Nuclear Power Plants

Sustainability Profile

Nuclear Energy

- ~100 nuclear reactors in the United States generating ~20% of US electricity; no newly operating plants between 1996 and 2016; Watts Bar 2 in Tennessee is the new US plant; Vogtle 3 and 4 in Georgia to come on-line in 2021 and 2022

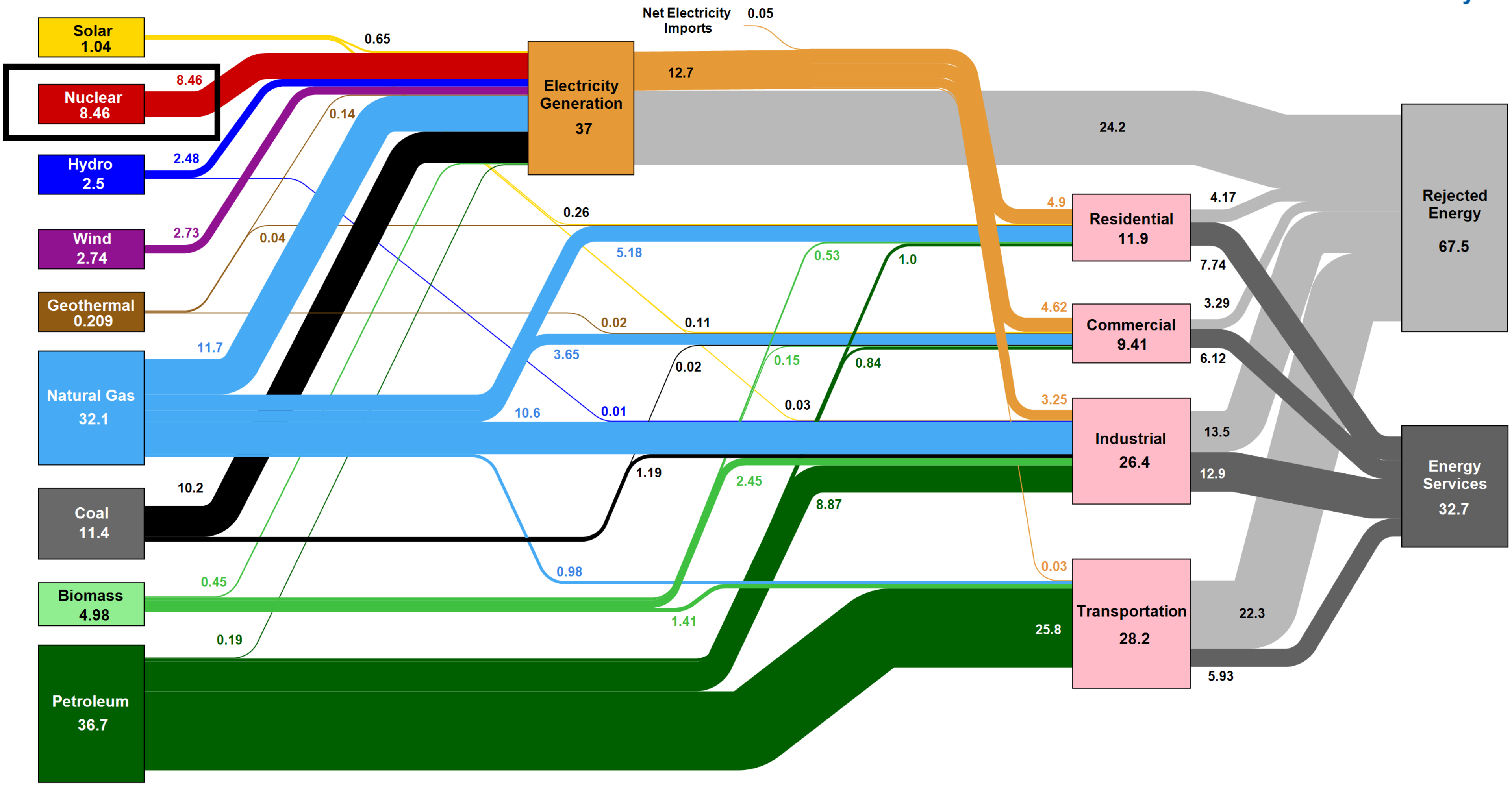
- ~450 nuclear reactors worldwide. France generates ~80 of its electricity from nuclear power

