Uranium$^{235/238}$ Light-Water Reactors

2 types: Pressurized-Water (PWRs) & Boiling-Water Reactors (BWRs)

Modern $^{235/238}$U Centrifuge

Workers

First Commercial US Reactor (60MW)

Shippingport, Penn, 1954-56

Fuel Rods

Containment Structure

Pressurizer Steam Generator

Control Rods

Reactor Vessel

Must Contain 160 Atmospheres (>2300psi) of Pressure in Event of Reactor Runaway

~7% Transmission Loss

To/From Cooling Tower, Lake or Sea

Modern Fuel Assemblies. Only ~6% of Uranium is consumed before rods must be removed & stored or reprocessed – ~300 tons Uranium needed per GW-Year.
Uranium Fission

Oklo, Gabon natural reactor

Ivy Mike (U + D) – Enewetak Atoll 1952
www.youtube.com/watch?v=h7vyK0dSTaE

Chernobyl

Radiotoxicity of LWR Spent Fuel

~40 Tons of Waste Containing >600lbs of Transuranics Per GW-Year

Neutron Captures (Transuranics) Long-Lived Wastes

Fission Products Are Short Lived (<1000 Years)

Fission Fragments

Relative CD Hazard

1.0E+04

1.0E+03

1.0E+02

1.0E+01

1.0E+00

1.0E-01

1.0E-02

1.0E-03

100

Time, years

1M
Uranium\textsubscript{235/238} Reactor Wastes

Indian Point NY (~2GW)

Enrichment Waste, U\textsubscript{235}-Depleted Below Ore

Depleted UF\textsubscript{6} in Ohio

1-4 Neutrons + pairs of ~20 other possible Fission fragments like: Rb, Cs, Sr, Xe...

Plus ~200 MeV or ~176 years of an American’s energy use, per kilogram of U\textsubscript{235}.

The Outcasts of Uranium Enrichment for 10% of the LWRs We’d Need to Replace Coal
>90% U Ore Wasted
>250 Tons/GW-Year

