Nuclear

GEOS 24705/ ENST 24705
Nuclear power just another way of making steam
A nuclear plant is a big tea-kettle driving a steam turbine

Nuclear engineering is all about keeping the system in the Goldilocks condition – not too cold and not too hot.

Most of it is thermal management

Images: copyright unknown
Main isotope is $^{238}\text{U}$ (99.28%)
Radioactive (4.5 Byr half-life)

Can’t sustain a chain reaction. Decays spontaneously

$^{238}\text{U} \rightarrow \alpha + ^{234}\text{Th}$

...eventually $\rightarrow ^{206}\text{Pb}$
2\textsuperscript{nd} most abundant is $^{235}\text{U}$ (0.72 \%)  
Radioactive (700 Myr half-life)  

This can decay spontaneously  

$^{235}\text{U} \rightarrow \alpha + ^{231}\text{Th}$  
...eventually $\rightarrow ^{207}\text{Pb}$
Fission of uranium discovered by Lise Meitner from Otto Hahn’s data in 1939

Hahn was trying to make heavier elements by neutron bombardment – didn’t understand his results.

But only Hahn got the Nobel prize...

Hahn and Meitner in the laboratory, Berlin, ca. 1925
Image: Technische Universität München
$^{235}\text{U}$ fissions spontaneously only one in 14 billion decays – but fissions reliably given neutron bombardment.

neutron bombardment: $^{235}\text{U} + n \rightarrow ^{236}\text{U}$

... instead of sticking, the new element fissions.... (one example)

$^{236}\text{U} \rightarrow ^{144}\text{Ba} + ^{89}\text{Kr} + 3n$

Multiple neutrons produced in turn make multiple new decays. $^{235}\text{U}$ can sustain a fission chain reaction. (It is “fissile”).

Fission products themselves are highly radioactive: decay by β emission. Short half-life: spent fuel is “hot”.
Nuclear chain reactions: good if you want them, bad if not

Each fission event makes more fission events. And each event produces heat.

For animation see
http://library.thinkquest.org/17940/texts/fission/fission.html
Can build a reactor whose only purpose is transmutation, turning one element into another – a “breeder” reactor.

Here the goal is to control the daughter product. 
(Generally make plutonium out of uranium). Can use breeders to reprocess spent nuclear fuel, but then you’re left with fuel that contains dangerous plutonium. Reactor meltdowns are worse if using reprocessed fuel.

Or can make a power reactor where what you want is the heat produced in nuclear decay.

Here the goal is to control the rate of heat production. 
Not too cool (low power) or too hot (meltdown).
Nuclear power reactor heat control: management choices

**CHOICES FIXED AT DESIGN TIME**

- Fuel type and moderator substance
  Moderator makes neutrons more useful by slowing them down – depending on the moderator can use different blends of $^{235}\text{U}$ / $^{238}\text{U}$. If using a great moderator can use natural abundance uranium ($< 1\% ~^{235}\text{U}$). If no moderator must enrich to $> 20\%$.
- Composition of fuel
  Choices: % uranium and form: solid U oxide, metal alloy, liquid, or ceramic. Most fuel is oxide ($\text{UO}_2$) which cannot burn.
- Size/shape/arrangements of fuel rods or pellets
- Cladding on fuel
- Control rods that absorb some neutrons

**OPERATIONAL MANAGEMENT**

- Cool reactor (often with water as coolant)
- Separate fuel rods or pebbles in emergency
Nuclear power reactor fuel options

Uranium oxide fuel pellet
*Image: Nuclear Regulatory Council*

Uranium oxide “TRISO” micro fuel pebble
Nuclear fuel pellets must have cladding, be separable

CANDU (CANada Deuterium Uranium) fuel rods, un-enriched uranium oxide pellets in ½ m zirconium tubes.

Uranium oxide pellets in fuel rod assembly (4 m long rods, zirc. clad? for PWR reactor)

Image: Atomic Energy of Canada

Image: Mitsubishi Nuclear Fuel Inc.
Nuclear power reactor characterization

Fast neutron reactors
- *highly enriched fuel* (high $^{235}$U/$^{238}$U)
  - Heavy water ($\text{D}_2\text{O}$)
    - un-enriched fuel
  - Light water ($\text{H}_2\text{O}$)
    - low-enriched fuel
  - Boiling water
  - Pressurized water

Thermal (slow) neutron reactors
- Other
  - (liquid salts, liquid metal, graphite)
    - e.g. Pebble bed reactor

Other
- yes
  - moderator is?
    - Water
      - has a moderator?
        - no
          - Fast neutron reactors
        - yes
          - Thermal (slow) neutron reactors
Nuclear power reactor characterization

