Liquid Fuel Fast Reactors and the Future of Nuclear Power

14^{th} Nucleon-Nucleus Conference

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In their meeting in 2022 the Ministers from the International Energy Agency's 31 Member Countries said in a joint communiqué:

> *Achieving net zero emissions by mid-century would give the world an even chance of limiting the rise in global temperatures to 1.5 °C, which is a critical threshold for avoiding the worst effects of climate change.*

The final COP28 Decision Text which was adopted at the end of conference, recognizes the need for:

> *Deep, rapid and sustained reductions in GHG emissions in line with 1.5 °C pathways and calls for global efforts to accelerate zero- and low-emission technologies, including nuclear, renewables, and abatement and removal technologies such as carbon capture and utilization and storage.*

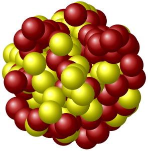
COP28 also saw 22 world leaders sign a declaration to make efforts to triple nuclear energy by 2050. The declaration, announced by President of France Emmanuel Macron on 2 December 2023, referenced 2022 NEA analysis which found that tripling nuclear energy capacity by 2050 would significantly help countries reach their net zero carbon emission targets while creating and maintaining energy security.

Elements used in nuclear power:

- Fissionable elements:
  - ${}_{92}U^{235}$ ($h_{\frac{1}{2}} = 7.04 \times 10^8 y$, 0.72%)
  - ${}_{92}U^{238}$ ($h_{\frac{1}{2}} = 4.47 \times 10^9 y$, 99.3%)
  - ${}_{92}U^{233}$ ($h_{\frac{1}{2}} = 1.59 \times 10^5 y$)
  - ${}_{92}U^{235}$
  - ${}_{94}Pu^{239}$($h_{\frac{1}{2}} = 2.41 \times 10^4 y$), trace
- Fertile elements:
  - ${}_{92}U^{238}$
  - ${}_{92}U^{235}$
  - ${}_{90}Th^{232}$($h_{\frac{1}{2}} = 1.41 \times 10^{10} y$, 100%)

Composition of Natural Uranium

$_{92}U^{235}$



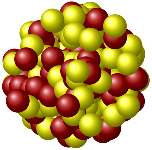
143 Neutrons

92 Protons

0.72% of Natural U

Highly Fissionable with Thermal Neutrons

$_{92}U^{238}$



146 Neutrons

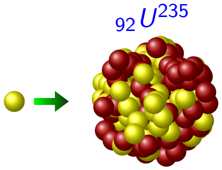
92 Protons

99.28% of Natural U

Moderately Fissionable

Highly Convertible to Pu with Fast Neutrons

Nuclear Fission:Induced



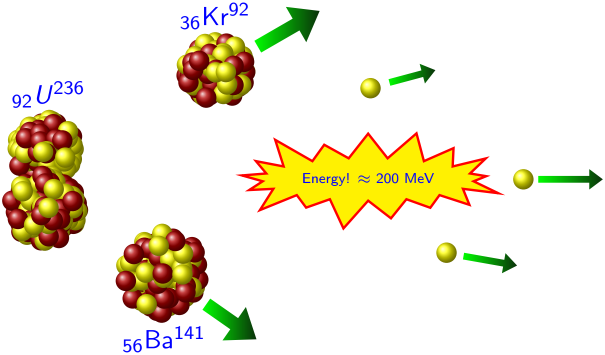
Nuclear Fission:Induced

$\approx$ 200 MeV $= 3.20\times10^{-11}$J, but

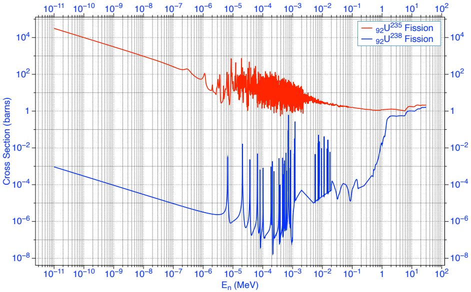
1kg U^{235} has: 2.56×10^{24}atoms

1kg U^{235} produces: 8.21×10^{13}J

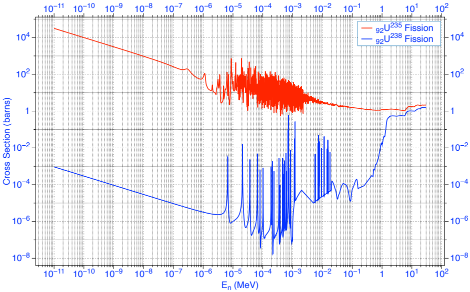
1kg U^{235} in 1y produces: 2.60×10^{6} W



