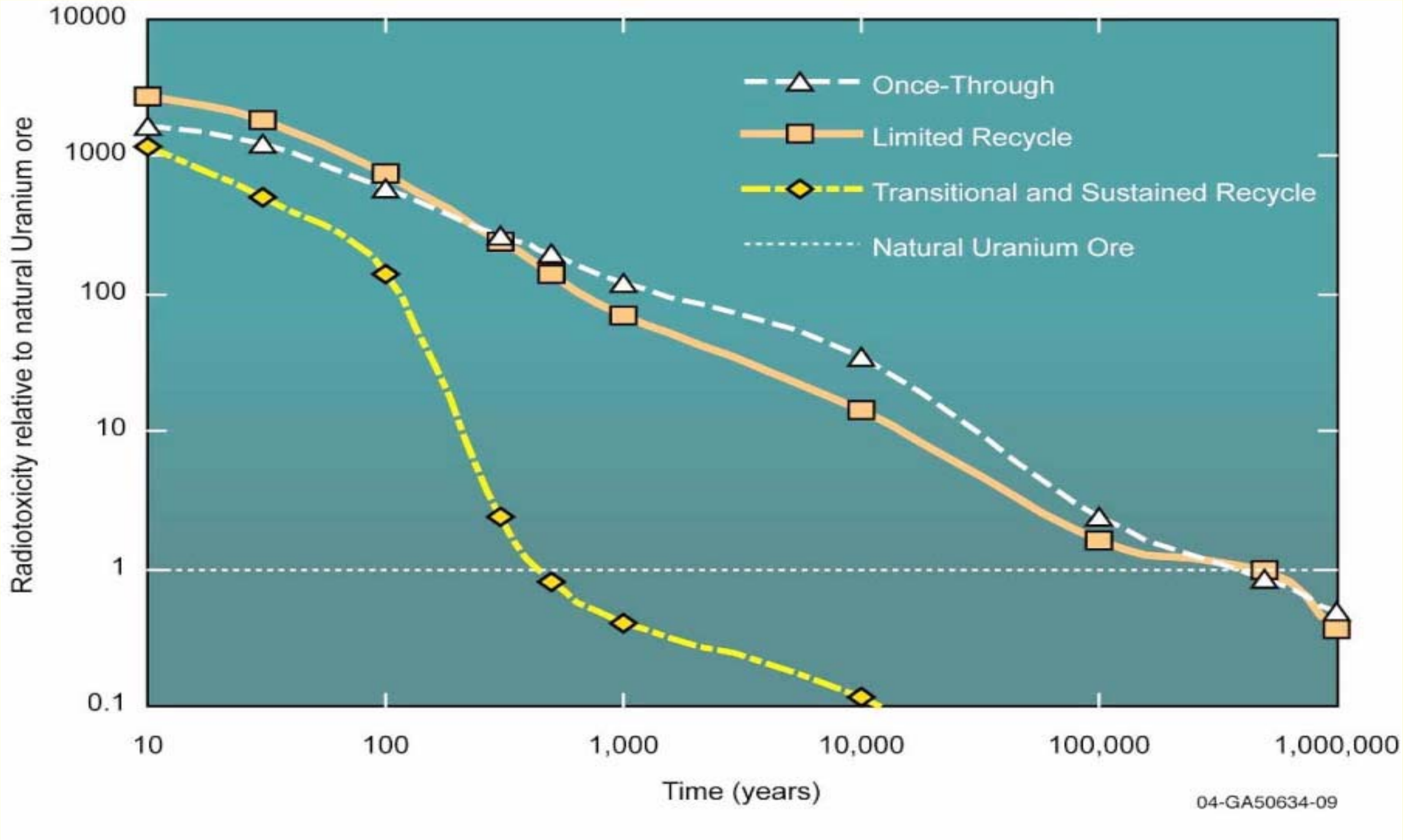
12 v/o – Fuel (TRU O_2)

