Nuclear Energy is important, old, new, and complicated

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Ad Delivery Team, Yelp

Advanced Learning Group, 2015–03–16

Outline

I am a devout supporter of nuclear energy

- BSNE at University of Maryland, College Park
  - Became a nuclear reactor operator
  - Spent 4 summers + 1 semester at the U.S. Nuclear Regulatory Commission
- PhDNE at UC, Berkeley and Lawrence Livermore Lab
  - Developed reactor simulations
  - Propagated uncertainties through them
  - Helped design a hybrid fusion-fission reactor
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"Dear future generations: Please accept our apologies, we were roaring drunk on petroleum."
- Kurt Vonnegut

- Coal particulates cause 10 thousand deaths annually in the US
- One quarter of California air pollution is from China
- Climate change is just getting ramped up

- Global energy use will increase by a third by 2040
- Natural gas and oil just got a lot cheaper
- Coal is and always will be cheap

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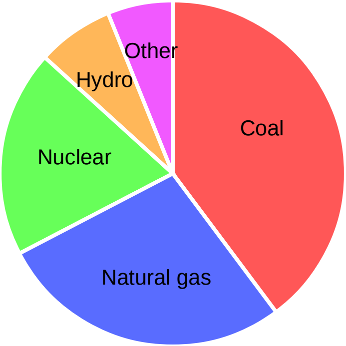
We need a scalable, baseload, carbon-free energy source. Right now!



US elecriticity sources (2014)

- Fossil Fuels generate 66%
- Nuclear generates 20%
- ... and 60% of carbon-free electricity
- Most of “other” is hydro (which is shrinking)
- Renewables are not ready

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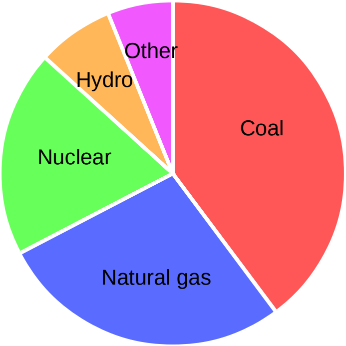

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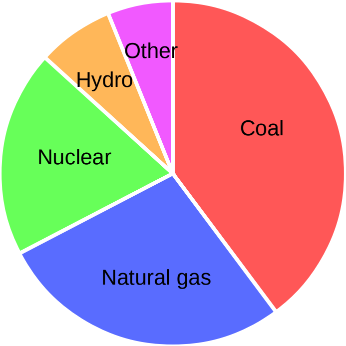

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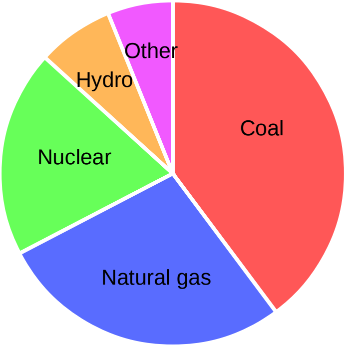

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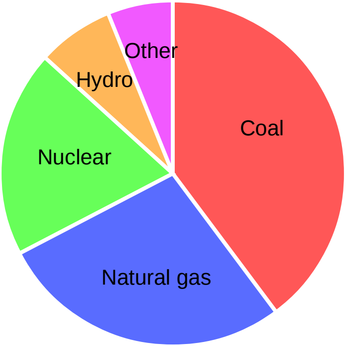

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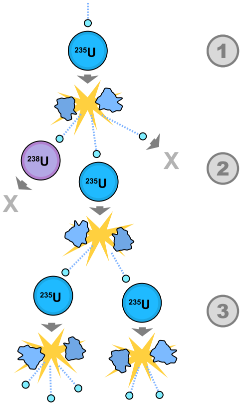
The fission chain reaction is at the heart of nuclear energy

1. A neutron tickles a fissile nucleus
2. ... which fissions into garbage, energy, and 2-3 neutrons
3. ... on average, 1-2 neutrons leak from the system or are consumed in a non-fission reaction
4. ... and 1 survives to cause another fission



