General Training On Methodologies For Geological Disposal in North America

IAEA Network of Centers of Excellence

Nuclear Fuel Cycle

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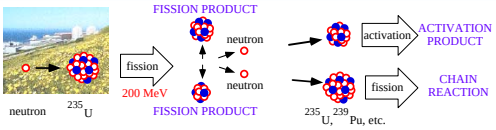
Overview

- Energy production: overview of the byproducts of different approaches to energy production
- Nuclear fuel cycle review
- Spent fuel and high-level waste characteristics
- Advanced fuel cycles and implications for repository capacity

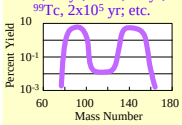
Energy from Nuclear Fission



- Fission Fuel Energy Density: 8.2 x 10^{13} J/kg
- Fuel Consumed by 1000-MW_e Plant: 3.2 kg/day
- **Waste:**

Fission Prod. (3.2 kg/day)

^{90}Sr, 30 yr; ^{137}Cs, 30 yr; ^{99}Tc, 2x10^5 yr; etc.



Activation Products

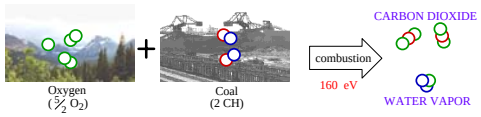
- Fuel → Transuranics, longer half lives (^{239}Pu, 24,000 yr; ^{237}Np, 2x10^6 yr; etc.)
- Structures → Moderate half lives, low-level waste (^{60}Co, 5 yr)
- Coolants → Low (water) to moderate (metals) half lives
- Transmutation → Convert from long to short half life

Mining

Radon from mill tails if not capped

Construction materials

Energy from Fossil Fuels



- 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

Construction Inputs for Several Energy Sources

- Nuclear: 1970's vintage PWR, 90% capacity factor, 60 year life [1]
  - 40 MT steel / MW(average)
  - 190 m^3 concrete / MW(average)
- Wind: 1990's vintage, 6.4 m/s average wind speed, 25% capacity factor, 15 year life [2]
  - 460 MT steel / MW (average)
  - 870 m^3 concrete / MW(average)
- Coal: 78% capacity factor, 30 year life [2]
  - 98 MT steel / MW(average)
  - 160 m^3 concrete / MW(average)
- Natural Gas Combined Cycle: 75% capacity factor, 30 year life [3]
  - 3.3 MT steel / MW(average)
  - 27 m^3 concrete / MW(average)

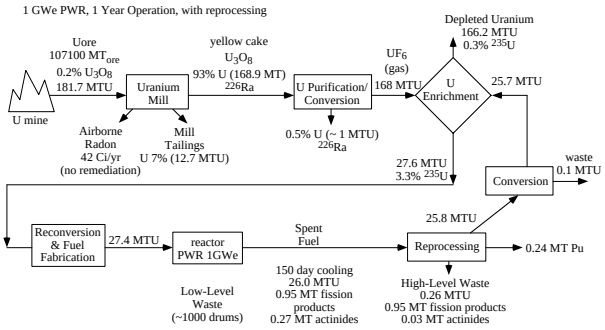
Concrete + steel are >95% of construction inputs

1. R.H. Bryan and I.T. Dudley, "Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant," Oak Ridge National Laboratory, TM-4515, June (1974)
2. S. Pacca and A. Horvath, *Environ. Sci. Technol.*, **36**, 3194-3200 (2002).
3. P.J. Meier, "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," U. WisconsinReport UWFDM-1181, August, 2002.