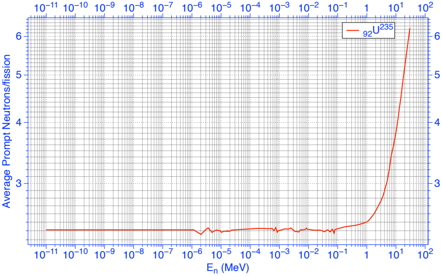
U^{235}



U^{235}

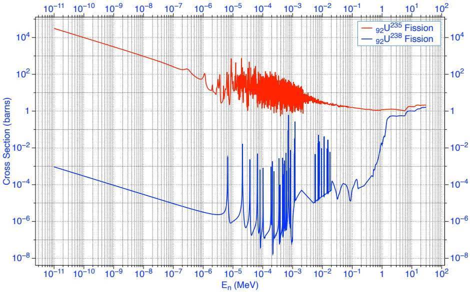


$_{92}U^{235}$ Fission
$_{92}U^{238}$ Fission
Cross Section (barns)
E_n (MeV)

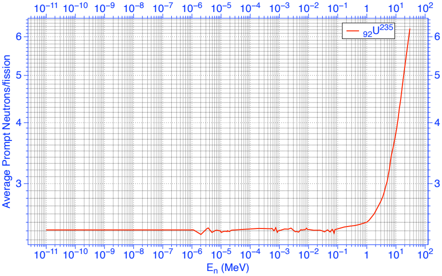


$_{92}U^{235}$
Average Prompt Neutrons/fission
E_n (MeV)

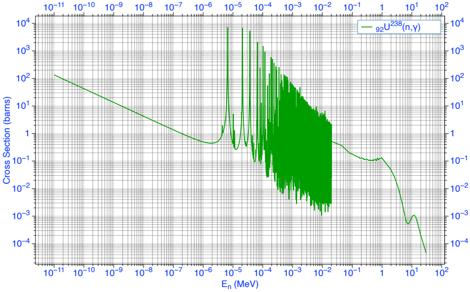
U^{235}



$_{92}U^{235}$ Fission
$_{92}U^{238}$ Fission
Cross Section (barns)
E_n (MeV)

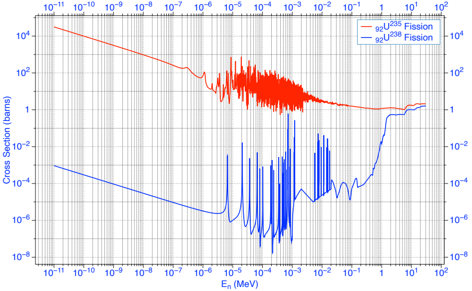


$_{92}U^{235}$
Average Prompt Neutrons/fission
E_n (MeV)

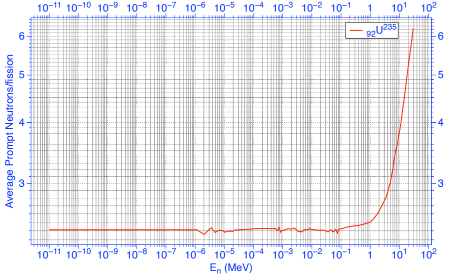


$_{92}U^{238}(n,\gamma)$
Cross Section (barns)
E_n (MeV)

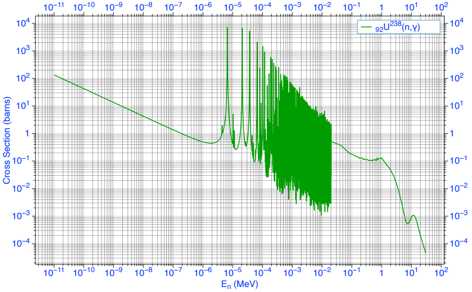
U^{235}



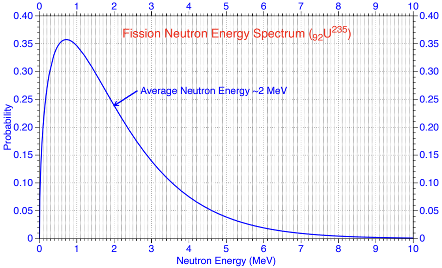
92U235 Fission
92U238 Fission
Cross Section (barns)
En (MeV)



92U235
Average Prompt Neutrons/fission
En (MeV)

