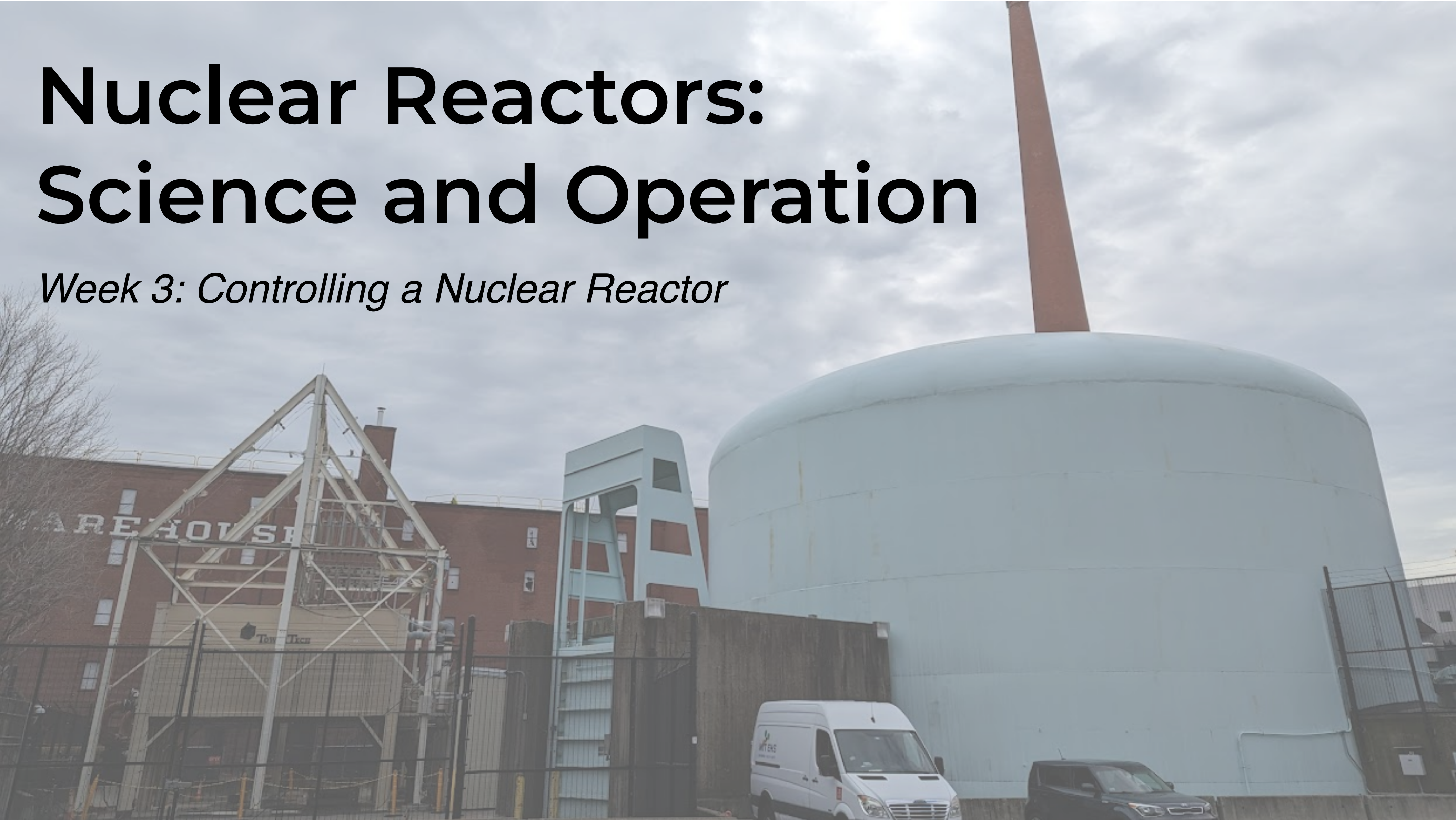
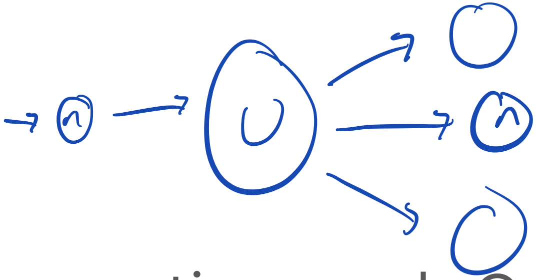
Nuclear Reactors: Science and Operation