Total 13.2 kg of TRU/assembly

This assembly produces zero net transuranics

Source: Shwageraus, Hejzlar, and Kazimi, Nuclear Technology, 2005

Radiotoxicity of wastes from Once-Through and Recycle (transmutation) Options



Impact of fuel cycle strategies on eventual repository needs in US through the year 2100*

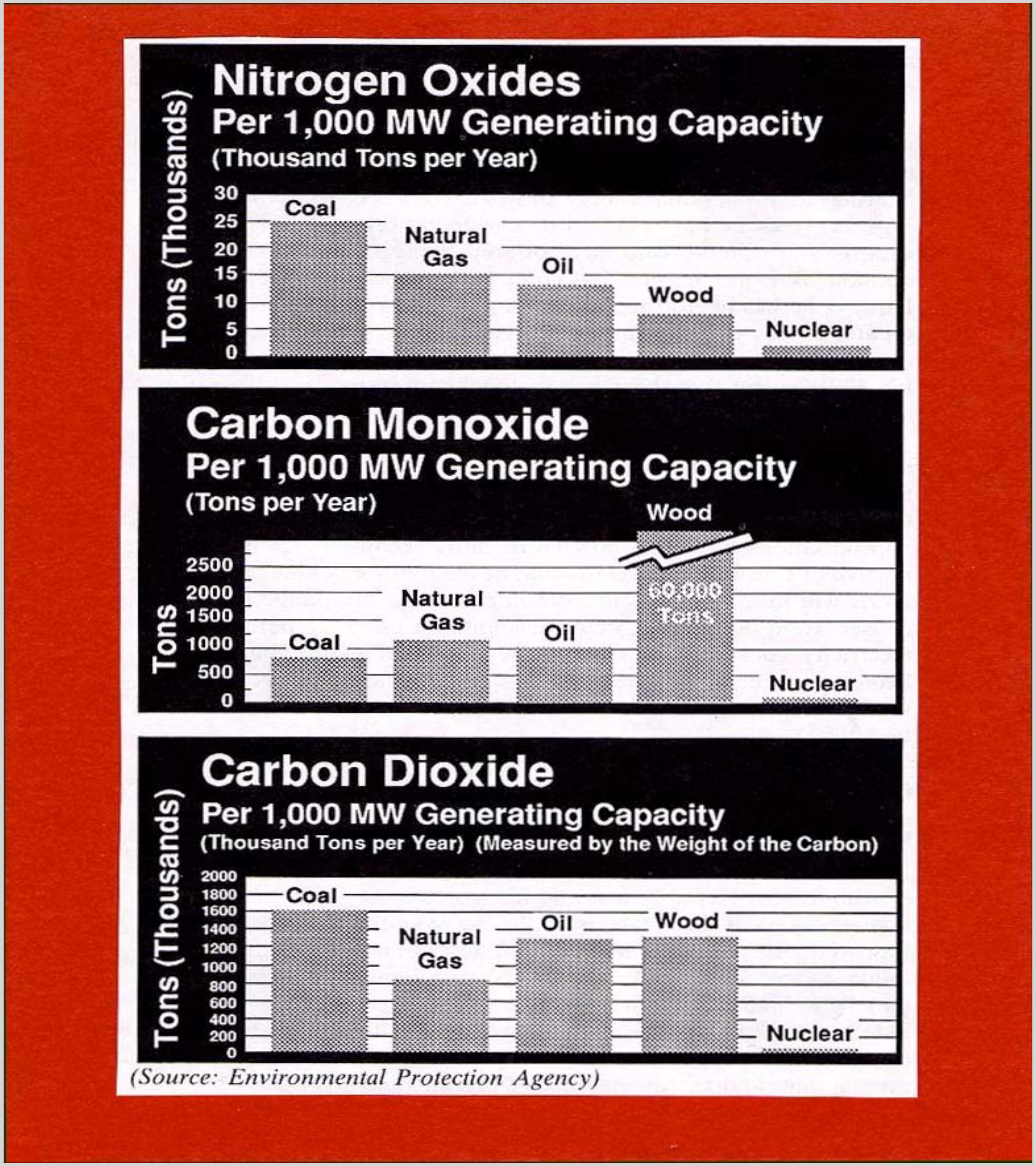
Nuclear Futures		Existing License Completion	Extended License Completion	Continuing Level Energy Generation	Continuing Market Share Generation	Growing Market Share Generation
Cumulative discharged fuel in the year 2100 (metric ton)		100,000	120,000	250,000	600,000	1,400,000
		Existing Reactors Only		Existing and New Reactors		
Fuel Management Approach		Number of Repositories Needed at 70,000 Metric Ton Each				
No Recycle	Once-Through	2	2	4	9	20
No Recycle	Once-Through, High Burnup Fuels	2	2	3	7	17
Reprocess & Recycle	Limited Recycle, High Burnup Fuels	Recycle not Recommended	Recycle not Recommended	2	5	10
Reprocess & Recycle	Transitional and Sustained Recycle	Recycle not Recommended	Recycle not Recommended	1	1	1