### Production from mines (tonnes U)

<table>
<thead>
<tr>
<th>Country</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kazakhstan</td>
<td>3300</td>
<td>3719</td>
<td>4357</td>
<td>5279</td>
<td>6637</td>
<td>8521</td>
<td>13820</td>
</tr>
<tr>
<td>Canada</td>
<td>10457</td>
<td>11597</td>
<td>11628</td>
<td>9862</td>
<td>9476</td>
<td>9000</td>
<td>10173</td>
</tr>
<tr>
<td>Australia</td>
<td>7572</td>
<td>8982</td>
<td>9516</td>
<td>7593</td>
<td>8611</td>
<td>8430</td>
<td>7982</td>
</tr>
<tr>
<td>Namibia</td>
<td>2036</td>
<td>3038</td>
<td>3147</td>
<td>3067</td>
<td>2879</td>
<td>4366</td>
<td>4826</td>
</tr>
<tr>
<td>Russia</td>
<td>3150</td>
<td>3200</td>
<td>3431</td>
<td>3262</td>
<td>3413</td>
<td>3521</td>
<td>3564</td>
</tr>
<tr>
<td>Niger</td>
<td>3143</td>
<td>3282</td>
<td>3093</td>
<td>3434</td>
<td>3153</td>
<td>3032</td>
<td>3243</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>1598</td>
<td>2016</td>
<td>2300</td>
<td>2260</td>
<td>2320</td>
<td>2338</td>
<td>2429</td>
</tr>
<tr>
<td>USA</td>
<td>779</td>
<td>878</td>
<td>1039</td>
<td>1672</td>
<td>1654</td>
<td>1430</td>
<td>1453</td>
</tr>
<tr>
<td>Ukraine (est)</td>
<td>800</td>
<td>800</td>
<td>800</td>
<td>800</td>
<td>846</td>
<td>800</td>
<td>840</td>
</tr>
<tr>
<td>China (est)</td>
<td>750</td>
<td>750</td>
<td>750</td>
<td>750</td>
<td>712</td>
<td>769</td>
<td>750</td>
</tr>
<tr>
<td>South Africa</td>
<td>758</td>
<td>755</td>
<td>674</td>
<td>534</td>
<td>539</td>
<td>655</td>
<td>563</td>
</tr>
<tr>
<td>Brazil</td>
<td>310</td>
<td>300</td>
<td>110</td>
<td>190</td>
<td>299</td>
<td>330</td>
<td>345</td>
</tr>
<tr>
<td>India (est)</td>
<td>230</td>
<td>230</td>
<td>230</td>
<td>177</td>
<td>270</td>
<td>271</td>
<td>290</td>
</tr>
<tr>
<td>Czech Repub.</td>
<td>452</td>
<td>412</td>
<td>408</td>
<td>359</td>
<td>306</td>
<td>263</td>
<td>258</td>
</tr>
<tr>
<td>Malawi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>104</td>
</tr>
<tr>
<td>Romania (est)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>77</td>
<td>77</td>
<td>75</td>
</tr>
<tr>
<td>Pakistan (est)</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>50</td>
</tr>
<tr>
<td>France</td>
<td>0</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Germany</td>
<td>104</td>
<td>77</td>
<td>94</td>
<td>65</td>
<td>41</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>total world</td>
<td>35574</td>
<td>40178</td>
<td>41719</td>
<td>39444</td>
<td>41282</td>
<td>43853</td>
<td>50572</td>
</tr>
<tr>
<td>tonnes U₃O₈</td>
<td>41944</td>
<td>47382</td>
<td>49199</td>
<td>46516</td>
<td>48683</td>
<td>51718</td>
<td>59640</td>
</tr>
<tr>
<td>percentage of world demand</td>
<td>65%</td>
<td>63%</td>
<td>64%</td>
<td>68%</td>
<td>68%</td>
<td>76%</td>
<td></td>
</tr>
</tbody>
</table>
Uranium content of ore is often only 0.1% to 0.2%, so large amounts of rock must be mined:

And tailings piled:

Even in an Australian national park,

or the Navajo Nation…
### The Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>1</td>
</tr>
<tr>
<td>Iron</td>
<td>26</td>
</tr>
<tr>
<td>Gold</td>
<td>79</td>
</tr>
<tr>
<td>Uranium</td>
<td>92</td>
</tr>
<tr>
<td>Neutrons = Protons</td>
<td></td>
</tr>
</tbody>
</table>

**Lanthanides:**
- La
- Ce
- Pr
- Nd
- Pm
- Sm
- Eu
- Gd
- Tb
- Dy
- Ho
- Er
- Tm
- Yb
- Lu

**Actinides:**
- Ac
- Th
- Pa
- U
- Np
- Pu
- Am
- Cm
- Bk
- Cf
- Es
- Fm
- Md
- No

---

**Transuranics**
- U & Pu
- Fission

---

**Neutrons Help Nuclear Stability**

**Star Fusion**

**Supernova Shocks**

**Instability, Radioactive Decay**

**Uranium, 92**

**Bismuth**

**Gold, 79**

---

**Protons Define the Elements**

**Neutrons**

---

**Heaviest Atom Our Sun’s Fusion Can Build**

**Heaviest Atom Any Star’s Fusion Can Build**

---

**Neutrons Help Nuclear Stability**
Power Generation & Health

- We now generate 16 TeraWatts, electric
  - Wasting >50% of gross generation at customers
  - Wasting ~60% of thermal fuel value at power plant
    - Thermal efficiency = \(1 - \frac{T_{\text{cold}}}{T_{\text{hot}}}\)
    - With health & environmental consequences
    - ‘Renewables’ won’t help much
      - Low energy density => huge land/sea usage
      - Need both instantaneous & diurnal storage
      - Biofuels unrealistic with 7% photosynthesis efficiency
      - Solar power <1kW/m\(^2\) maximum in daylight hours
        - But, cell efficiency improving (~20% now, 40% in labs)
        - Not thermal generation, but IR = (1 – Efficiency) kW/m\(^2\)
        - Can meet DG (locally-distributed generation) needs
  - We need high energy-density, localized sources