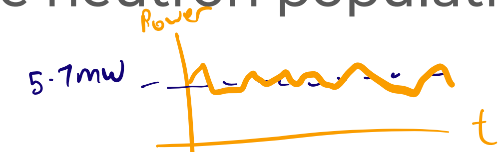
Week 3: Controlling a Nuclear Reactor

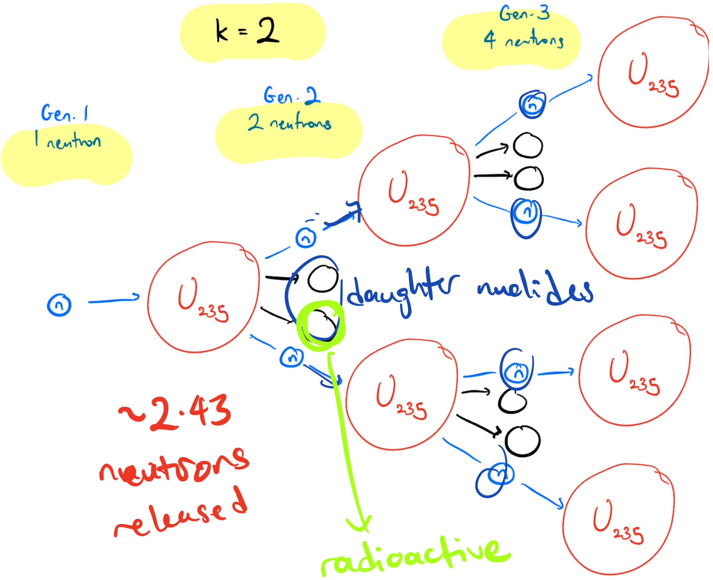


K-eff and criticality

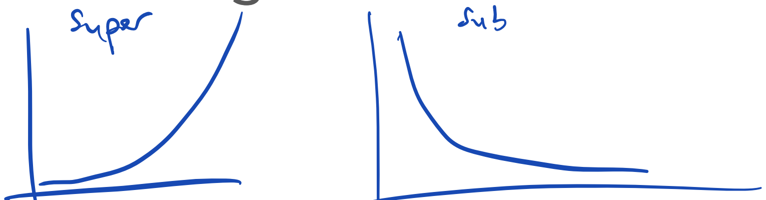


In week 1, we talked about how chain reactions work. One way to measure a chain reaction is the effective multiplication factor "K-eff"- basically, this is the factor by which the neutron population multiplies between each generation.





A reactor at k = 1 is called critical - its neutron population stays constant. When k > 1 it is supercritical (increasing neutron population), and when k < 1 it is subcritical (decreasing neutron population).



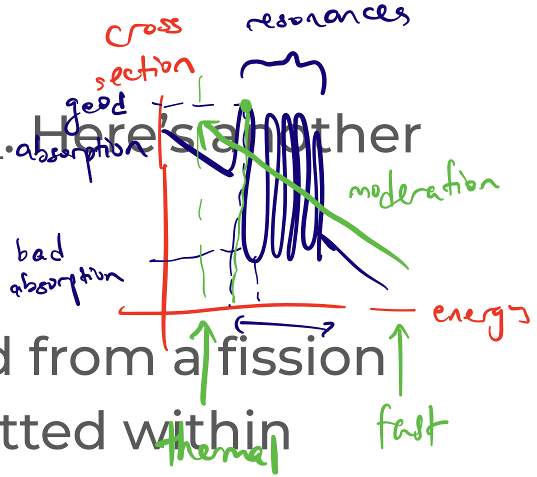
Prompt and delayed neutrons

easier to cause fission

high-energy lower energy

We've previously classified neutrons as fast or thermal. Here's another classification of neutrons:

"epithermal" in between

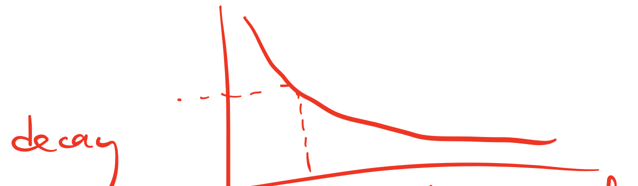


most fission neutrons

- A prompt neutron is a neutron that's directly emitted from a fission event. Usually, prompt neutrons are fast neutrons emitted within 0.0001s of the fission. (10^{-4} s)
- A delayed neutron is a neutron emitted from the decay of fission products. Usually, delayed neutrons are "epithermal" (faster than thermal, but not quite fast) and are emitted up to a minute after the fission.

MITR longest lived "neutron precursors"

$t_{1/2} \sim 55$ s



Gen 2 Gen 3

Gen 1

100 n → 101 n → 102 n

0.0001 0.0001

$t_{1/2}$ = the time for radioactive isotope to decay to ½ original amount

Prompt and delayed neutrons

Delayed neutrons are a tiny fraction (for U-235 fission, about 0.65%) of neutrons produced, but they are very important as they make controlling a nuclear chain reaction practical (not just possible)!

just barely above critical

If all neutrons were prompt, each generation of neutrons would only have 0.0001s between them. Even if k = 1.01, in one second the neutron population has already multiplied by this value 10000 times - this exponential growth is simply too fast to control.

1 s increase by 1.01^{10000}

$\sim 10^{43}$?!

k = 1.00001

A reactor being "prompt supercritical" is when it is supercritical with only the prompt neutrons - this is the basis of a nuclear bomb.

Prompt and delayed neutrons

However, suppose we were supercritical but not prompt supercritical. This means the prompt neutrons alone are not enough to make up the neutron population, and we must rely on the delayed neutrons for the increase. Since delayed neutrons are on a multi-second timescale, this gives us a slower, controllable rise in power. Suppose ~~0.5~~% of neutrons are delayed (so ~~99~~ 95.5% are prompt), and k = 1.01:

20s

5 % delayed

95 % prompt

Time	Prompt	Delayed	Total	Change / Delta-n
"0" 0 s	~~9950~~ 9500	500 ~~50~~	10000 × 1.01	= 10100 new gen
Gen 1 0.0001 s	9595	500	10095 × 1.01 × 95%	+95
Gen 2 0.0002 s	9686	500	10186 × 1.01 × 95%	+91
0.0003 s	9773	500	10273 × 1.01 × 95%	+87
0.0004 s	9857	500	10357	+ 84