04-GA50634-20

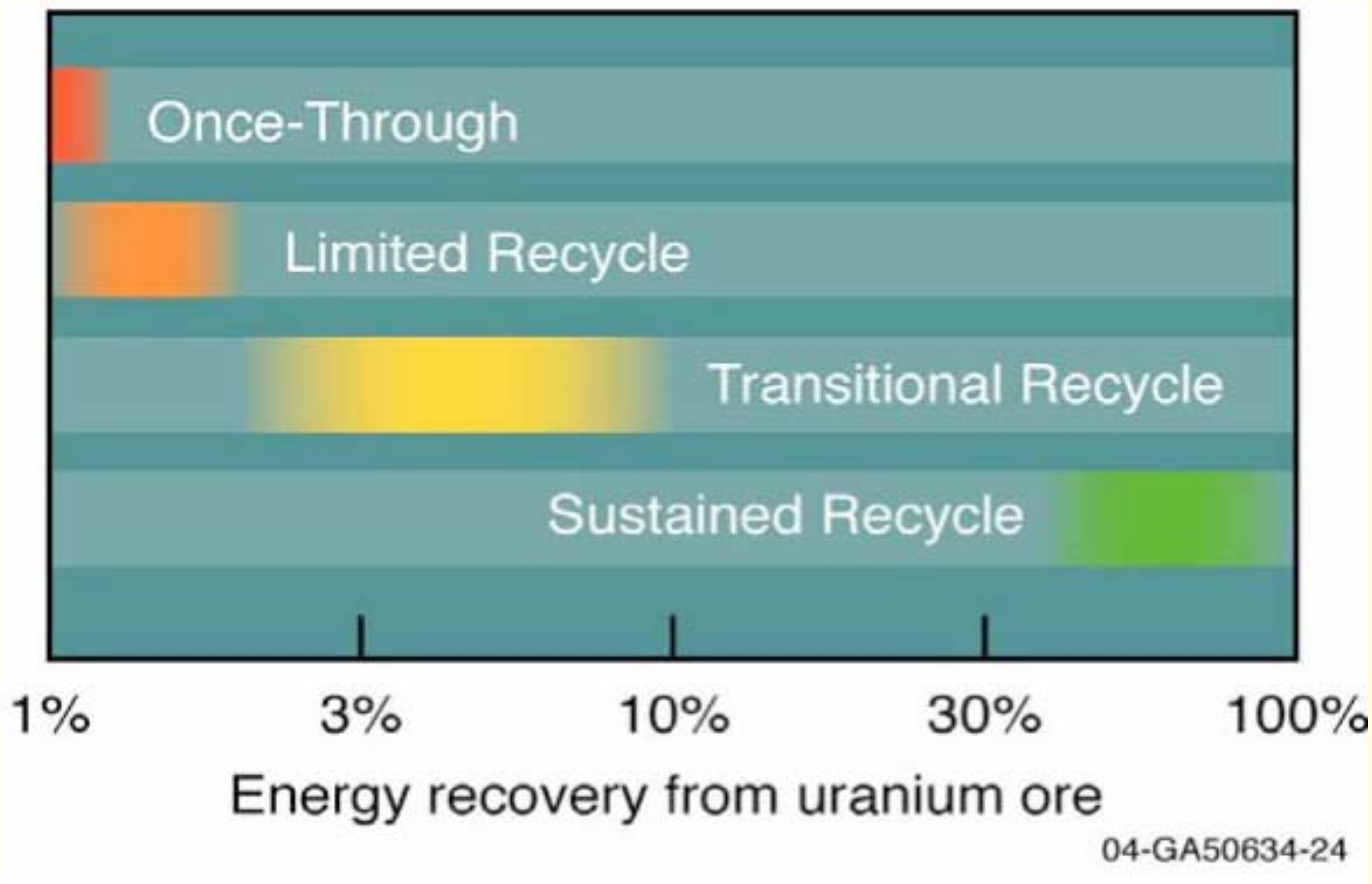
* Estimated by DOE-AFCI program in 2005 given a YM limit of 70.000 MT. Recent EPRI estimates nearly triples the Yucca Mountain capacity.