Public Health Impacts per TWh*

<table>
<thead>
<tr>
<th></th>
<th>Coal</th>
<th>Lignite</th>
<th>Oil</th>
<th>Gas</th>
<th>Nuclear</th>
<th>PV</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years of life lost:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonradiological effects</td>
<td>138</td>
<td>167</td>
<td>359</td>
<td>42</td>
<td>9.1</td>
<td>58</td>
<td>2.7</td>
</tr>
<tr>
<td>Radiological effects:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal operation accidents</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td>0.015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiratory hospital admissions</td>
<td>0.69</td>
<td>0.72</td>
<td>1.8</td>
<td>0.21</td>
<td>0.05</td>
<td>0.29</td>
<td>0.01</td>
</tr>
<tr>
<td>Cerebrovascular hospital admissions</td>
<td>1.7</td>
<td>1.8</td>
<td>4.4</td>
<td>0.51</td>
<td>0.11</td>
<td>0.70</td>
<td>0.03</td>
</tr>
<tr>
<td>Congestive heart failure</td>
<td>0.80</td>
<td>0.84</td>
<td>2.1</td>
<td>0.24</td>
<td>0.05</td>
<td>0.33</td>
<td>0.02</td>
</tr>
<tr>
<td>Restricted activity days</td>
<td>4751</td>
<td>4976</td>
<td>12248</td>
<td>1446</td>
<td>314</td>
<td>1977</td>
<td>90</td>
</tr>
<tr>
<td>Days with bronchodilator usage</td>
<td>1303</td>
<td>1365</td>
<td>3361</td>
<td>397</td>
<td>86</td>
<td>543</td>
<td>25</td>
</tr>
<tr>
<td>Cough days in asthmatics</td>
<td>1492</td>
<td>1562</td>
<td>3846</td>
<td>454</td>
<td>98</td>
<td>621</td>
<td>28</td>
</tr>
<tr>
<td>Respiratory symptoms in asthmatics</td>
<td>693</td>
<td>726</td>
<td>1786</td>
<td>211</td>
<td>45</td>
<td>288</td>
<td>13</td>
</tr>
<tr>
<td>Chronic bronchitis in children</td>
<td>115</td>
<td>135</td>
<td>333</td>
<td>39</td>
<td>11</td>
<td>54</td>
<td>2.4</td>
</tr>
<tr>
<td>Chronic cough in children</td>
<td>148</td>
<td>174</td>
<td>428</td>
<td>51</td>
<td>14</td>
<td>69</td>
<td>3.2</td>
</tr>
<tr>
<td>Nonfatal cancer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Thorium Solution

From the 2010 Thorium Energy alliance Conference...


...Thorium has a special property—it breeds [via neutron/proton capture] to uranium-233 and uranium-233 fissions [more efficiently than U235 or Pu239] and gives off 2 or 3 neutrons that enable it to keep converting more thorium into uranium-233 and burning it. This means that once we start a thorium reactor we can keep it going indefinitely just by adding thorium. But how do we get it started? How much uranium-233 do we need? Well, most of the studies done by Oak Ridge in the 1960s indicated that we could start a one-Gigawatt thorium reactor with about 1 tonne [2200 lbs] of uranium-233. How much do we have right now? About one tonne. So we could only start one reactor, right? With uranium-233, yes, but we need to go about quickly “converting” our fissile materials into uranium-233 so we can start more. Why does it only take one tonne of uranium-233 to start a thorium reactor but it takes 5-10 tonnes of plutonium to start a fast breeder?