- PROS: no CO_2 emissions; dispatchable (available 24/7) vs. variable or intermittent (as with solar and wind); energy dense—1 million times as energy dense as hydrocarbon fuels

- CONS: storage of hazardous nuclear waste; nuclear weapons proliferation; expensive initial investment; risk of nuclear accidents (Three Mile Island in 1979; Chernobyl in 1986; Fukushima Dai-ichi in 2010)

Estimated U.S. Energy Consumption in 2019: 100.2 Quads

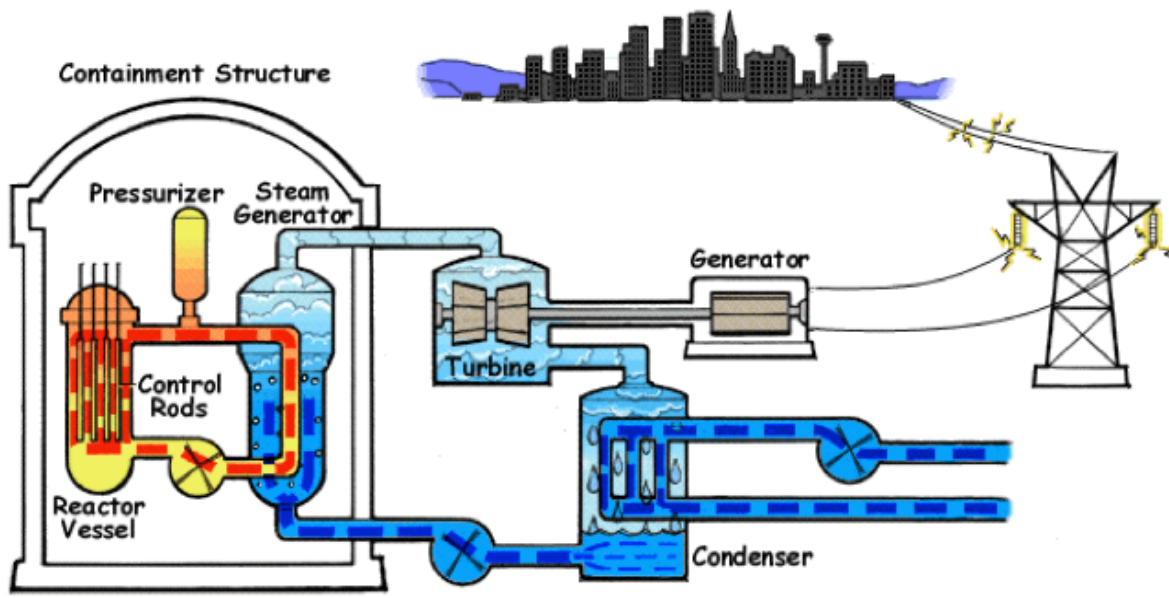
Lawrence Livermore National Laboratory



Source: LLNL March, 2020. Data is based on DOE/EIA MER (2019). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Light Water Reactor