Nuclear energy emissions to environment are thousands of times less by volume or mass than fossil fuels.

Nuclear need for land is 10,000 times less per MWhr-e than biofuel, and 100s times less than wind, or solar.



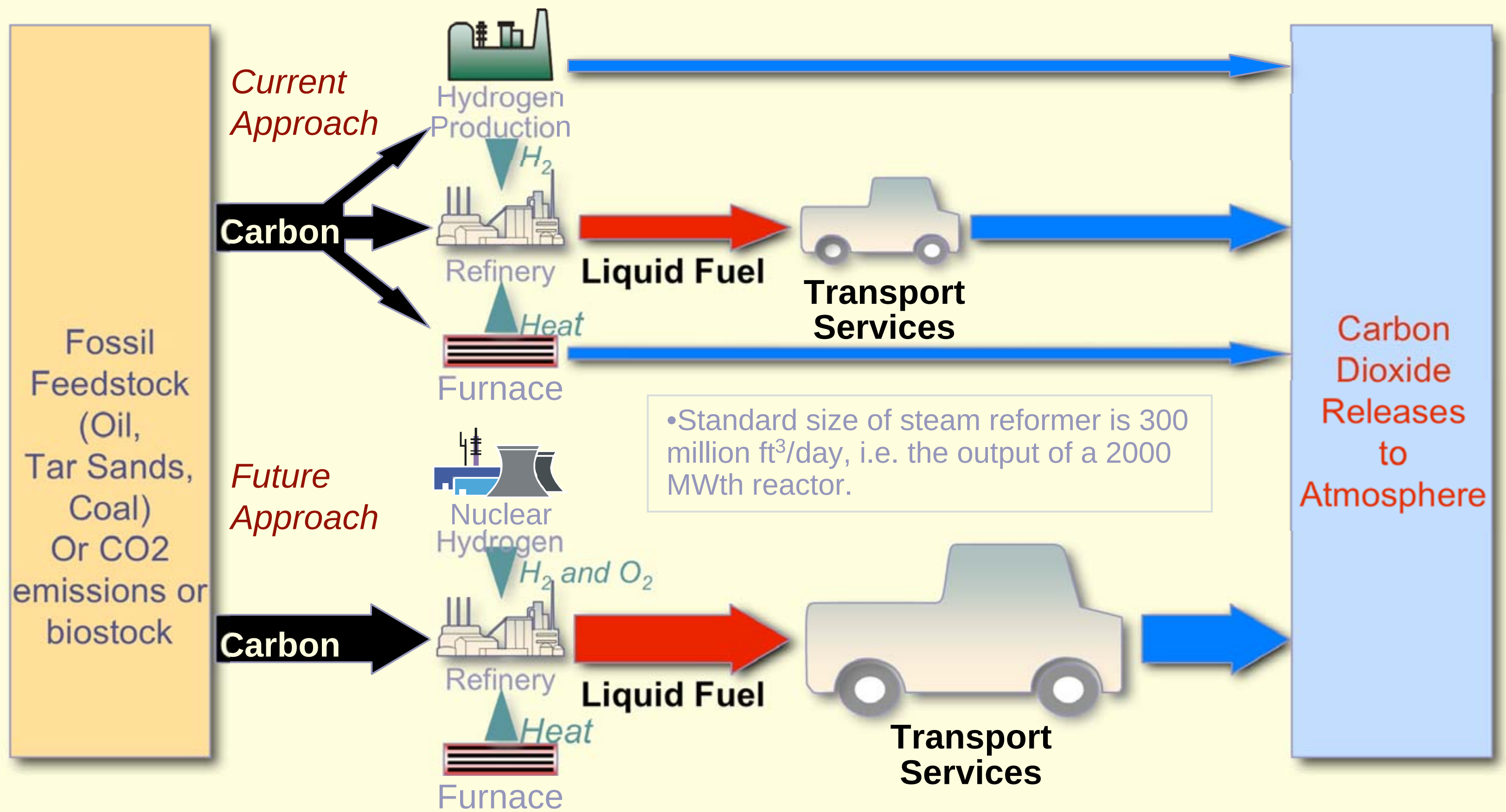
Energy recovery rates from uranium ore for the different fuel cycle stages