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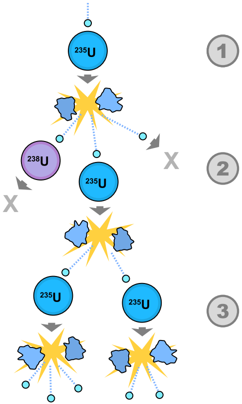

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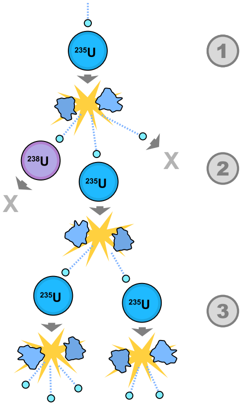

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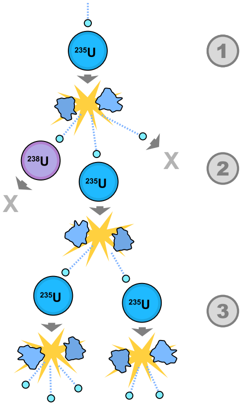
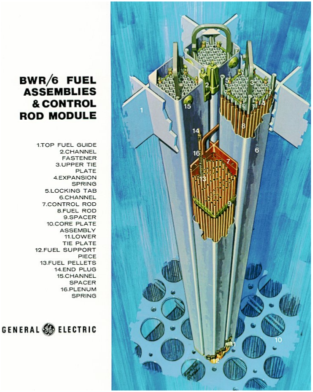
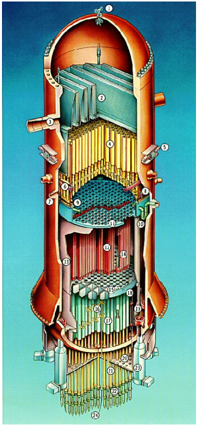


The fission chain reaction

The US nuclear fleet is composed of roughly 100 light water reactors (LWR)

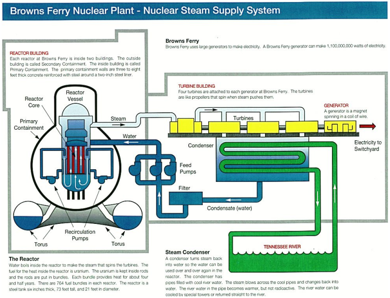


A fuel assembly



A nuclear reactor core

Nuclear reactors power 1800's era steam engines just like coal, oil, and some natural gas



Neutrons to electrons

- Fission chain reaction releases heat
- ... which boils water
- ... which turns a turbine
- ... which rotates a generator
- ... which generates electricity!

- One third of heat energy is converted to electricity

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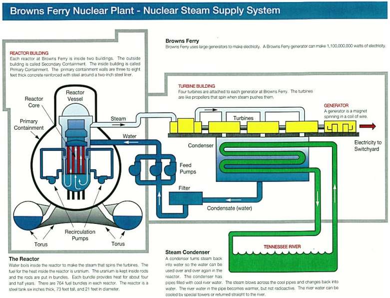

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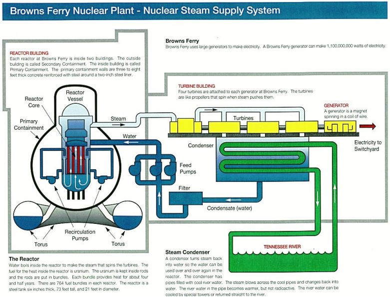

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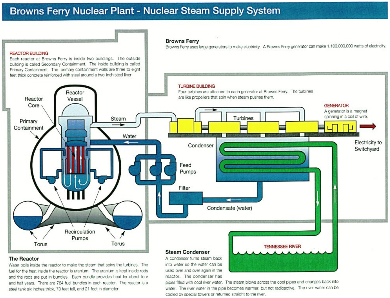

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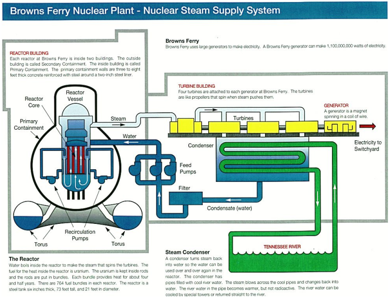

