Lecture 24 Nuclear Power

I. Principles of Operation

A. Review of Neutron Induced Fission

$$\left\{ {}^{A}_{Z}X + {}^{1}_{0}n \rightarrow \left[{}^{A+1}_{Z}X\right]^{*} \xrightarrow{<10^{-18}\,s} {}^{A_1}_{Z_1}X_1 + {}^{A_2}_{Z_2}X_2 + \nu\,{}^{1}n + Q \right\}$$

Bookkeeping: $A + 1 = A_1 + A_2 + \nu$

$Z = Z_1 + Z_2$

$$Q \approx 180\ \text{MeV} \approx 2 \times 10^{10}\ \text{kJ/mole} \Rightarrow \underset{\sim 160\ \text{MeV}}{E_{kinetic}} + \underbrace{E^{*}_{1} + E^{*}_{2}}_{\sim 20\ \text{MeV}}$$

1. IF $\langle\nu\rangle \geq 1$, chain reaction possible
2. Controlled conditions: power reactor
3. Maximum efficiency: nuclear explosion

HEAT	ACTIVITY
90%	10%

B. Fuels

Only U and Th of nature's elements undergo fission readily
Reaction cross sections largest for thermal neutrons (0.03 eV @ 300 K)

1. ${}^{232}_{90}Th$ (100%): $\sigma(n,f) \leq 2 \times 10^{-4}$ b
   (e-e) $\sigma(n,\gamma) = 7.36$ b $\Rightarrow {}^{232}Th \xrightarrow{\beta^-} \xrightarrow{\beta^-} {}^{233}_{92}U$ ($\sigma_f = 530$ b)
   $\bar{\nu} = 2.51$
2. ${}^{238}_{92}U$ (99.27%): $\sigma(n,f) \leq 5 \times 10^{-4}$ b
   (e-e) $\sigma(n,\gamma) = 2.71$ b $\Rightarrow {}^{239}U \xrightarrow{\beta^-} \xrightarrow{\beta^-} {}^{239}_{94}Pu$ ($\sigma_\gamma = 742$ b)
   $\bar{\nu} = 2.89$
3. ${}^{235}U$ (0.72%): $\sigma(n,f) = 577$ b ; $\bar{\nu} = 2.44$
   $\sigma(n,\gamma) = 101$ b
4. Conclusions
   - ${}^{235}U$ good fuel
   - ${}^{232}Th$ and ${}^{238}U$ – poor fuels but good feed stocks (Breeder reactors)

C. Chain Reaction Conditions: ^{235}U

1. Minimum Conditions

   Since neutrons have a long range, can escape volume of uranium.
   QUESTION: What fraction of emitted neutrons ($\bar{\nu}$) must be captured to sustain a fission chain reaction? i.e., capture efficiency?

2. Efficiency Example: start with 1000 neutrons

GO $\boxed{1000\text{ n} + \text{U}}$

$\rightarrow$ (n,γ) ^{236}U: $\frac{\sigma(n,\gamma)}{\sigma_R} = \frac{101\text{b}}{678\text{b}} \times 1000 = 150\ ^{236}\text{U}$ NO NEUTRONS

$\rightarrow$ (n,f): $\frac{\sigma(n,f)}{\sigma_R} = \frac{577\text{b}}{678\text{b}} \times 1000 = 850$ fissions × 2.44 n/fission

2074 n's

1000 needed

∴ capture efficiency must be 1000/2074 × 100% ≦ $\boxed{48\%}$

3. Stated Mathematically

   Minimum Efficiency for chain reaction $\Big\} \leq \frac{\sigma_R}{\sigma_f \bullet \bar{\nu}}$

   a. IF Efficiency > 48%, explosion
   b. IF Efficiency < 48%, no chain reaction
   c. IF Efficiency = 48%, steady-state energy production: REACTOR
      (can operate with lower abundance ^{235}U if efficiency > 48%)

4. Critical Mass: M_{crit}

   a. M_{crit} is the minimum mass of fissionable material necessary to exceed the minimum efficiency criterion; Geometry problem:

   b. Depends on surface to volume ratio of sphere (optimum shape), since this determines the escape probability for neutrons.

   c. Critical conditions: $M \geq M_{crit}$
      $\tau \sim 10^{-6}$s; $M_{crit} \sim 2$ kg for ^{235}U; R ≈ baseball (10^{15} dps)

II. Reactor Construction

A. Components

1. Fuel Rods: Energy Source
   - 3% enriched ^{235}U uranium in Zr-stainless steel rods
   - rod design ; 3% abundance make explosion impossible in reactor
   - fission neutron energy spectrum 0-5 MeV; ∴ need to slow down n's

2. Moderator: Enhance Efficiency
   - Low A materials thermalize neutrons best; must have low $\sigma(n,\gamma)$ to keep neutrons alive and minimize activation