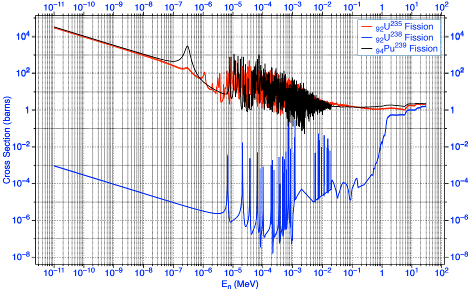


92U238(n,γ)
Cross Section (barns)
En (MeV)

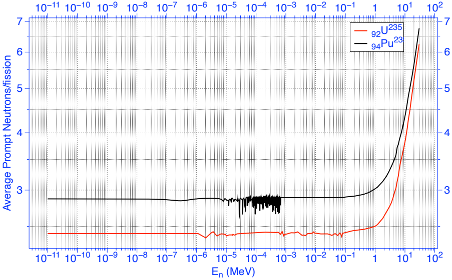


Fission Neutron Energy Spectrum (92U235)
Average Neutron Energy ~2 MeV
Probability
Neutron Energy (MeV)

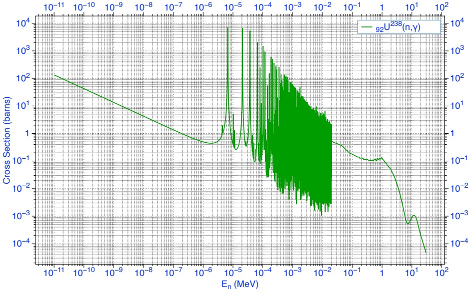
U^{235}



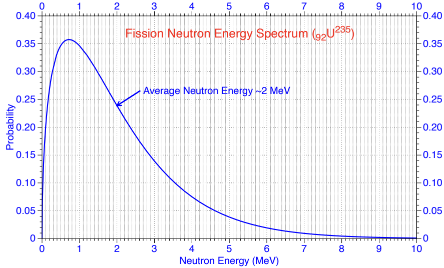
$_{92}U^{235}$ Fission
$_{92}U^{238}$ Fission
$_{94}Pu^{239}$ Fission
Cross Section (barns)
E_n (MeV)



$_{92}U^{235}$
$_{94}Pu^{23}$
Average Prompt Neutrons/fission
E_n (MeV)



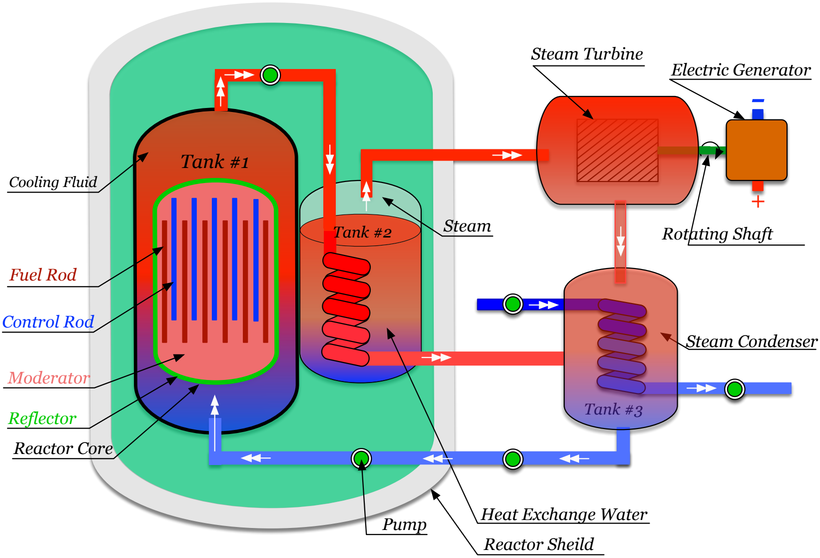
$_{92}U^{238}(n,\gamma)$
Cross Section (barns)
E_n (MeV)



Fission Neutron Energy Spectrum ($_{92}U^{235}$)
Average Neutron Energy ~2 MeV
Probability
Neutron Energy (MeV)

Current Nuclear Power

- Current nuclear power reactors (up to GIII+) suffers from many serious problems
- They use solid fuel, thermal neutrons, and pressurized water (PWR) lead to:
  - Very low efficiency
  - Very complex designs
  - High construction costs due to:
    - ★ Very expensive pressure tank ($>$70 atm) to raise the boiling temperature of water to $\sim$300 $^\circ$C
    - ★ Addition of a "moderator" to reduce fast neutron energy to thermal energy
    - ★ Control rods for output control and shutdown
  - Very long construction times
  - High fuel cost due to use of ${}_{92}U^{235}$ thermal fission that requires enriched fuel to $\sim$ 5.0 - 20%, instead of 0.7%
  - Long life radioactive waste
  - Vulnerable to core meltdown (three Miles Island and Fukushima incidents)