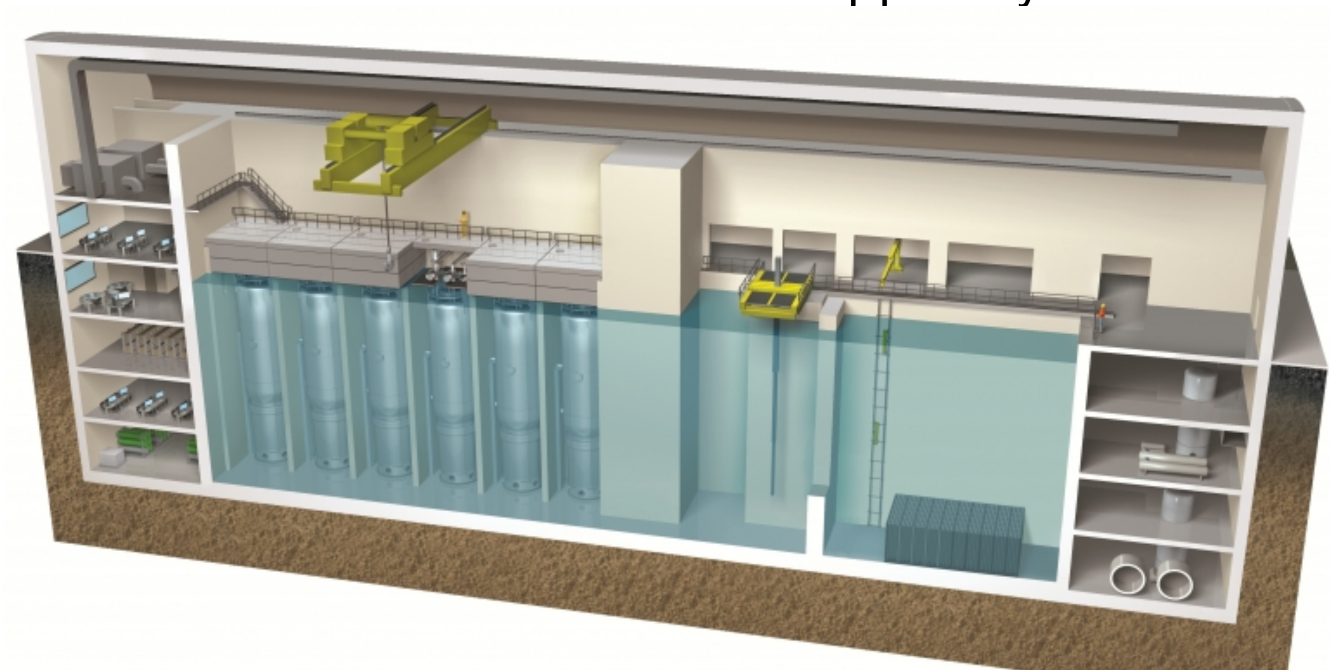
- Similar to coal-fired power plant except energy from a nuclear reaction is used to make high pressure steam instead of the combustion of coal. Boiler, turbine, generator, condenser are all basically the same.
- The reactor vessel where the nuclear fission reaction takes place contains:
  1) **fuel rods** containing enriched ^{235}U
  2) boron, cadmium, or carbon **control rods** that absorb neutrons to control the chain reaction
  3) a **moderator** (in "slow reactors") such as pressurized liquid water (the red, orange, and yellow in the schematic)
  4) a **coolant** or heat transfer material (also the red, orange, and yellow in the schematic.



