World total primary energy supply from 1971 to 2009 by fuel (Mtoe)

- Coal/peat
- Oil
- Natural gas
- Nuclear
- Biofuels and waste
- Hydro
- Other*

-IEA Key World Energy Stats 2011
World* CO₂ emissions** from 1971 to 2009
by fuel (Mt of CO₂)

-IEA Key World Energy Stats 2011
Uranium Fuel Cycle vs. Thorium

1000 MW of electricity for one year

800,000 tons Ore

35 tons Spent Fuel
Yucca Mountain (~10,000 years)
- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium
- 1.0 t fission products

250 tons Natural uranium

215 tons depleted uranium - disposal plans uncertain

35 tons Enriched Uranium (Costly Process)

Uranium-235 content is “burned” out of the fuel; some plutonium is formed and burned

200 tons Ore

1 ton Natural Thorium

1 Ton Fission products; no uranium, plutonium, or other actinides

Thorium introduced into blanket of fluoride reactor; completely converted to uranium-233 and “burned”

Within 10 years, 83% of fission products are stable and can be partitioned and sold.

The remaining 17% fission products go to geologic isolation for ~300 years.
<table>
<thead>
<tr>
<th>16</th>
<th>LEAD</th>
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<tbody>
<tr>
<td>15</td>
<td>GALLIUM</td>
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<td>GADOLINIUM</td>
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<td>BERYLLIUM</td>
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<tr>
<td>1.5</td>
<td>TIN</td>
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</table>

1000 ppG
1 TUNGSTEN
1 MOLYBDENUM
0.2 MERCURY
0.1 SILVER
0.018 URANIUM-235
0.005 PLATINUM
0.002 GOLD

Fig. 5.13. The chemical composition of the Earth’s crust.
Thorium Concentrations

Source of data: U.S. Geological Survey Digital Data Series DDS-9, 1993

<table>
<thead>
<tr>
<th>Country</th>
<th>RAR Th</th>
<th>EAR Th</th>
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<tbody>
<tr>
<td>Australia</td>
<td>489,000</td>
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<tr>
<td>USA</td>
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<td>&quot;Other countries&quot;</td>
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<tr>
<td>&quot;World total&quot;</td>
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</table>
Energy Extraction Comparison

Uranium-fueled light-water reactor: 35 GW*hr/MT of natural uranium

Conversion to UF₆

365 MT of natural UF₆ (247 MT U)

Conversion and fabrication

39 MT of enriched (3.2%) UO₂ (35 MT U)

32,000 MW*days/tonne of heavy metal (typical LWR fuel burnup)

33% conversion efficiency (typical steam turbine)

3000 MW*yr of thermal energy

1000 MW*yr of electricity

Thorium-fueled liquid-fluoride reactor: 11,000 GW*hr/MT of natural thorium

Conversion to metal

Thorium metal added to blanket salt through exchange with protactinium

0.8 MT of thorium metal

0.8 MT of $^{233}$Pa formed in reactor blanket from thorium (decays to $^{233}$U)

914,000 MW*days/MT $^{233}$U (complete burnup)

50% conversion efficiency (triple-reheat closed-cycle helium gas-turbine)

2000 MW*yr of thermal energy

1000 MW*yr of electricity

Uranium fuel cycle calculations done using WISE nuclear fuel material calculator: http://www.wise-uranium.org/hfcm.html
Energy Generation Comparison

6 kg of thorium metal in a liquid-fluoride reactor has the energy equivalent (66,000 MW*hr electrical*) of:

230 train cars (25,000 MT) of bituminous coal or 600 train cars (66,000 MT) of brown coal,

or, 440 million cubic feet of natural gas (15% of a 125,000 cubic meter LNG tanker),

*Each ounce of thorium can therefore produce $14,000-24,000 of electricity (at $0.04-0.07/kW*hr)

or, 300 kg of enriched (3%) uranium in a pressurized water reactor.
Multiple Layers of Safety at Nuclear Power Plants

- **Shield Building Wall**
  - Three-foot thick reinforced concrete metal reinforcement
  - 2.5-inch diameter steel rods spaced one foot apart

- **Containment Vessel**
  - 1.5-inch steel cylinder
  - 182 feet tall

- **Dry Well Wall**
  - Metal reinforcement
  - 2.5-inch diameter steel rods spaced one foot apart
  - Five-foot thick reinforced concrete

- **Bio Shield**
  - Four-foot thick leaded concrete with one-inch thick interior and exterior steel lining

- **Reactor Vessel**
  - 70 feet tall
  - 21 feet in diameter
  - High Tensile Steel four to eight inches thick

- **Reactor Fuel**

- **Weir Wall**
  - 1.5-foot thick concrete
  - 24 feet tall

- **Pedestal**
  - Six-foot thick concrete with one-inch thick interior and exterior steel lining

Boiling Water Reactor
The reactor is equipped with a “freeze plug”—an open line where a frozen plug of salt is blocking the flow.

The plug is kept frozen by an external cooling fan.

In the event of TOTAL loss of power, the freeze plug melts and the core salt drains into a passively cooled configuration where nuclear fission and meltdown are not possible.
Molten Salt Reactor Experiment

Bldg. 7303, Oak Ridge National Laboratory