Nuclear Physics and Astrophysics

PHY-302

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Lecture 17 - War and Peace

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We are able to calculate the reproduction factor k:

$$k = \eta\epsilon p f(1 - l_f)(1 - l_t)$$

ratio of thermal neutrons in one generation to available thermal neutrons in next generation

For chain reaction we require k=1

These neutrons not immediately available after fission - reactions take time:

- moderation ~ 10^{-6} s
- diffusion at thermal energy before absorption ~ 10^{-3} s

Total characteristic time for all interactions is τ

In time interval dt, increase is:

$$dN = (kN - N)\frac{dt}{\tau}$$

$$N(t) = N_0 e^{(k-1)t/\tau}$$

Generation	time	Number neutrons
1	0	N
2	$t+\tau$	kN
3	$t+2\tau$	k^2N

k>1 leads to exponential growth

k<1 leads to exponential suppression

k=1 stable state - desired state for reactor

Reactors with k = 1.0064 are "prompt critical"
the reaction is almost unstoppable

- For k=1.01 (slightly supercritical) $\tau \sim 0.1$s
- Difficult to control reactor on timescale of 0.1 seconds!
- Better to have longer τ to allow time for control
- Use **control rods**: rods of Cadmium / Boron - very high n^0 capture cross section
- Can be rapidly inserted to absorb neutrons and kill chain reaction
- Typically pile designed to be subcritical for prompt neutrons...
- ... achieve critical operation relying on delayed neutrons
- These have $\tau \sim$ sec - minutes. Time enough to manipulate control rods

Nuclear Reactor Design Issues

Reactor design is very complex engineering

Many features common to all designs

- Fuel fissile material: enriched UO_2 with 2-3% ^{235}U
- Moderator - to thermalise neutrons
- Reflector - surrounds core to reduce neutron leakage
- Containment Vessel - prevent escape of radionuclides
- Shielding - prevent neutrons & gamma rays from causing biological harm
- Coolant - remove heat from the core - prevent meltdown of pile - often pressurised water / liquid metal
- Control & Emergency systems
- Turbine - convert heat into electricity - typically ~30% efficient (!)

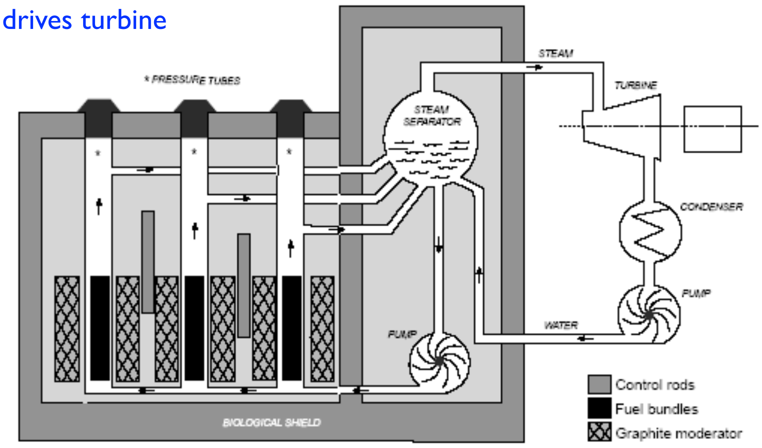
Graphite moderated boiling light water reactor

Water (coolant) boils - heated by fuel - steam drives turbine

3200 MW thermal energy output

1000 MW electrical energy output

Chernobyl Reactor Design



26th April 1986 reactor was 16 years old

Design is particular to Russian (N. Korean?) reactors

Design has 3 notable features. As power increases:

a) fuel temp increases, but neutron flux decreases

b) more water boils - steam absorbs less n^0, f increases (so k increases ® more fission)

c) no containment shell to contain core in event of meltdown

At high power (a) dominates, at low power ~20% (b) dominates (details on next page)

Soviet design optimised for energy & plutonium production
Required removal of fuel cells whilst still in operation
Means reactor too large for containment shell

Design has a notable behaviour at low and high core temperatures - 3 competing effects