Fast neutron reactors
- *highly enriched fuel* (high $^{235}\text{U}/^{238}\text{U}$)
- *low-enriched fuel*

Thermal (slow) neutron reactors
- *moderator is?*
  - yes
    - Water
      - Light water ($\text{H}_2\text{O}$)
        - *low-enriched fuel*
        - Pressurized water
      - Heavy water ($\text{D}_2\text{O}$)
        - *un-enriched fuel*
        - Boiling water
  - no

Other (liquid salts, liquid metal, graphite)
- e.g. Pebble bed reactor

Most commercial reactors
Nuclear power reactor characterization

Fast neutron reactors

- *highly enriched fuel* (high $^{235}\text{U}/^{238}\text{U}$)
- Heavy water ($\text{D}_2\text{O}$) — *un-enriched fuel*
- Boiling water
- Pressurized water

Thermal (slow) neutron reactors

- *has a moderator?*
- yes: Other (liquid salts, liquid metal, graphite)
- no: Light water ($\text{H}_2\text{O}$) — *low-enriched fuel*

Diagram:

- Left branch: Fast neutron reactors
  - *highly enriched fuel* (high $^{235}\text{U}/^{238}\text{U}$)
  - Heavy water ($\text{D}_2\text{O}$) — *un-enriched fuel*
  - Boiling water
  - Pressurized water

- Right branch: Thermal (slow) neutron reactors
  - *has a moderator?*
  - yes: Other (liquid salts, liquid metal, graphite)
    - e.g. Pebble bed reactor
  - no: Light water ($\text{H}_2\text{O}$) — *low-enriched fuel*
Heavy water is a great moderator, so critical for nuclear fission without enriched U

Important to development of bomb, hence sabotage of heavy-water facility in occupied Norway, 1943
Nuclear power reactor characterization

- Fast neutron reactors
  - *highly enriched fuel* (high $^{235}\text{U}/^{238}\text{U}$)
- Thermal (slow) neutron reactors
  - Other
    - (liquid salts, liquid metal, graphite)
  - Water
    - Heavy water ($\text{D}_2\text{O}$)
      - un-enriched fuel
    - Light water ($\text{H}_2\text{O}$)
      - low-enriched fuel
  - Boiling water
  - Pressurized water

- has a moderator?
  - no
  - yes
  - moderator is?

- e.g. Pebble bed reactor
Pressurized-water reactor **turbine water separate from fuel**

3 separate water loops (reactor, turbine, and cooling water)
Boiling-water reactor  turbine water touches fuel
2 separate water loops (reactor + turbine, cooling water)
Boiling-water reactor  turbine water touches fuel
Simple to build, a bit uncomfortable as a concept

Basically a BWR is a big hot pot
Who uses boiling-water reactors?

Dresden power station
(Exelon)
1970 GE Mark I BWR

Fukushima power station
(Tokyo Elect. Power)
Units 1, 2, 6
1971 GE Mark I BWRs
Boiling-water reactor turbine water touches fuel
Worse if you don’t build it very well: the GE Mark I reactor

Torus is for .....
Spent nuclear fuel still very radioactive
Use only small fraction of $^{238}\text{U}$, 2/3 of $^{235}\text{U}$, fission products still “hotter”
Spent nuclear fuel variety of half-lives in fission products
Short = dangerous immediately; long = radioactive for millenia

Composition of Conventional Nuclear Fuel
(17x17 Westinghouse, 3% en r., 1100 day irradiation, 33,000 MWD/MTU, discharge composition, Origen Arp analysis)

- Very-low radioactivity, unused uranium fuel
- Highly radioactive, but rapidly decaying fission products with a variety of potential applications
- Long-lived, fairly radioactive "transuranic" isotopes, with potential for consumption in a reactor; drives disposal concerns
- Very-low radioactivity, unused uranium
Re-use: can reprocess spent fuel in a breeder reactor

Why waste all that good radioactive stuff? Remember the reactors whose only purpose is transmutation, turning one element into another – a “breeder” reactor. Can use breeders to reprocess spent nuclear fuel and boost fissionable content until the fuel can once again support a chain reaction in a power reactor.

But... the fuel you’re left contains dangerous plutonium. Reactor meltdowns are worse if using reprocessed fuel. This reprocessed fuel that has more-than-just-uranium is commonly called “MOX” (for “mixed oxide” fuel).
Spent nuclear fuel storage fuel pools are default strategy
No long-term national strategy for disposal, so keep in pools on site

While we ponder the best long-term solution we’re doing the worst possible practice…

Energy Northwest spent fuel pool
Image: Nuclear Fuel Reprocessing Coalition

Image: source unknown