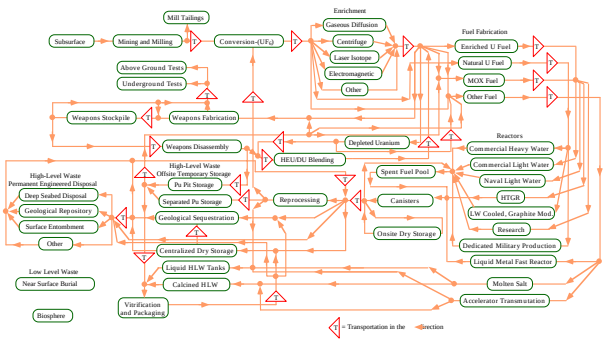
Uranium Use in Different Reactors

	HWR	PWR once-through	PWR recycle	FBR
burnup MWday/ton	6800	33,000	33,000	-
capacity factor	0.8	0.8	0.8	0.8
thermal efficiency	0.3	0.33	0.33	0.4
U consumption/yr	144 MT	201 MT	123 MT	1.5 MT
facilities required	U conversion Fuel Fab.	U conversion Fuel Fab. Enrichment	U conversion Fuel Fab. Enrichment Reprocessing	U conversion Fuel Fab. Reprocessing

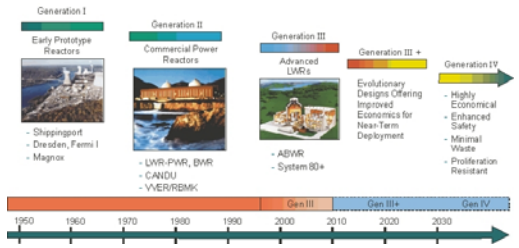
Example: Fuel Cycle Mass Balance



Detailed Summary of Fuel Cycle Facilities



The Generations of Nuclear Energy



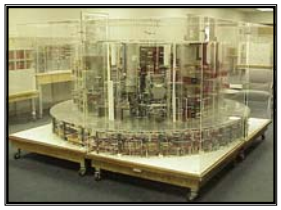
Generation III: The ABWR

- 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 reduces construction time to 52 months

Computer Modeling Simplifies Nuclear Construction

1978: Plastic models on roll-around carts



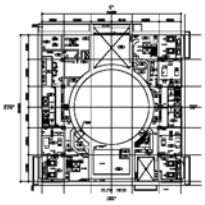
McGuire Nuclear Station Reactor Building Models.

2000: 4-D computer aided design and virtual walk-throughs

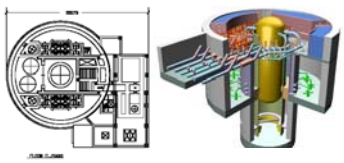
1000 MW Reactor (Lianyungang Unit 1)

Gen III+ Evolution is Toward Reduced Complexity/Materials

The ESBWR is now in pre-certification review at the Nuclear Regulatory Commission



ABWR



ESBWR: >50% reduction in building volume and number of components (~30% reduction in capital cost)

The PBMR is an Example of a Gen III+ Gas-Cooled Reactor

- Pebble Bed Modular Reactor specifications:
  - 165 MWe modular high-temperature helium-cooled gas-turbine reactor
  - Based on 15MWe German AVR that operated from 1967-1989
  - Fuel temperatures:
    - Average fuel: 1095°C
    - Peak fuel shut-down: 1600°C
    - Maximum tolerable: >2000°C
  - Uses helium gas turbine (45% thermal efficiency)
  - 3.5 m diameter x 10 m high graphite lined vessel; 440,000 6-cm diameter pebbles
  - Power controlled by adding or removing helium coolant—no control rods
  - Pebble recycling maintains constant reactivity and achieves very high fuel burnup
  - Construction time estimate: 24 months

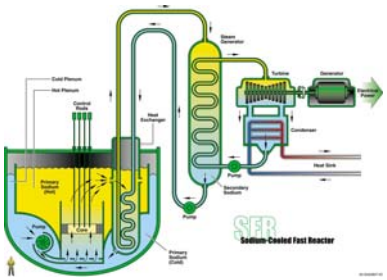
Generation IV Systems

	Neutron Spectrum	*Fuel Cycle*	*Size*	*Applications*	*R&D*
Sodium Cooled Fast Reactor (SFR)	Fast	Closed	Med to Large	Electricity, Actinide Mgmt. (AM)	Advanced Recycle
Lead-alloy Cooled Fast Reactor (LFR)	Fast	Closed	Small to Large	Electricity, Hydrogen Production	Fuels, Materials compatibility
Gas-Cooled Fast Reactor (GFR)	Fast	Closed	Med	Electricity, Hydrogen, AM	Fuels, Materials, Safety
Very High Temp. Gas Reactor (VHTR)	Thermal	Open	Med	Electricity, Hydrogen, Process Heat	Fuels, Materials, H_2 production
Supercritical Water Reactor (SCWR)	Thermal, Fast	Open, Closed	Large	Electricity	Materials, Safety
Molten Salt Reactor (MSR)	Epithermal	Closed	Large	Electricity, Hydrogen, AM	Fuel, Fuel treatment, Materials, Safety and Reliability