- water coolant also absorbs n^0 and needs to be accounted for in k
  i.e. it affects thermal utilisation factor f as well as the moderator graphite

- as fuel temperature increases, k decreases from <u>two</u> effects:
  - Thermal energy of n^0 increases

  ⇒ fission cross section drops with increasing n^0 energy

  Thus fission rate and k decreases

  - Density of water drops due to thermal expansion

  ⇒ n^0 have longer mean free path in material (fewer elastic collisions)

  ⇒ Resonance escape probability, p decreases : more n^0s absorbed by (n,γ) reactions

  Thus k decreases

- as moderator/fuel temperature increases, k increases:
  - Water will absorb fewer n^0 i.e. thermal utilisation factor, f increases ⇒ **k increases**

At high power 1st factor dominates (k decreases)

At low power ~20% 2nd factor dominates (k increases)

This can lead to unstable operation:

strong oscillations as k is suppressed then enhanced

Chernobyl Disaster Report from IAEA (United Nations International Atomic Energy Agency)

Scheduled test: reactor to be shutdown - check turbine emergency power supply

Test not properly communicated to engineers of water cooling system

At low power reactor became unstable - power surges every few seconds

Operators removed all control rods to increase power (meant 20s delay in event of surge)

Brief 10 GW(!) power surge caused steam explosion rupturing core - exposed to atmosphere

Graphite control rods burnt fiercely for 10 days releasing radionucleids high into atmosphere

Many factors contributed to accident:

reactor design, operator errors, miscommunication, poor culture of safety

About 70 people died from direct result - indirect cancer deaths estimated < 10,000

Burning fossil fuels: ~10,000 deaths per year in USA (2 million worldwide!!!)

Chernobyl is only nuclear accident to harm public in 11,000 reactor years

20% UK power is nuclear - dropping to 6% in 2020! Germany will stop fission reactors

Chancellor Angela Merkel is reconsidering this now!

To avoid global warming: nuclear fuel <u>seems</u> obvious short to mid-term solution

Nuclear reactors cannot have a nuclear explosion - Fissile material is too dispersed

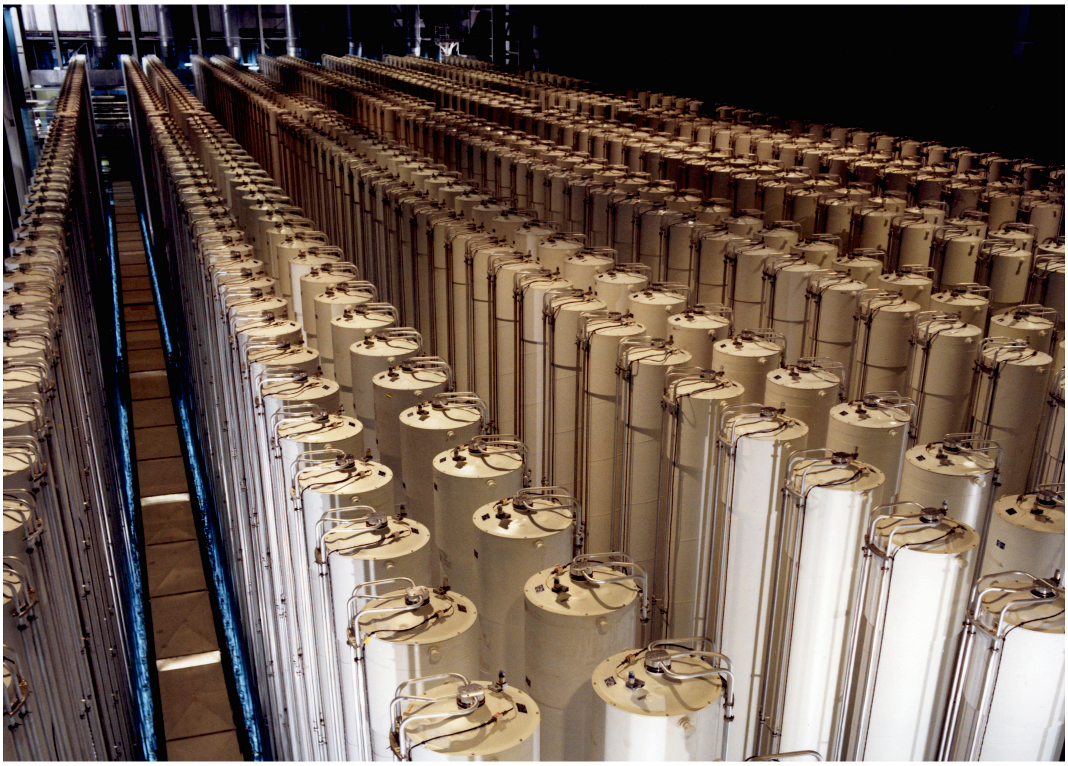
When part of fuel cell 'ignites' remainder is blown away extinguishing nuclear reaction