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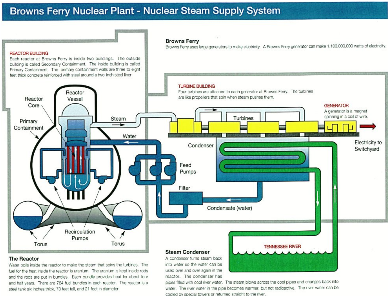

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There is room for improvement

- Spent nuclear fuel is waiting for disposal
- The core needs to be actively cooled
- The fuel can melt
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- The most recent plant was built in 1996
- ... its construction began in 1978
- ... its design process took place in the early 1970's
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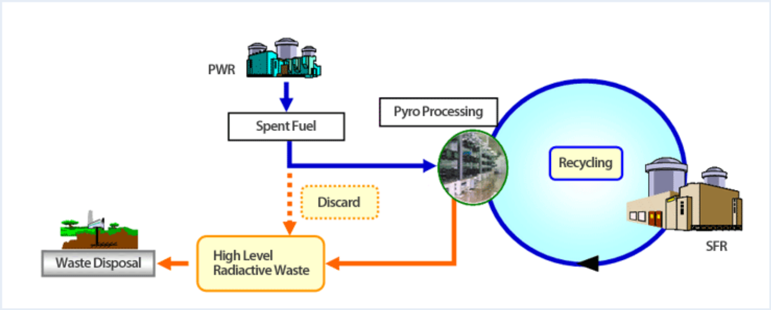
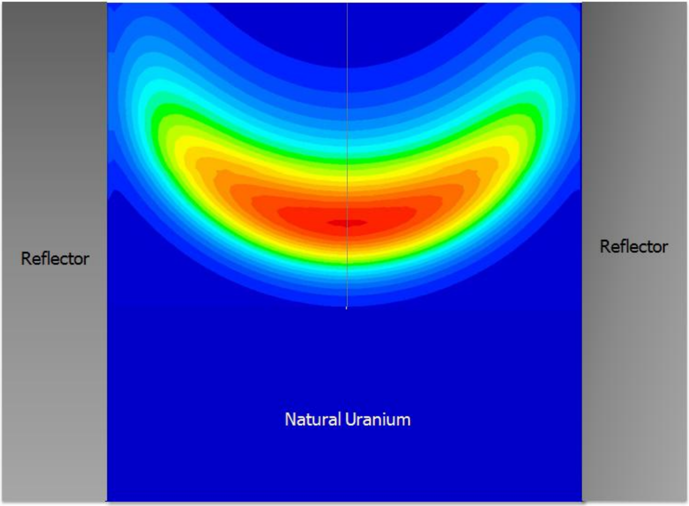
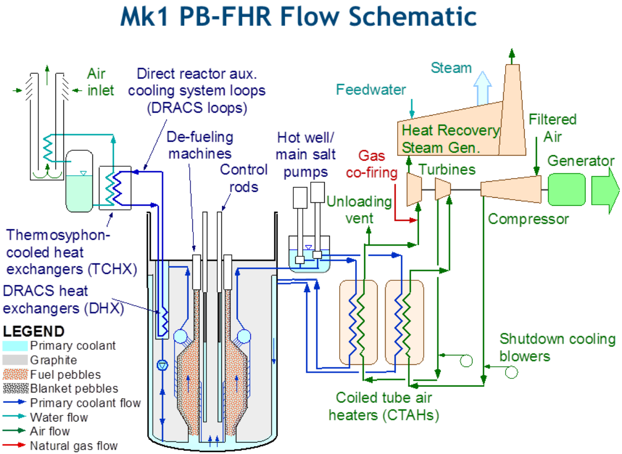
Sodium-cooled Fast reactors (SFR) consume nuclear waste, recycle it, and consume it again