Steam Turbine
Electric Generator
Tank #1
Cooling Fluid
Tank #2
Steam
Rotating Shaft
Fuel Rod
Control Rod
Steam Condenser
Moderator
Tank #3
Reflector
Reactor Core
Heat Exchange Water
Pump
Reactor Sheild

1. In spite of this, PWRs are much better than Fossil fuels, Solar Panels, and Wind Mills
   - No emission of green house gases (GHG) during operation
   - Cost of electricity still competitive
   - “Higher” Energy Returned on Energy Invested (EROI)
   - 1 GW_e reactor produces ∼1 cubic meter of waste/year

1. Can Nuclear Power do bette?
2. The answer is Yes, much better actually on all counts

More Disturbing News

1. Neutrons induce fission, but also
2. Get absorbed in Uranium and other material to produce Radioactive Nuclei mostly heavier than uranium. Examples:
3. ${}_{92}U^{235} + {}_{0}n^{1} \longrightarrow {}_{92}U^{236} + \gamma$
4. ${}_{92}U^{236} + {}_{0}n^{1} \longrightarrow {}_{92}U^{237} \xrightarrow[\text{n to p}]{\beta^-} {}_{93}Np^{237}$
5. ${}_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239} \xrightarrow[\text{n to p}]{\beta^-} {}_{93}Np^{239} \xrightarrow[\text{n to p}]{\beta^-} {}_{94}Pu^{239}$
6. ${}_{92}U^{238} + {}_{0}n^{1} \longrightarrow 2\times({}_{0}n^{1}) + {}_{92}U^{237} \xrightarrow[\text{n to p}]{\beta^-} {}_{93}Np^{237}$

The Bad News

Table: Some of the radioactive elements in PWR waste

Element	Half Life	Unit	Activity
$_{92}U^{235}$	7.00×10^8	years	Fission, α, β, γ
$_{92}U^{236}$	2.34×10^7	years	α
$_{92}U^{238}$	4.50×10^9	years	Slight fast fission, α, Pu
$_{93}Np^{237}$	2.10×10^6	years	Fission, α, β
$_{93}Np^{239}$	2.34	days	β
$_{94}Pu^{239}$	2.40×10^4	years	High fast Fission, α

The Good News, Liquid Fuel?

A liquid fuel experimental nuclear reactor, called "Molten Salt Reactor Experiment MSRE[1]" was designed and built at Oak Ridge National laboratory in 1960 with following properties:[2]

1. A 7.4 MW_{th} thermal reactor operated at 635 °C
2. It used one fluid as fuel and primary coolant
3. The fluid was a molten salt that has many chemical elements: LiF-BeF_2-ZrF_4-UF_4
4. The Uranium in the fluid was $_{92}U^{235}$
5. It also had a secondary coolant: $2LiF$-BeF_2
6. MSRE successfully demonstrated the use of "Fuse Plugs" as an excellent safety feature (more on that later)
7. MSRE was design to also use Thorium as a breeder reactor, but never been used that way
8. The reactor went critical in June 1965 and was shut down in December 1969

[1] P.N. Haubenreich & J.R. Engel (1970). ""Experience with the Molten-Salt Reactor Experiment". Nuclear Applications and Technology. 8 (2): 118–136. doi:10.13182NT8-2-118

[2] https://en.wikipedia.orgwiki/Molten-Salt_Reactor_Experiment

The Good News, Liquid Fuel?

The MSRE was an excellent concept, however, it wast not an optimum design:

1. Using one fluid as fuel and coolant forced a compromise: less efficient fuel and less efficient coolant.
2. The use of a molten salt forced the operation at a relatively low temperature, reducing efficiency of heat transfer
3. One complex fluid reduced the fuel density resulting in less energy production.

The Good News, Liquid Fuel?

Can we do better using liquid fuel?

The Better News, The Dual Fluid Reactor!