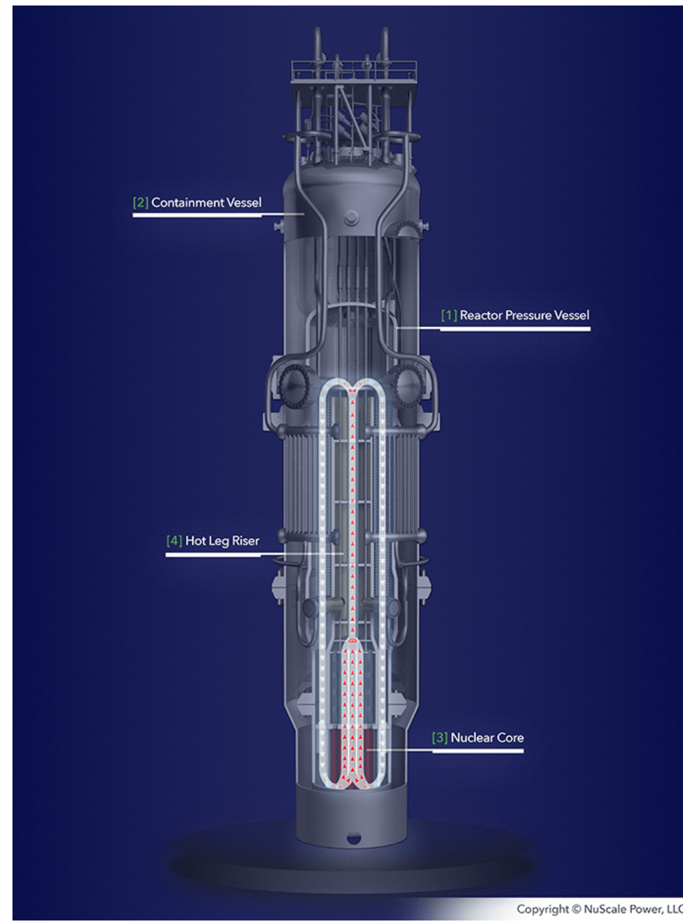
Small Modular Reactors

- Smaller size and modularity allows for factory mass production that reduces cost