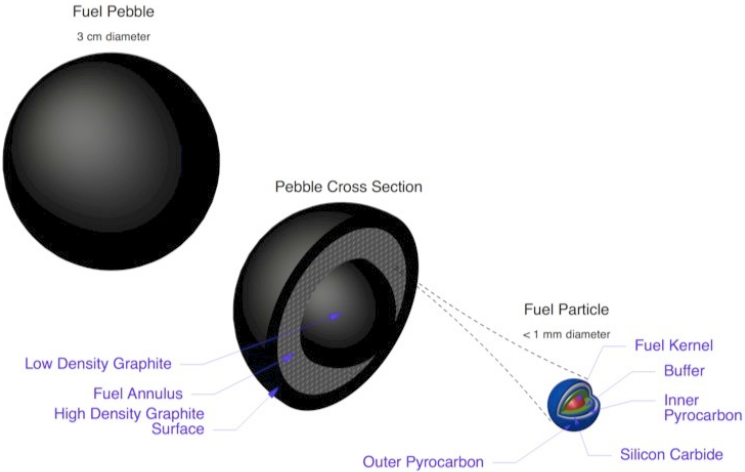
Traveling wave reactors (TWR; Breed & Burn reactors) breed their own fuel without reprocessing



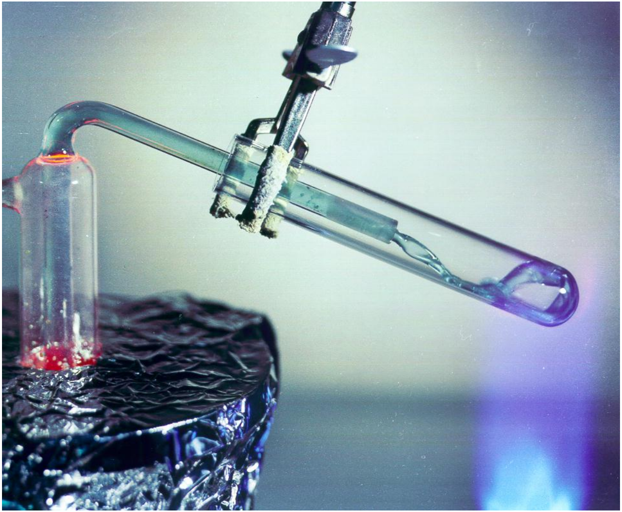
Fluoride-salt high-temperature reactors (FHR) can be passively cooled with ambient air



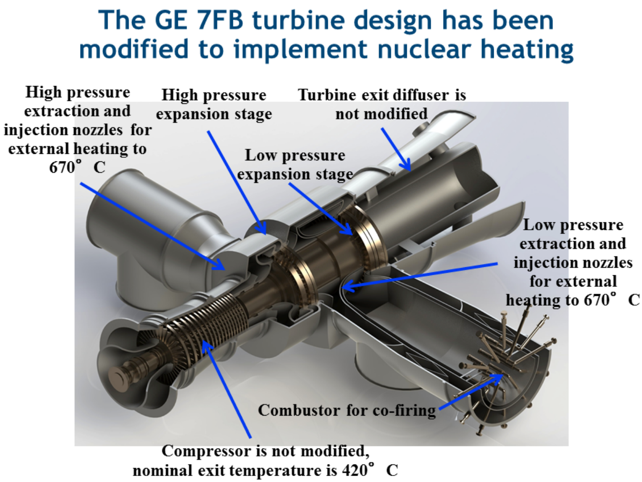
FHR's use coated particle fuel which cannot melt



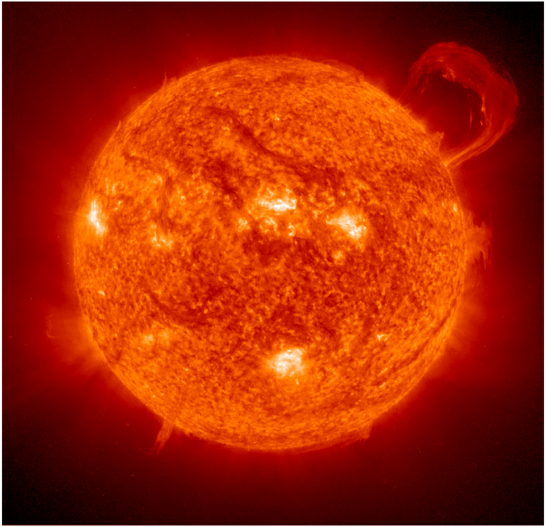
FHR's replace water with fluoride salts which boil at 1430°C