Not required for exam

Uranium Enrichment

- Enrichment expensive & technologically challenging process
- Rely on tiny mass difference between ^{235}U and ^{238}U in gaseous UF_6
- Use many gas centrifuges in series (or diffusion)
- Diffusion process requires ~10 MW energy(!) - heat dissipation observed from satellites
- Centrifuges require precision engineering: rotates at speed of sound
- Need to repeat process many times
- Highly enriched: 20-90% ^{235}U only needed in nucl. weapons & fast breeder reactors
- Enrichment process is same for 5% or >20%
- Thus enrichment can always be used for arms programmes...

Uranium Enrichment



Fast Breeder Reactors

Fast Breeder reactors - **utilise fast neutrons**: produce power & fissile material

Require ^{235}U at 20-30% concentration - fast neutron fission is sustainable chain reaction

No moderator required - Need liquid metal coolant - no moderation effects

Could produce more fissile material than they consume!

Fast neutrons used to transmute U to Pu

$$^{238}U + n \rightarrow \ ^{239}U \rightarrow \ ^{239}Np + \beta^- + \bar{\nu} \rightarrow \ ^{239}Pu + \beta^- + \bar{\nu}$$

More expensive to build

Produce plentiful supply of weapons grade plutonium

Plutonium (Pu-239) is also fissile (like ^{235}U, i.e. for thermal energy neutrons)

Almost non-existent in nature

Can design reactor with $\eta > 2$

i.e. 1st neutron feeds chain reaction

2nd neutron creates ^{239}Pu

- Reactors recycle fuel rods to extract ^{239}Pu: gain additional 25% energy production
- Spent fuel rods contain ~1% ^{239}Pu from initial 4% ^{235}U
- Longer usage of fuel rods produces other isotopes of Pu
- Weapons production needs high concentrations of ^{239}Pu/^{235}U
  because fission cross section (n,f) for ~MeV n^0 is small
- Thus "too frequent" recycling of fuel rods could indicate weapons production
- Simple recycling plant could produce this from a civil nuclear power facility
- Technically easier than U enrichment - more expensive

Nuclear Weapons

Manhattan Project began in 1941 - technological research to develop nuclear bomb

First weapons test performed in 1945 in New Mexico

Two bombs deployed later that year in Japan: Hiroshima & Nagasaki

Much information is classified - look at general principles

For weapons we require maximum energy release in smallest time
- increase k
- decrease τ

$$N(t) = N_0 e^{(k-1)t/\tau}$$

Increase k by increasing purity of fissile material

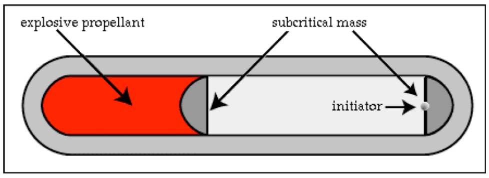
Decrease τ by relying on **fast fission**: no moderation - use MeV neutrons to induce fission

For k~2.5 and τ~10^{-6} s: after 10 μs get 10^6 neutrons!