Here’s why—things look different when you’re a slowed-down [thermal or moderated] neutron versus a fast neutron [right out of a fission]. When you’re a fast neutron, all of this fuel looks really small to you, and you have a lot less probability of causing fission. So you need a lot more fuel to insure that you get enough collisions with fuel to generate the energy you need. On the other hand, when you’re a slowed-down neutron, each fuel nucleus looks a lot bigger and you have a much better chance of causing a fission. So having slowed-down neutrons makes your fuel go a lot further than using fast neutrons. This is the basic reason why a thorium reactor with slowed-down neutrons can start with a lot less fuel for a given power rating than a fast reactor with fast neutrons. Each little bit of fuel counts for a lot more in a reactor with slowed-down neutrons.

Two breeding technologies provide $10^2$ X more energy than 0.7% U-235.

<table>
<thead>
<tr>
<th>nucleons</th>
<th>Th 90</th>
<th>Pa 91</th>
<th>U 92</th>
<th>Np 93</th>
<th>Pu 94</th>
<th>Am 95</th>
</tr>
</thead>
<tbody>
<tr>
<td>241</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>240</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plutonium</td>
<td>239</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uranium</td>
<td>238</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>237</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>236</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>235</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>234</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thorium</td>
<td>233</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>232</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LMFBR

PWR

LFTR

LWR's U$_{235}$ Fuel-Enrichment Target

Th$_{232}$'s Breeding Target

fertile

fission

beta decay

neutron absorption
The Thorium Solution

We don’t have to limit ourselves to just uranium-233 to start these thorium reactors. We can use the highly-enriched uranium that we’re recovering from all of the nuclear weapons that we are decommissioning to help us. We can use the plutonium we’re recovering from those weapons. We can use the plutonium that’s been generated in our reactors over the last sixty years to help us.

By using slowed-down neutrons and thorium, the startup power of this fuel is magnified by about 1000 to 1500% [10-15 times] over a fast reactor.

So what should we do first? Well, the first thing we should do is stop the Department of Energy’s effort to destroy the one tonne of uranium-233 that we already have. They don’t think that that uranium-233 has any value to their mission and are going to spend $500M to mix it with uranium-238 [Uranium ore] and throw it away in the desert. That’s a bad idea. We’re going to need that one tonne and a whole lot more.

The next step is to get going on the research and development of the liquid-fluoride thorium reactor. This is the machine that can burn thorium as a fuel and only needs about a tonne of U-233 or other fissile material to start it up. The US hasn’t invested any money to develop LFTR since 1974, the year I was born. Other countries are making investments. We need to get going before we get completely left behind on something that we invented.

-------------------------------------------------------------
http://tinyurl.com/29mem3x (Kutsch video)
http://tinyurl.com/2av6row (Hargraves & Moir)
http://tinyurl.com/yedlem (Oliver)
http://tinyurl.com/25mgqkd (Cannara)

Liquid Fuel Reactors

Molten salt coolants

with dissolved uranium and thorium fluorides

promise reactors that can generate electric power cheaper than coal

<table>
<thead>
<tr>
<th>Estimate</th>
<th>Year</th>
<th>$/watt</th>
<th>2009 $/watt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sargent &amp; Lundy</td>
<td>1962</td>
<td>0.650</td>
<td>4.64</td>
</tr>
<tr>
<td>Sargent &amp; Lundy ORNL TM-1060</td>
<td>1965</td>
<td>0.148</td>
<td>1.01</td>
</tr>
<tr>
<td>ORNL-3996</td>
<td>1966</td>
<td>0.243</td>
<td>1.62</td>
</tr>
<tr>
<td>Engel et al, ORNL TM7207</td>
<td>1978</td>
<td>0.653</td>
<td>2.16</td>
</tr>
<tr>
<td>Moir</td>
<td>2000</td>
<td>1.580</td>
<td>1.98</td>
</tr>
</tbody>
</table>
Waste Comparisons

Conventional (LWR): ~40 Tons/GW-Year of Fission Products, Uranium, Transuranics & Associated Reactor Materials

- Enriched uranium fuel
- 96.5% U-238
- 3.5% U-235

x5 Enrichment Over Nature Via Centrifuging UF₆

3% fission products

1% plutonium

- 0.50% Pu-239 FUEL
- 0.25% Pu-240 future FUEL
- 0.15% Pu-241 FUEL

96% uranium

- 0.83% U-235 FUEL
- 0.40% U-236 a poor FUEL
- 94.77% U-238 future FUEL

trace % minor actinides
Np, Am, Cm, ...