- Pre-assembled reactors can be shipped by truck or rail

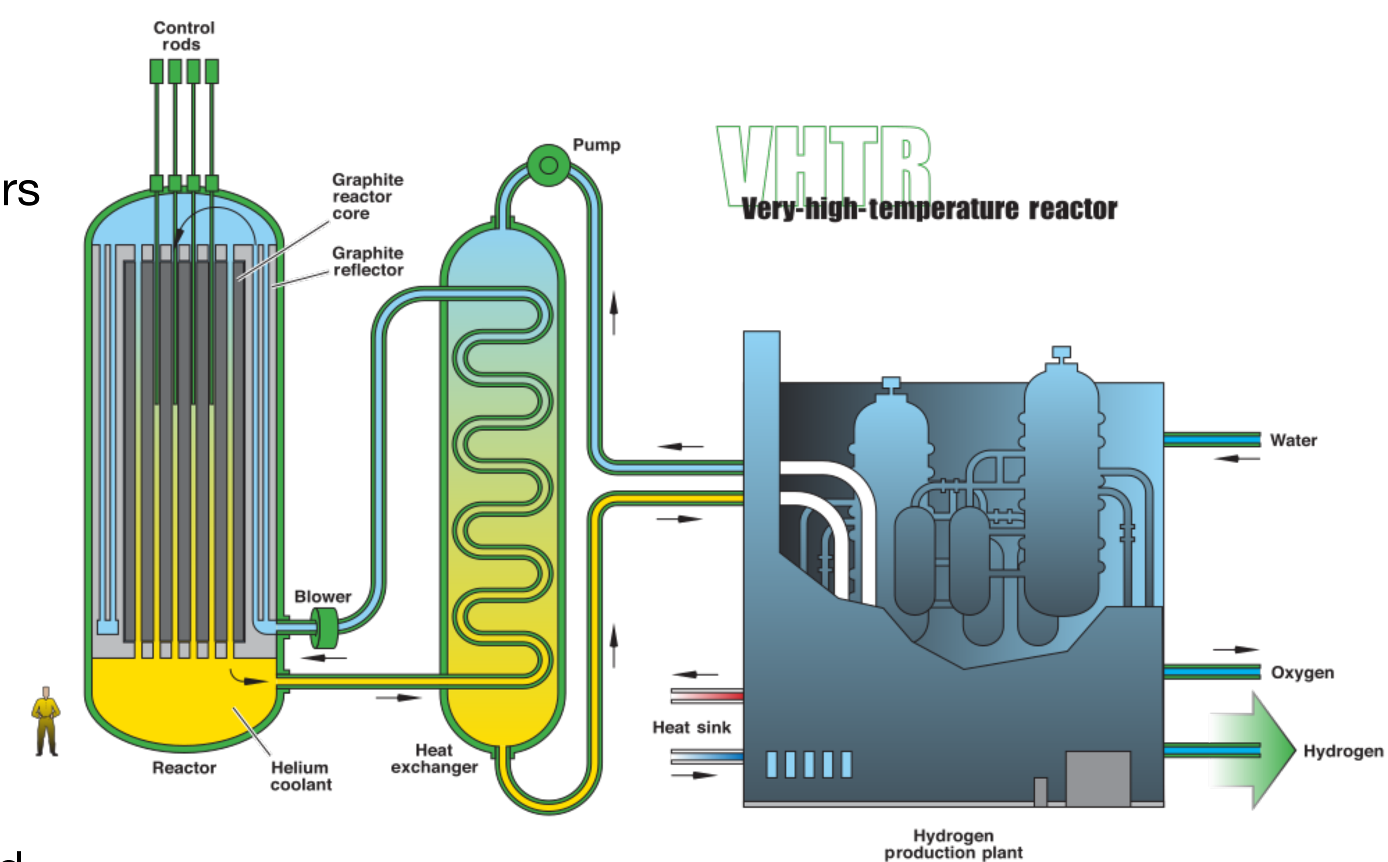


https://www.youtube.com/watch?v=wDMsXEur1fs



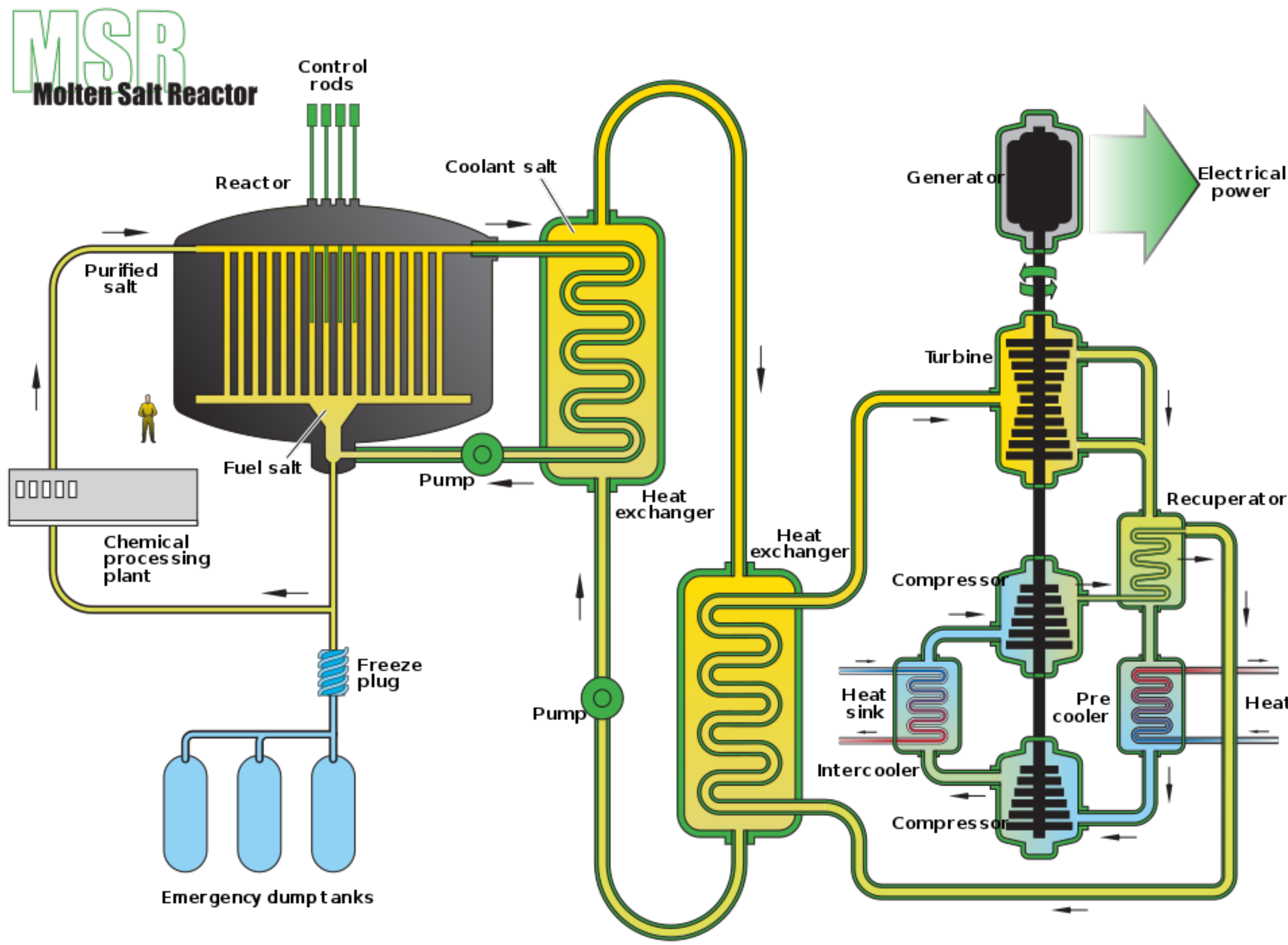
4th Generation Reactors: VHTR

- Variable High Temperature Reactors (VHTR)
- Graphite (not water) moderators
- Less risk of water decomposition and hydrogen explosion when overheated
- Helium or molten salt is the coolant and heat transfer medium; safer, lower pressure operation
- Once-through fuel cycle with fuel rods that must be replaced approximately yearly



4th Generation Reactors: MSR

- Molten Salt Reactor (MSR)
- High temperature, but low pressure operation; good heat distribution; expands upon overheating which makes the nuclear reaction go sub-critical
- Less risk of water decomposition and hydrogen explosion when overheated
- Freeze plug allows for fuel to be removed from the reactor upon overheating
- Closed fuel cycle when fuel is mixed with molten salt; waste can be removed, new fuel added on a continuous basis



Nuclear Waste

- Today's nuclear fuel contains only 3-4% fissionable material (^{235}U)
- Today's nuclear waste include fission products but also the 96-97% unfissionable ^{238}U and transuranium unfissioned transmutation products
- Nuclear waste is typically stored on-site; this may seem bad, but coal-fired power plant waste is emitted into the atmosphere. Coal ash is often simply buried in the ground.
- Next generation fast reactors would only produce fission products. ^{238}U would be transmuted into fissionable transuranium elements and subsequently fissioned. Much less waste is produced and the fission products are relatively short-lived.

Breeder Reactor Reactions

$$^{238}_{92}\text{U} + ^{1}_{0}\text{n} \longrightarrow ^{239}_{92}\text{U}$$

$$^{239}_{92}\text{U} \longrightarrow ^{239}_{93}\text{Np} + ^{0}_{-1}\beta \qquad t_{1/2} = 23.4 \text{ min}$$

$$^{239}_{93}\text{Np} \longrightarrow ^{239}_{94}\text{Pu} + ^{0}_{-1}\beta \qquad t_{1/2} = 2.35 \text{ days}$$