Nuclear Energy Applied to Transportation Fuels

- Use of nuclear for enhanced recovery of oils from unconventional sources
  - The temperature needed for recovery of oil from tar sands is relatively low, and that allows existing technologies to be candidates to replace natural gas as the source of heat.
  - However, shale oil recovery requires higher temperature which may be accomplished using a high temperature reactor.
- Nuclear Energy can be used for Hydrogen and Heat Production at refineries
  - A nuclear reactor can be coupled to a water-splitting, hydrogen production, plant based on one of the following three methods:
    - Using high temperature electrolysis of steam
    - Using thermo-chemical cycles, such as the S-I, Ca-Br or Cu-Cl cycles
    - Using hybrid cycles.
- Application of nuclear heat and hydrogen in production of synthetic fuels from captured CO_2
  - About half of the emitted CO_2 from coal plants in the US would be sufficient to produce synthetic methanol or ethanol to displace gasoline, resulting in about 20% CO_2 emission reduction.

Nuclear H_2 can Increase Liquid Fuel per Unit of Feedstock and Reduce Emissions



- Standard size of steam reformer is 300 million ft^3/day, i.e. the output of a 2000 MWth reactor.

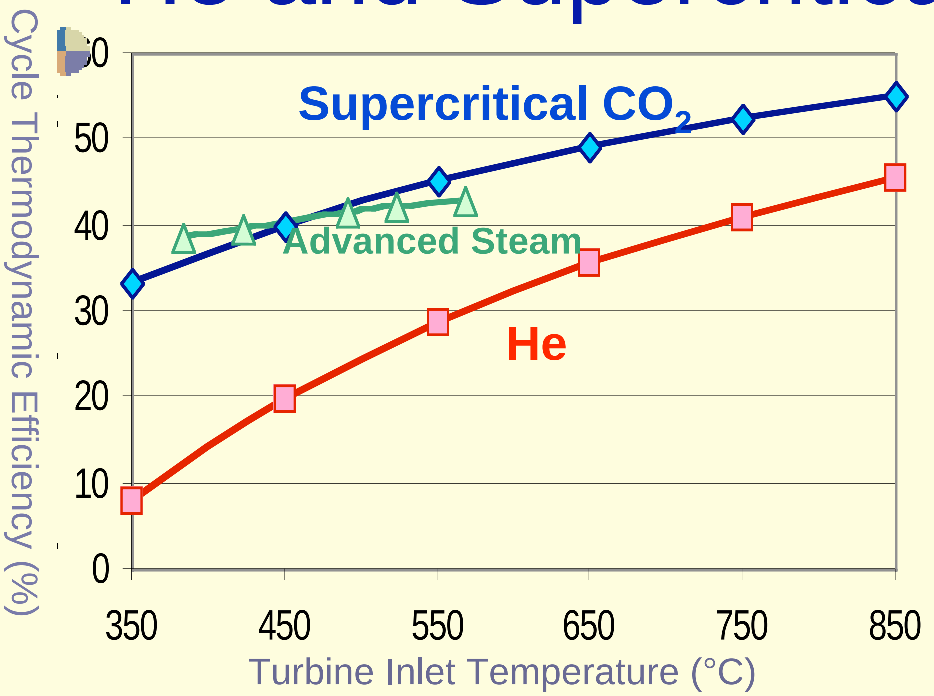
Synergistic Fossil and Nuclear H_2 can start in sweetening heavy oils