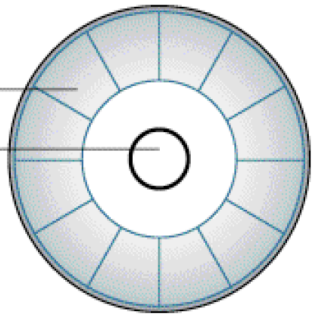
Timing is crucial - need to form supercritical mass & sufficient fissions before remaining fissile material is blown apart

Two types of design are employed

Gun type design:
Two masses of fissile material are fired together
Create supercritical mass
Initiator provides neutron pulse to initiate chain reaction
Easier to create, but larger masses required for given energy output



Implosion design:
Subcritical fissile material surrounded by explosives
Explosion compresses fissile material to supercritical state
Initiator is fired providing initial neutron pulse
Requires precision to create supercritical state
Less fissile material required for given energy



Fat Man Schematic

Bombs used on Japan were equivalent to 20 kTon TNT explosive

A 20 kTon bomb of ^{235}U needs ~ 15 Kg fissile material

A 20 kTon bomb of ^{239}Pu needs ~ 5 Kg fissile material

Only about 10% of this fissions during explosion

Searching For Nuclear WMDs

Searching for covert weapons programme is difficult

- Nuclear facilities should be monitored by IAEA (signatories of Non-Proliferation Treaty)
- Treaty requires open IAEA inspections of all sites
- Inspections not required until 6 months before introduction of radioactive material

- Search for uranium enrichment facilities
- Heavy construction work - underground facilities
- Look for specialised equipment for precision gas centrifuges
- Look for huge thermal power output from gas diffusion enrichment
- Look out for procurement of high grade steel and components
- Site inspections look for radioactive contaminants
  can test purity of UO_2 ore (i.e. abundance of ^{235}U)
- Ground penetrating radar - look for hidden structures / equipment
- Examine seismic data - clear signature of nuclear test (e.g. Pakistan 1998)
  nuclear tests announce weapons capability to the world

Not required for exam

NATANZ, IRAN -- CLOSE-UP

INSTITUTE FOR SCIENCE AND INTERNATIONAL SECURITY

IMAGE CREDIT: DIGITALGLOBE
DATE OF IMAGE: 16 SEPTEMBER 2002

THE GAS CENTRIFUGE URANIUM ENRICHMENT PLANT AT NATANZ, IRAN.

Site in Iran claimed to be for uranium enrichment

Underground facility: 5,000 centrifuges

Another site declared by Iran as D_2O production facility - moderator

At that time Iran had no heavy water reactors

Note:
I make no comment on the validity of this!
I use Iran only for its topical interest now

Not required for exam

This site found to contain radiation detection device - not a problem

...but site not declared for any nuclear activity - device is out of place

Lavizan-Shian Site, Iran -- August 11, 2003

Later site is demolished

Furthermore earth appears to be scraped

This might be done to remove contaminated soil traces

But, might be done for legitimate building...

This US claim not verified by IAEA

Not required for exam

Lavizan-Shian Site, Iran -- May 10, 2004

Recent International Atomic Energy Agency (IAEA) report:
absence of any evidence of military aspects of the Iranian nuclear program

Not required for exam

IAEA has surveillance cameras at the Natanz enrichment facility and has conducted numerous unannounced visits there since March 2007

The US's intelligence report on Iran (Dec 2007) concluded:
Iran's nuclear program has not been geared towards "weaponization" since 2003

Iran may have experimented with sophisticated two-point detonation design for a nuclear warhead (Nov 2009)

TEHRAN TIMES
IRAN'S LEADING INTERNATIONAL DAILY
Thursday, October 30, 2008 | Volume: 10448
Latest News : I'm frozen with fear — could Obama still lose the election?

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Iran to press ahead with uranium enrichment: FM
Tehran Times Political Desk

TEHRAN - Foreign Minister Manuchehr Mottaki on Sunday vowed that Iran will continue its uranium enrichment work.

IAEA report 15/09/2010

"...a small number of particles from samples taken in the cascade area were found with enrichment levels of between 5.0% and 7.1% U-235"