   - Materials: H_2O – light water, ^1H: $\sigma(n,\gamma) = 0.333$ b
     D_2O – heavy water, ^2H: $\sigma(n,\gamma) = 5.2 \times 10^{-4}$ b
     Graphite – Fermi's first reactor, Chernobyl

     ^{16}O: $\sigma(n,\gamma)=2\times10^{-4}$

3. Control Rods: Thermostat
   - Maintain the P(fission)/ P(n,γ) ≈ 1

   - Control with neutron sponges ^{10}B: $\sigma(n,\alpha) = 3838$ b
     ^{113}Cd: $\sigma(n,\gamma) = 2\times10^4$ b

     need alloys; both have low melting points

   - Inserting or removing rods reduces or increases neutron flux and controls fission rate

4. Coolant
   a. Primary Coils: Heat exchange agent between fuel rods and secondary coolant; H_2O, D_2O, CO_2, He, Na (not a problem in large volume).

   b. Secondary Coil: Converts heat to steam
      - Steam drives turbine and generates electricity; from steam on, operation same as conventional power plant.
      - Designed to interact minimally with environment.

5. Reactor Shielding

Reflector: low Z material (low σ also) to reflect neutrons that escape moderator back into the reactor; concrete (cheap); personnel protection also – radiation safety.

6. Containment Shield – Accident Safeguard

Barrier against air and liquid escape – both under routine operation and extreme conditions, such as an earthquake

B. Sources of Neutron Loss

1. ^{238}U capture: $\sigma(n,\gamma) = 2.71$ b

Cross-section not large but fuel has 30 × more ^{238}U than ^{235}U

2. Capture in Reactor Components

Need to use materials with low $\sigma(n,\gamma)$ and high materials resistance to neutron damage.

3. Fission-Product Poisons

Many fission products have high $\sigma(n,\gamma)$; as these build up, the reactor becomes less efficient; e.g. ^{135}Xe: $\sigma(n,\gamma) = 3 \times 10^6$ b

4. Neutron Escape

C. Types of Reactors

1. Power Reactors: Production of electricity is design objective

   a. BWR: Boiling Water Reactor –
      Primary Coil = ~ 70 atm @ 280°C (steam)
   b. PWR: Pressurized Water Reactor
      Primary Coil: ~ 150 atm @ 315°C (liquid)

2. Research Reactors

Design Objective: high neutron flux – both basic and applied research; transuranium element production (e.g., ^{241}Am).

3. Breeder Reactor: Uses ^{232}Th and ^{238}U as feed stock to produce ^{233}U and ^{239}Pu

- i.e., make both energy and fuel simultaneously
- Liquid Na coolant – liquid at high T and excellent heat conductor
- No development in US ; Japan has operating breeder reactors and Europe developing them.

4. Natural Reactor – Oklo (Gabon, Africa)

Natural reactor that existed billions of years ago
gauthier@illite.u-strasbg.fr

III. Commercial Reactors

A. Current Use: Electrical Power

(also used on ships and subs; USSR – satellites)

1. Location of Reactors

U.S.: 104 now in operation; rest of the world ~442

2. Fraction of power generated by nuclear reactors:

U.S. – 20%; Japan – 25%; Sweden – 50%; France – 78%;
Belgium – 56% Total $\cong$ 3.4×10^5 MW/yr

3. Relative Cost

Variable ; 1 kg ^{235}U ~ 50,000 tons of coal

B. Advantages

1. Indigenous Resource

Lots of U/Th in western U.S.
cf: foreign oil dependence (50-60%)

2. No Chemical Emissions

- Fossil Fuels → $CO_2/CO/O_3/SO_x/NO_x$ and particulates

  ∴ Minimizes greenhouse effect and acid rain
- Improved air quality
- Fewer oil spills

3. Efficient Land Usage

- Mining 1 kg of uranium much simpler than 50,000 tons of coal
- No strip-mining damage (recently in WVA, and entire mountain was leveled)

- No land destruction by lakes for hydroelectric power

4. Limited Radiation Emission
Coal-fired power plants release on average ten times more radiation than nuclear reactors due to U and Th content of coal. TN coal highest; IN/IL coal next

5. Safety
Safety record of US, Japan and EEC is far superior to any other source of electrical power; USSR not so good
Reason: Regulation (much tighter regulations than tobacco and alcohol industries)

6. Cost Effective
Location dependent – depends on proximity to coal deposits and hydroelectric power. Northeast and Southeast – competitive ; IN/IL and Pacific Northwest – not so good; for nuclear power, environmental cost is up front; for fossil fuels – pay after the fact.

SO WHY ALL THE FUSS ??

C. Disadvantages

1. Personnel Exposure to Radiation
Workers may receive up to 5 r/year; dangers of low levels of radiation are uncertain (underground coal miners and airline pilots/flight personnel have higher average exposure.)