Synthetic Fuel Requirements: H_2 and O_2 are natural products of water splitting

CO_2 from air or directly from coal plants provide large environmental benefits.

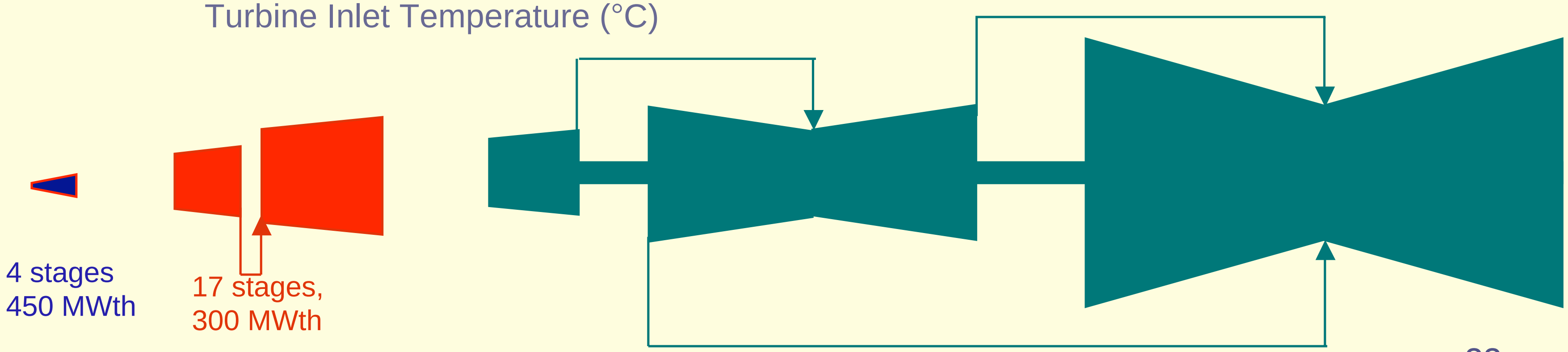
Modified from C. Forsberg, ORNL

Advanced Power Cycles: He and Supercritical CO_2 Gas Turbines



While a He gas turbine plant is already 25 times smaller than the steam turbine equipment, a CO_2 turbine size is smaller by another factor of 8.

Steam turbine: 55 stages / 250 MWe
Mitsubishi Heavy Industries Ltd., Japan (with casing)



Source: Dostal, Hejzlar & Driscoll, MIT, 2004

Concluding Remarks

Nuclear Energy Advantages are Compelling

- Long term domestic and international supply of uranium
- No air pollution by toxic gases or particulates
- No emissions of global warming gases
- Has 1/10,000 smaller solid waste volume than coal.
- US plant reliability record since 2000 is impressive, and among the best in the World.
- Excellent safety record in US: Almost 2500 reactor years since first commercial reactor. A similar number for naval-reactors. One core,TMI-2, melted in 1979, but did not harm public.
- Current economics are favorable to nuclear plants, especially with CO_2 credits

The Challenges are worth addressing

- Issues of radioactivity of waste and proliferation can be managed
- Technology is young, and room for innovation abounds