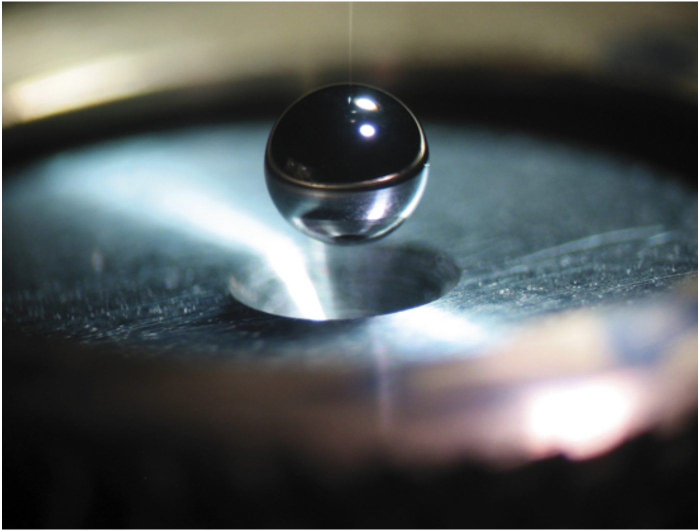
FHR's use modern air turbines which are efficient and offer load following



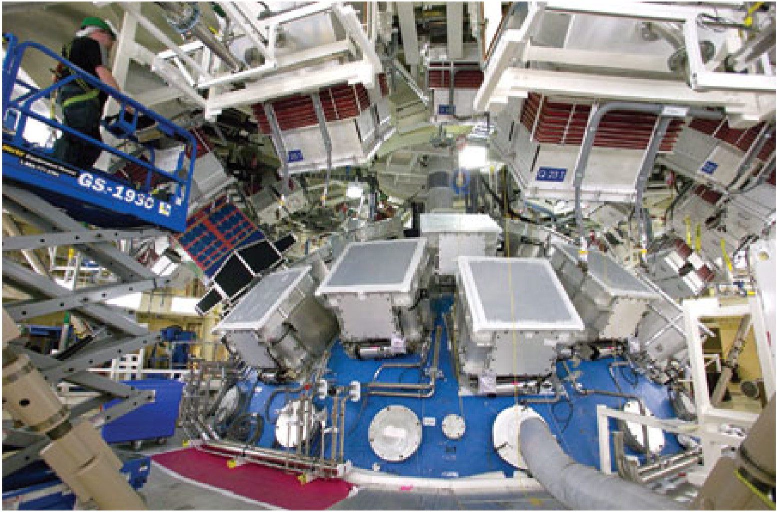
Fusion energy is star power on earth! It produces no carbon or nuclear waste!



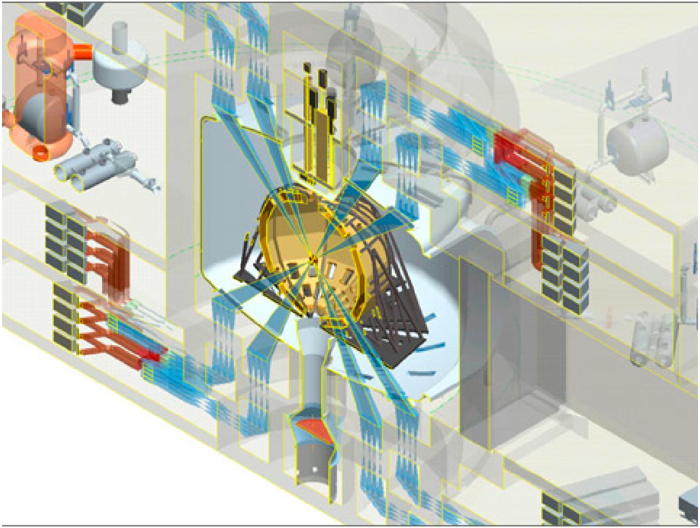
There is enough fusion fuel in the ocean to power humanity until the earth spins into the sun.