Reprocessing Exposure

Conventional LWR Transuranics ~660 lbs/GW-Year

PWR uranium actinides

x10⁴

MSR Transuranics <1-44 lbs/GW-Year

For 30 years total:

<table>
<thead>
<tr>
<th>Fissile requirement</th>
<th>FUJI-U3 (1GWe)</th>
<th>Relative to 1GWe BWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu production</td>
<td>4 kg</td>
<td>0.1%</td>
</tr>
<tr>
<td>MA (Np/Am/Cm)</td>
<td>23 kg</td>
<td>4 %</td>
</tr>
</tbody>
</table>
Uranium$_{235}$ Versus Thorium$_{232}$ Cycle

- **$^{238/235}U$**
  - Mine → Refine → Fluorinate
  - ~300 Tons/GW-Year

- **$^{232}Th$**
  - Mine → Refine → Fluorinate
  - ~30 Tons/GW-Year

**Gas Diffusion** → Enrich $$$ → De-Fluorinate → Centrifuge

- **LWR/PWR/BWR**
  - Make Rods
  - Load Rods
  - Consume <6% of Fuel, Remove Rods
  - Fabricate Waste
  - $$$

- **LFTR/TFTR**
  - Vent Noble Gas
  - (Krypton...)

- **Capture Gas, Fluorinate Out Wastes**
  - $<$6% of Fuel, Remove Rods

- **Store Waste For >10,000 Years**
  - >80,000 lbs/GW-Year $\text{?}$

**Conversion**:

- **Weapons**
  - Remove U & Pu → Fluorinate
  - <8 lbs/GW-Year, ~2 Gas Cylinders

**French Reprocessing**:

- **Contracted Tons**
  - le Hague Processing
  - Completed Tons

**Stored Tons**

- Quantities in storage (ton, barrel, metric)

- **LWR**
  - Initial
  - Enriched
  - Used
  - Spent
  - Spent Fuel

- **PWR**
  - Initial
  - Enriched
  - Used
  - Spent
  - Spent Fuel

- **BWR**
  - Initial
  - Enriched
  - Used
  - Spent
  - Spent Fuel

- **Fast Reactors**
  - Initial
  - Enriched
  - Used
  - Spent
  - Spent Fuel

**Notes**:

- Available at current time, in barrel units.
- Note: The estimated quantity of nuclear waste stored in the storage facility is based on historical data and assumptions about the future evolution of the facility. The actual quantity may vary based on future operations and regulatory changes.

**Sources**:

- WIPP (U.S.) data
- OECD/NEA data
- IAEA data

**Le Hague Processing**

- **Contracted Tons**
  - France
  - Germany
  - Japan
  - Switzerland
  - Belgium
  - Netherlands

- **Completed Tons**
  - France
  - Germany
  - Japan
  - Switzerland
  - Belgium
  - Netherlands
Thorium Schedule & Benefits

A Thorium LFTR could be working in 5 years...

- $1 B  Develop  2010
- $5 B  Scale up  2015
- $70 B per year industry  Produce  Export  2020

One LFTR per day  Commercialize

Rickover’s Shippingport was built in 32 months. (1954)
Weinberg-engineered Oak Ridge X-10 was built in 9 months.

LFTR can make products beyond water desalinization, but we still don’t want to burn hydrocarbons, if we can avoid it, and Nitrogen fertilizers must be used with care...

Dissociate water at 900°C to make hydrogen: sulfur-iodine process.

\[ \text{CO}_2 + 3 \text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O} \]

Methanol for gasoline

Dimethyl ether for diesel

Ammonia for fertilizer