The Dual Fluid Reactor (DFR):

1. Two separate fluids: one for fuel and another for cooling
2. The coolant is molten lead
3. The fuel is molten “NaturalUranium-Chromium” eutectic alloy
   - Uranium melts at 1132 °C , boils at 3818 °C
   - Cr melts at 1890 °C , boils at 2482 °C
   - U-Cr eutectic (80% - 20% atom) melts at 859 °C
   - Pb melts at 327.5 °C , boils at 1749 °C
4. A fast breeder: converts ${}_{92}U^{238}$ to fast fissionable ${}_{94}Pu^{239}$
5. Consumes ∼100% of core fuel and can use any of the following:
   - Natural Uranium or Natural Thorium
   - Uranium from the waste of current PWRs
   - Uranium and Plutonium from dismantled bombs
6. DFR operates at ≃1000 °C and atmospheric pressure.
7. No moderator or control Rods
8. No mechanical part in core
9. extensive use of fuse plugs

Important Issues

Many Fast breeder reactors were build world wide over the years. However, they were mostly prototypes, or research reactors. Only one I am aware of was used to desalinate sea water. Most used Sodium as a coolant. None, so far, has been developed for use in the civilian energy sector.

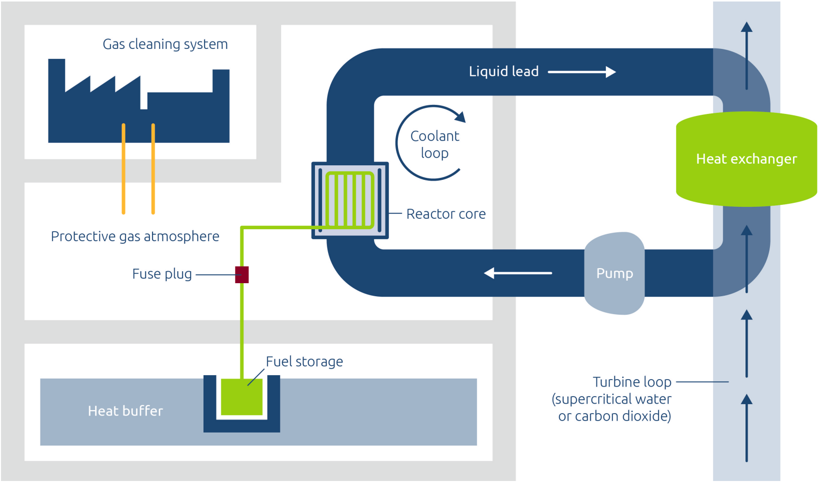
This led to many difficulties in developing fast reactors to be used in the civilian energy sector, for example:

- Choice of fuel
- Choice of core and structure materials
- Emergency shut down
- Siting
- Licensing
- Financeing