However, controlled fusion is really difficult ... the NIF experiment at Livermore came close to break-even



Hybrid fusion-fission reactors will be an economic stepping stone until fusion energy is perfected



Outline

Accurate simulation of neutron fields requires their description 7-dimensional neutron phase space

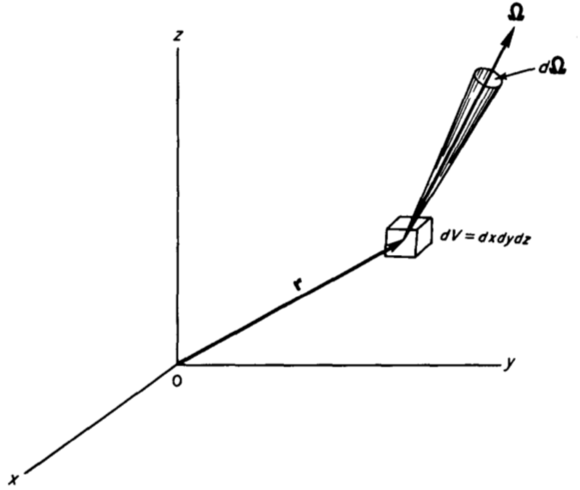
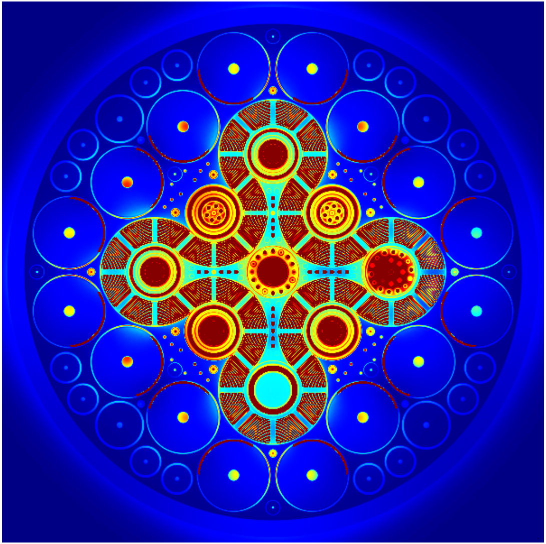


FIG. 1.2 THE VOLUME ELEMENT dV AND THE DIRECTIONAL ELEMENT $d\Omega$.

Spatial distributions ($\vec{r}$) can be complicated



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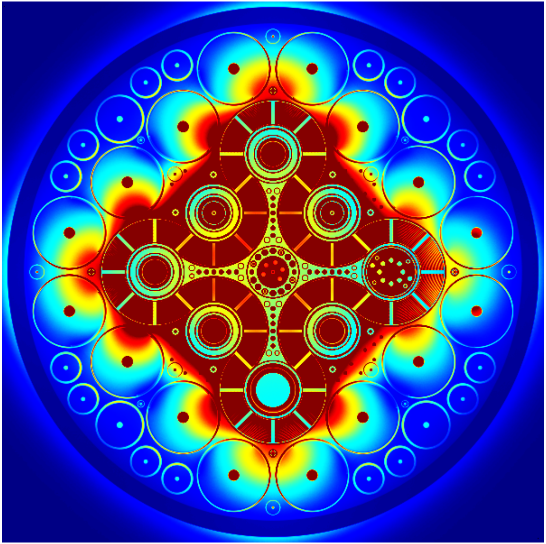

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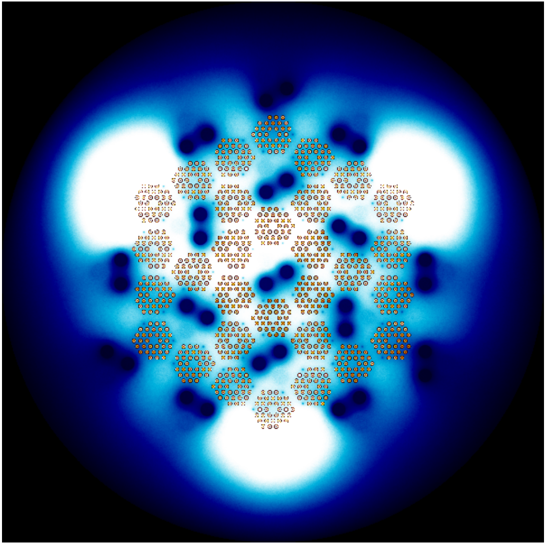