2. Radioactivity Release: ^{3}H, ^{85}Kr, ^{135}Xe gases (β^- emitters)
Small with respect to: coal, natural background, nuclear weapons tests and military waste storage.

3. Accidents
    a. Loss of Coolant
        - Possible venting of fission products to atmosphere.

        Three Mile Island lesson: H_2 gas from radiolysis of water is an explosion hazard; chemical problem, not nuclear

    b. Core Meltdown
        - expensive, worker exposure (TMI)

- Chernobyl – worst documented nuclear accident.
  Design flaw: not adequate containment shield; C moderator; operated irresponsibly – were testing effects of withdrawing control rods and reducing coolant flow simultaneously; reactor went critical, T reached ~2000 C

- Casualties: 36 dead, 200 hospitalized; expect 1500 ± 500 subjected to elevated cancer risk; 200 mi^2 contaminated – severe agricultural disruption in area.

c. Earthquakes
fissure of containment shield; US OK, but third world ???

4. Reprocessing and Storage of Nuclear Fuels

a. Short-term storage – above ground in cooling ponds (~ 800°C)
b. Transportation after cooling
c. Reprocessing and fuel rod refabrication
d. Long-term wast storage
   - WIPP – New Mexico – now operating (in state-wastes only)
   - Yucca Mountain – Nevada – debate (6" rain/year average)
   - Encapsulation in ceramics
   - NIMBY Syndrome – outer space?
   - West Texas

5. Civilian vs. Military wastes

Military wastes are 10-20 times greater than civilian wastes.
(~ 60% due to nuclear power; remainder from industry and medicine)

6. Theft of fissionable material – esp in Third World countires

D. Solutions

U.S. Navy, EEC and Japanese nuclear power programs very successful.

1. Technical Issues
   - a. Smaller reactors – minimize indifference associated with anonymity in humongous facilities.
   - b. Standardized reactors
     Every plant (or most) is (are) different in the U.S.; emphasis has been on fewer and bigger reactors – compounds repair and safety problems; if standardized (like Navy and France), both personnel and parts interchangeable; nonexistent in U.S. power reactors at present – inefficient and expensive.
   - c. Emergency System
     Use gravity-dependent scramblers instead of pumps to flood reactor with water.
   - d. More advanced coolants
     He/graphite coolant/moderator; liquid Na
   - e. Breeder Reactor ???

2. Institutional Issues
   - a. Public Acceptability – nukes need an impeccable safety record and educated public.; [officials: 72% approve; public: 73% approve; officials on public view: 26% approve]
   - b. Regulatory Uncertainty
     Regulations imposed after design and beginning of construction are expensive; e.g. new rules implemented **after** TMI accident greatly inflated cost of reactors then under construction. (e.g. Marble Hill in southern Indiana). Companies unwilling to build if safety costs make it unprofitable. Need grandfather clause.
   - c. Licensing – at present construction and operating permits are issued separately; thus, if regulations change during construction, operation can be prohibited. Need to issue combined construction/operating permits.

d. Waste Disposal – recipients of waste (NM and NV) must be compensated satisfactorily; public must be convinced of long-term safety.

?? ALTERNATIVE ??

IV. Fusion Power

Use the Sun's reactions to create power

A. LiD fuel

1. Reactions:

$$\left.\begin{array}{l} {}^{3}H + {}^{2}H \rightarrow {}^{4}He + {}^{1}n + 17.6\ \text{MeV} \\ {}^{1}n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.8\ \text{MeV} \end{array}\right\}$$

^{3}H a catalyst; chain reaction.

$$\boxed{{}^{2}H + {}^{6}Li \rightarrow 2\ {}^{4}He + 22.4\ \text{MeV}}$$

2. Li Blanket surrounded by ^{2}H – ^{3}H plasma

3. Other Permutations ; e.g. ^{2}H and $^{3}H \rightarrow {}^{4}He + Q$

4. Energy Generation
   - a. $\Delta E \approx 5 \times$ fission/gram of fuel
   - b. ^{2}H and ^{6}Li cheap and abundant; sea water a good source
     < 1 dollar/gallon
   - c. Fewer radioactive products – mostly short-lived; minimizes waste storage problems

B. Problems

1. Very high temperatures required to ignite LiD.
   Coulomb barrier problem (not the case for $^{1}n + {}^{235}U$)

   $T \gtrsim 10^{7}$ K for reasonable rates

   Containment problem – stability of structural materials

C. Thermonuclear Weapons

1. Fission Detonator
   Fallout Problem
   No critical mass limitation ; ∴ size not limited.

2. USSR Test ~ 100 M tons TNT
   cf Hiroshima and Nagasaki ~ 25 ktons TNT (fission bombs)

D. Power Reactors

1. Magnetic Containment

2. Laser-induced heating

3. Prospects: Steady progress, but just now reaching the power-in power-out break even point.
   Guess: ~ 20 years and major investment along the way