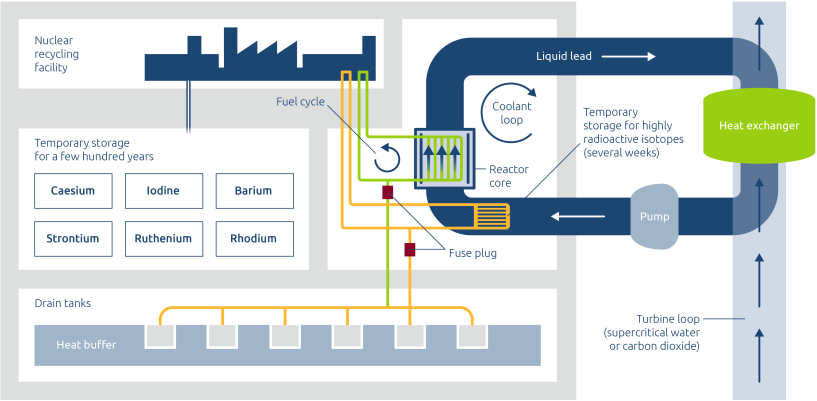
DFR Basic Concept

MAKE IT SIMPLE, AS SIMPLE AS POSSIBLE BUT NO SIMPLER

ALBERT EINSTEIN



DFR 300 MW_e

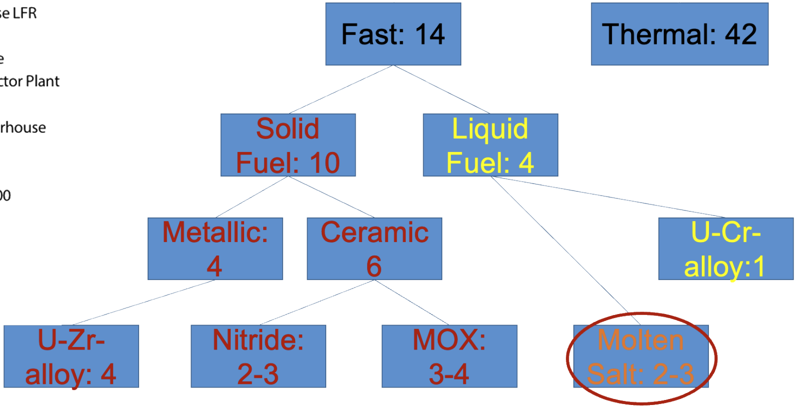

Nuclear recycling facility
Fuel cycle
Temporary storage for a few hundred years
Caesium
Iodine
Barium
Strontium
Ruthenium
Rhodium
Liquid lead
Coolant loop
Reactor core
Temporary storage for highly radioactive isotopes (several weeks)
Heat exchanger
Pump
Fuse plug
Drain tanks
Heat buffer
Turbine loop (supercritical water or carbon dioxide)

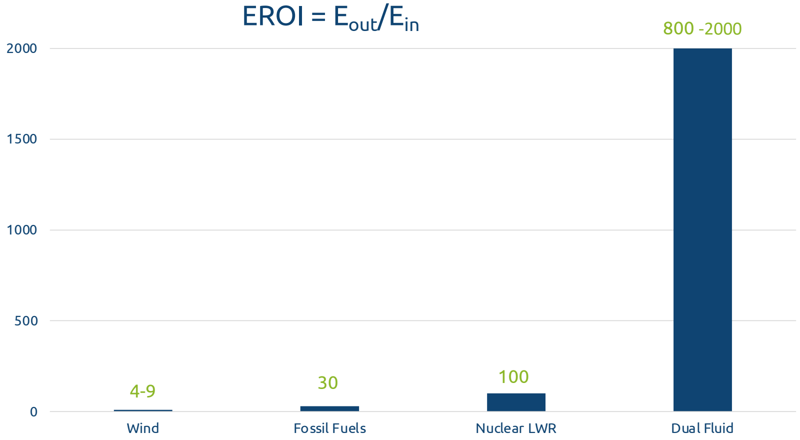
Cost of Electricity

- Cost Estimate
  - Price of electricity and industrial heat will be comparable or cheaper than fossil fuels (based on 2020 prices)
  - Natural Gas 7-9.5 ¢/MWh
  - Nuclear power today 6.5 ¢/MWh
  - DFR300 2.7 ¢/MWh
  - DFR1500 2.1 ¢/MWh

56 SMR concepts in NEA Dashboard

- Westinghouse LFR
- 4S
- Thorizon One
- Natrium Reactor Plant
- Otrera 300
- Aurora Powerhouse
- LFR-AS-200
- XAMR
- BREST-OD-300
- SSR-W
- HEXANA
- DF300
- SEALER-55
- ARC-100




EROI = Eout/Ein
2000
1500
1000
500
0
4-9
30
100
800 -2000
Wind
Fossil Fuels
Nuclear LWR
Dual Fluid

DFR Modul Engineering Concept

It's kind of disappointing that they make solar energy panels.

'Running shoes?'

The Bad News

Table: Partial list of fission products of $_{92}U^{235}$ in PWR waste

Yield	Element	Isotope	Half Life	Unit
6.79%	Caesium	$Cs^{133} \rightarrow Cs^{134}$	2.065	years
6.33%	Iodine, xenon	$I^{135} \rightarrow Xe^{135}$	6.57	hours
6.30%	Zirconium	Zr^{93}	1.53×10^6	years
6.10%	Molybdenum	Mo^{99}	2.75	days
6.09%	Caesium	Cs^{137}	30.17	years
6.05%	Technetium	Tc^{99}	2.11×10^5	years
5.75%	Strontium	Sr^{90}	28.9	years
2.83%	Iodine	I^{131}	8.02	d
2.27%	Promethium	Pm^{147}	2.62	years
1.09%	Samarium	Sm^{149}	virtually stable	
0.90%	Iodine	I^{129}	1.57×10^7	years
0.42%	Samarium	Sm^{151}	90.00	years
0.39%	Ruthenium	Ru^{106}	1.02	years
0.27%	Krypton	Kr^{85}	10.78	years
0.16%	Palladium	Pd^{107}	6.50×10^6	years
0.05%	Selenium	Se^{79}	3.27×10^5	years
0.03%	Europium, gadolinium	$Eu^{155} \rightarrow Gd^{155}$	4.76	years
0.03%	Antimony	Sb^{125}	2.76	years
0.02%	Tin	Sn^{126}	2.30×10^5	years
0.01%	Gadolinium	Gd^{157}	stable	