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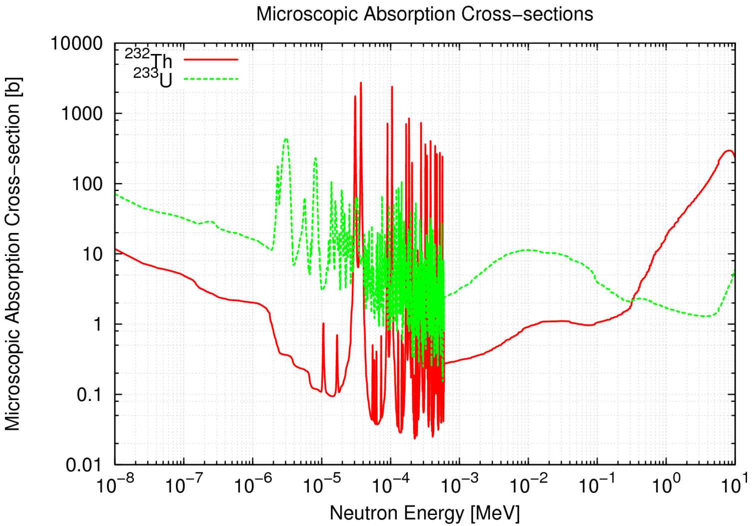

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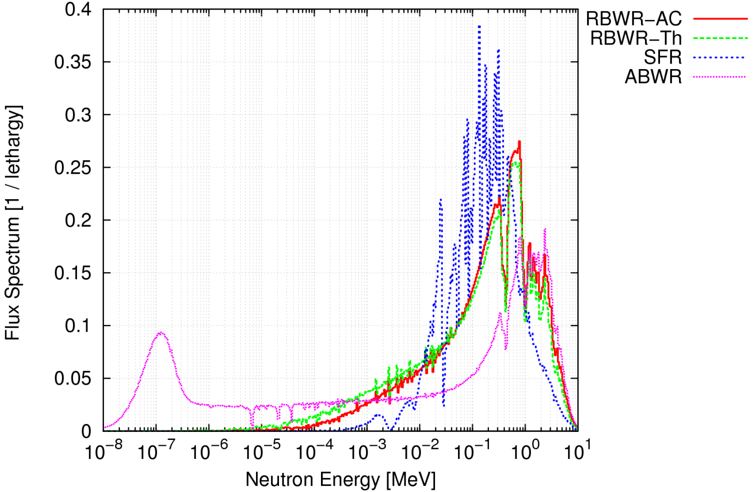

The neutron transport equation (NTE) balances sources and sinks within neutron phase space

$$
\begin{aligned}
&\vec{\Omega} \cdot \vec{\nabla} \;\; \psi(\vec{r}, E, \vec{\Omega}) \\
&+\sigma_{total}(\vec{r}, E) \;\; N(\vec{r}) \;\; \psi(\vec{r}, E, \vec{\Omega}) \\
= \int_0^\infty dE \int_{4\pi} d\vec{\Omega} \;\; &\sigma_{scatter}(\vec{r}, E' \rightarrow E, \vec{\Omega}' \cdot \vec{\Omega}) \;\; N(\vec{r}) \;\; \psi(\vec{r}, E', \vec{\Omega}') \\
&+\frac{\chi(E)}{4\pi} \int_0^\infty dE'' \;\; \nu(E'') \;\; \sigma_{fission}(\vec{r}, E'') \;\; N(\vec{r}) \;\; \psi(\vec{r}, E'', \vec{\Omega}'') \\
&+\mathcal{S}_{ext}(\vec{r}, E, \vec{\Omega})
\end{aligned}
$$

The easiest approach is simplification

- Ignore energy dependence
- Assume direction dependence is isotropic or linearly anisotropic
- Approximate the system as a smeared homogeneous lump
- Assume the spatial/spectral/directional dependencies are separable (e.g., $\psi(\vec{r}, E, \vec{\Omega}) = \mathcal{R}(\vec{r})\mathcal{E}(r)\mathcal{W}(\vec{\Omega})$) and solve them independently

- You can get creative!
- Also, garbage in, garbage out!