Gen IV: Sodium-Cooled Fast Reactor (SFR)

Characteristics
- **Sodium coolant**
- **550°C Outlet Temp**
- **150 to 500 MWe**
- **Metal fuel with pyro processing / MOX fuel with advanced aqueous**

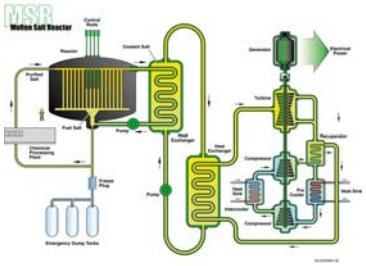
•Benefits
- **Consumption of LWR actinides**
- **Efficient fissile material generation**



Gen IV: Molten Salt Reactor (MSR)

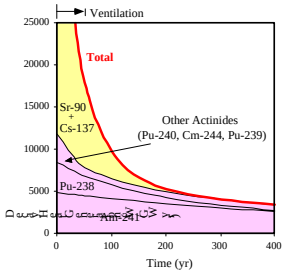
Characteristics
- Fuel: liquid Na, Zr, U and Pu fluorides
- 700-800°C outlet temperature
- 1000 MWe
- Low pressure (<0.5 MPa)

•Benefits
- Waste minimization
- Avoids fuel development
- Proliferation resistance through low fissile material inventory



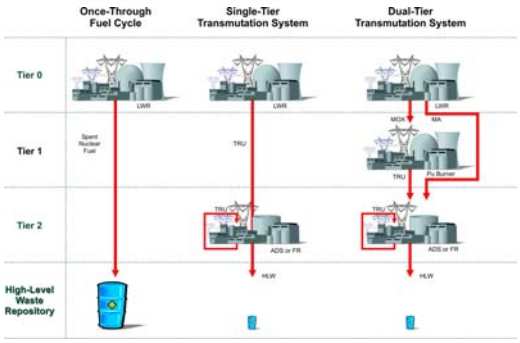
Advanced Fuel Cycles can Impact Repository Performance

- Fission products
  - are produced in direct proportion to fission power
  - dominate early (few decade) decay heat (Cs-137/Sr-90)
  - only modestly affect long-term radiotoxicity
- Actinides
  - dominate spent fuel volume (uranium)
  - dominate intermediate decay heat (particularly Am-241, important for ventilated repositories)
  - can be recycled and fissioned if desired



LWR Spent Fuel Heat Generation

AFCI and AAA System Studies



Economics for Recycle Depend on Several Factors

- Current uranium prices are too low to justify recycle to recover energy in spent fuel
  - Reprocessing and fuel fabrication costs make plutonium recycle to LWRs uneconomic compared to once-through, increases net quantity of minor actinides requiring management
  - Fast reactors have less expensive recycle/fuel fabrication costs, but reactor capital costs are high (~30%) compared to LWRs
- Yucca mountain provides an example for understanding recycle economics
  - When electricity is generated (1 mill/kWhr): ~$310/kg
  - Yucca Mountain cost: ~$540/kg spent fuel
  - Waste fund real interest rate: 2.6% to 4.2%
    after 25 years storage: $590 to $870/kg
  - Current reprocessing costs: $900 to $2500/kg
  - Current fast reactor fuel fabrication: $1400 to $5000/kg

Conclusions

- For Yucca Mountain, the current Waste Fund Fee Adequacy study indicates that spent fuel can be disposed at 1 mill/kWhr, up to the capacity limit set by political/technical requirements
  - Disposal costs for the second repository could be higher (infinite?)
- R&D on advanced fuel cycles has the potential eliminate the need for multiple repositories at modest cost
  - Convergence of waste fund interest accumulation with R&D cost reductions of closed fuel-cycle technology