Unfissionable ^{235}U transmuted into fissionable ^{239}Pu

$$^{232}_{90}\text{Th} + ^{1}_{0}\text{n} \longrightarrow ^{233}_{90}\text{Th}$$

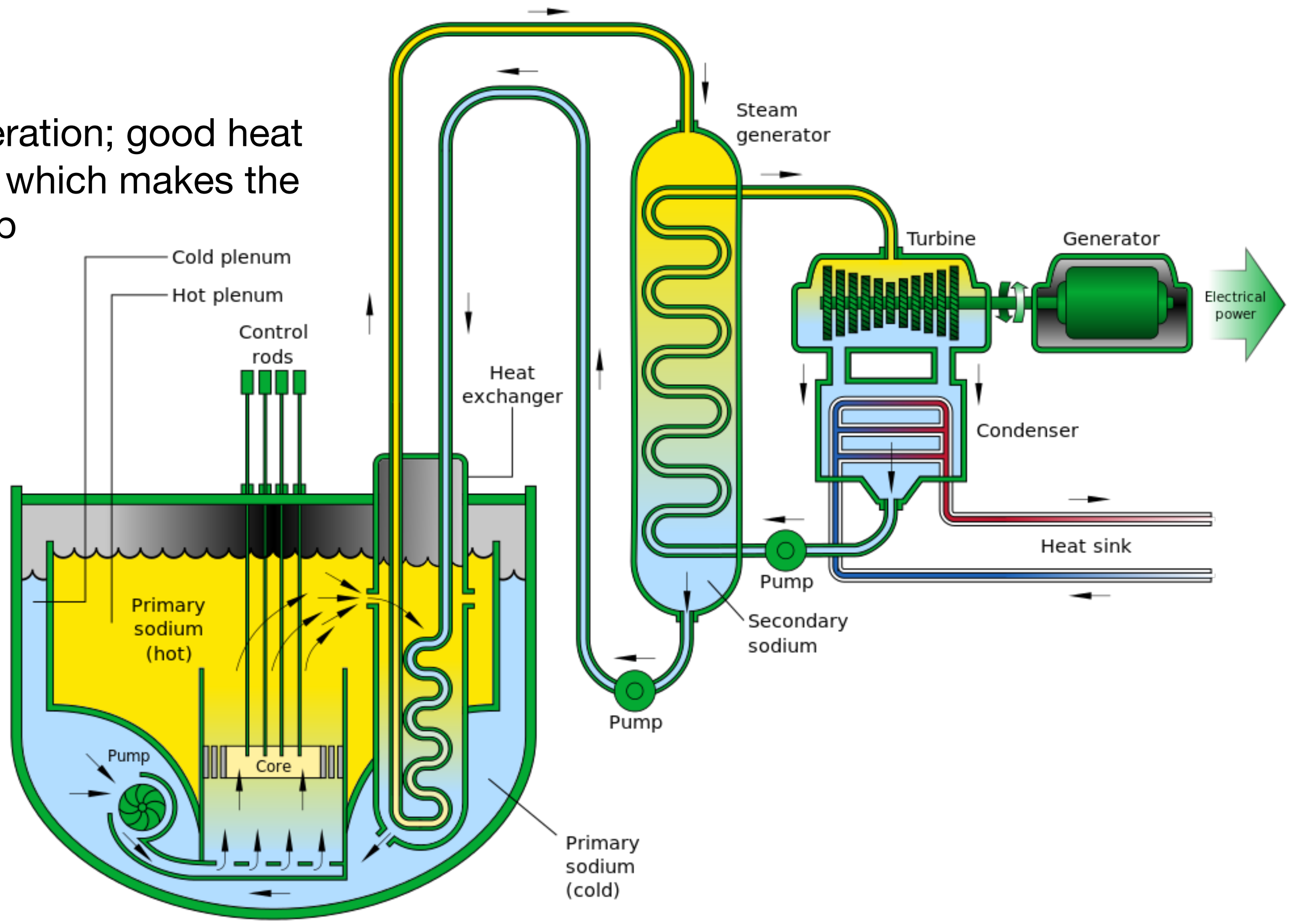
$$^{233}_{90}\text{Th} \longrightarrow ^{233}_{91}\text{Pa} + ^{0}_{-1}\beta \qquad t_{1/2} = 22 \text{ min}$$

$$^{233}_{91}\text{Pa} \longrightarrow ^{233}_{92}\text{U} + ^{0}_{-1}\beta \qquad t_{1/2} = 27.4 \text{ days}$$

Unfissionable ^{232}Th transmuted into fissionable ^{233}U

4th Generation Reactors: SFR

- Sodium Cooled Fast Reactor (SFR)
- High temperature, but low pressure operation; good heat distribution; expands upon overheating which makes the nuclear reaction go sub-critical and stop
- Less risk of water decomposition and hydrogen explosion when overheated; although molten sodium must not ever come in contact with water.
- Fast neutrons enable breeder reactions; nuclear waste and unfissioned isotopes are transmuted into fissionable material and then fissioned.
- Closed fuel cycle; core is robotically removed, processed, and re-used; spent nuclear fuel (SNF) can be used
- Traveling Wave Reactor uses similar technology but has a one time using up of the fuel over a multi-decade time period.



Integral Fast Reactor: https://www.youtube.com/watch?v=Sp1Xja6HIlU
Traveling Wave Reactor: https://www.youtube.com/watch?v=qwRYtiSbbVg