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1. Divide spatial regions into cubes or tetrahedra, with interfaces
2. Divide the energy axis into hundreds or thousands of bins
3. Expand directional dependence in spherical harmonics
4. Consider at pseudo-steady-state snapshots in time
5. Write an enormous linear system and iterate until convergence
6. Sweep through the solution in a manner which mimics the physical path of neutrons

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The accurate approach is Monte Carlo neutron transport

1. Assume a source distribution
2. Sample a neutron from it ($\vec{r}$, E, $\vec{\Omega}$)
3. Sample how far the neutron travels before a leak or collision
4. Sample the collision type (e.g., scatter, fission, capture)
5. Sample the collision outcome ($\vec{r}$, E, $\vec{\Omega}$)
6. Iterate until the source distribution converges
7. Consider accelerating with the simpler models above

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Often other solutions need to be coupled and solved simultaneously

- Neutron behavior is strongly dependant upon the density and temperature of water
- Fluids flow (Navier-Stokes)
- Heat spreads (heat equation) and expands things (equation of state of the material)
- Boiling water behaves differently from liquid water (closure relations)
- Solve each one independently (holding the rest constant) and iterate!
- Choose a smart path and consider relaxation for acceleration or stability

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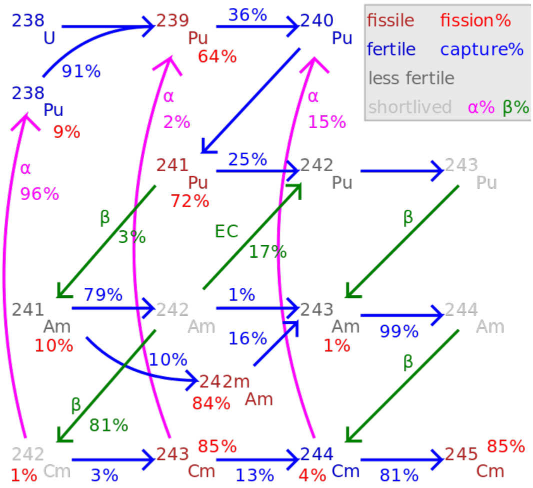
Outline

Isotope depletion, breeding, and decay can be complicated



The Bateman equations describe the time-evolution of isotopes during decay and irradiation

$$
\begin{aligned}
&\frac{\partial N_i(\vec{r},t)}{\partial t} \\
&+\lambda_i \;\; N_i(\vec{r},t) \\
&+\int_0^\infty dE \;\; \sigma_{absorption,i}(\vec{r},E) \;\; \int_{4\pi} d\vec{\Omega} \;\; \psi(\vec{r},E,\vec{\Omega}) \;\; N_i(\vec{r},t) \\
&= \sum_j \left[b_{j\to i} \;\; \lambda_j \;\; N_j(\vec{r},t) \right] \\
&+\sum_k \left[b_{k\to i} \int_0^\infty dE \;\; \sigma_{absorption,k}(\vec{r},E) \;\; \int_{4\pi} d\vec{\Omega} \;\; \psi(\vec{r},E,\vec{\Omega}) \;\; N_k(\vec{r},t) \right]
\end{aligned}
$$

If you take the Laplacian an analytical solution exists!

$$N_n(t) = \Pi_{j=1}^{n-1}\lambda_j \sum_{i=1}^{n}\sum_{j=1}^{n}\left(\frac{N_i(0)e^{-\lambda_j t}}{\Pi_{p=i,p\neq j}(\lambda_p - \lambda_j)}\right)$$

- The formulation is numerically unstable in real cases
- So, on practice, it is solved numerically

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The ODE is homogeneous so it can be written as a linear system

$$\frac{\partial \vec{N}}{\partial t} = \mathbb{T}\vec{N}$$

$$\vec{N}(t) = \vec{N}_0 e^{\mathbb{T}t}$$

$$\vec{N}(t) \approx \mathbb{I} + \mathbb{T}t + \frac{(\mathbb{T}t)^2}{2!} + \dots$$

- $\mathbb{T}$ is large and ill-conditioned in real cases
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- ... new
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