power increase slows down

prompt supercritical

505

over

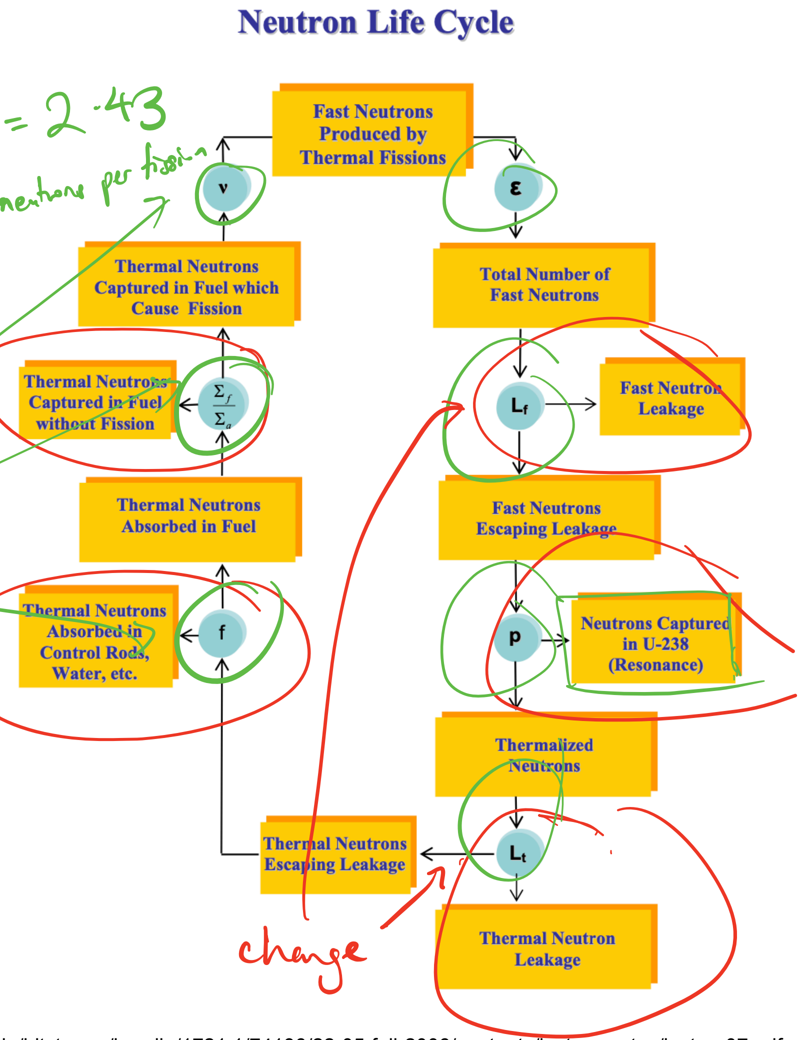
speeds up

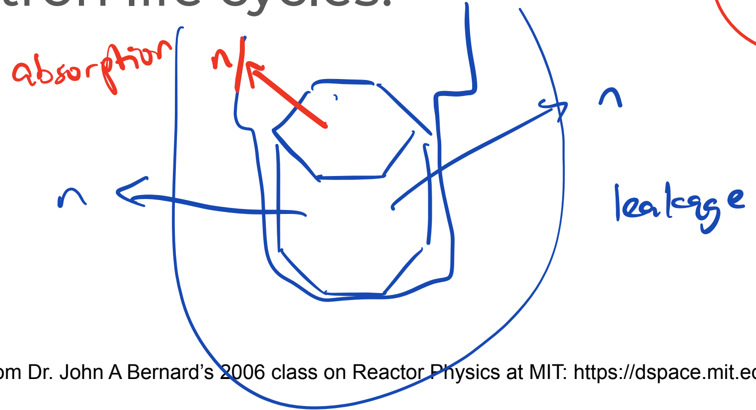
What happens to a neutron?

Criticality isn't easy to achieve. Of the ~2.4 neutrons each U-235 fission emits, over half of them are lost to leakage (neutrons escaping the core) or absorption (neutrons being absorbed by materials that aren't fuel). Look up the six-factor formula if you're interested in neutron life cycles!

$\bar{\nu} = 2.43$

neutrons per fission


Neutron Life Cycle



From Dr. John A Bernard's 2006 class on Reactor Physics at MIT: https://dspace.mit.edu/bitstream/handle/1721.1/74136/22-05-fall-2006/contents/lecture-notes/lecture07.pdf

Reactivity and control systems

$k=1,\ \rho=0$

$k=2,\ \rho=\frac{1}{2}$

reactivity

$$\rho = \frac{k-1}{k}$$

$k=.5,$

$\rho=-1$

unitless

Reactivity is a measure of how far a reactor is from being critical, with zero being perfectly critical, positive values being supercritical and negative ones subcritical.

"inverse hour"

An equation called the Inhour Equation relates reactivity with the reactor period (the time it takes for reactor power to increase by a factor of e).

natural log 2.718

$\left(\begin{matrix}\text{U-235}\\ 0.65\%\end{matrix}\right)$

delayed neutron fraction

effective

period

$$\tau(t) \approx \frac{\bar{\beta} - \rho(t)}{\dot{\rho}(t) + \lambda_e(t)\rho(t)}$$

rate of change

"decay constant" of neutron

(Note: it can be tempting to say $k = 1+\rho$, especially with all the rounding that happens with the small values we use - but this is not true in general!)

decay constant λ

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

half-life $t_{1/2}$

Reactivity and control systems

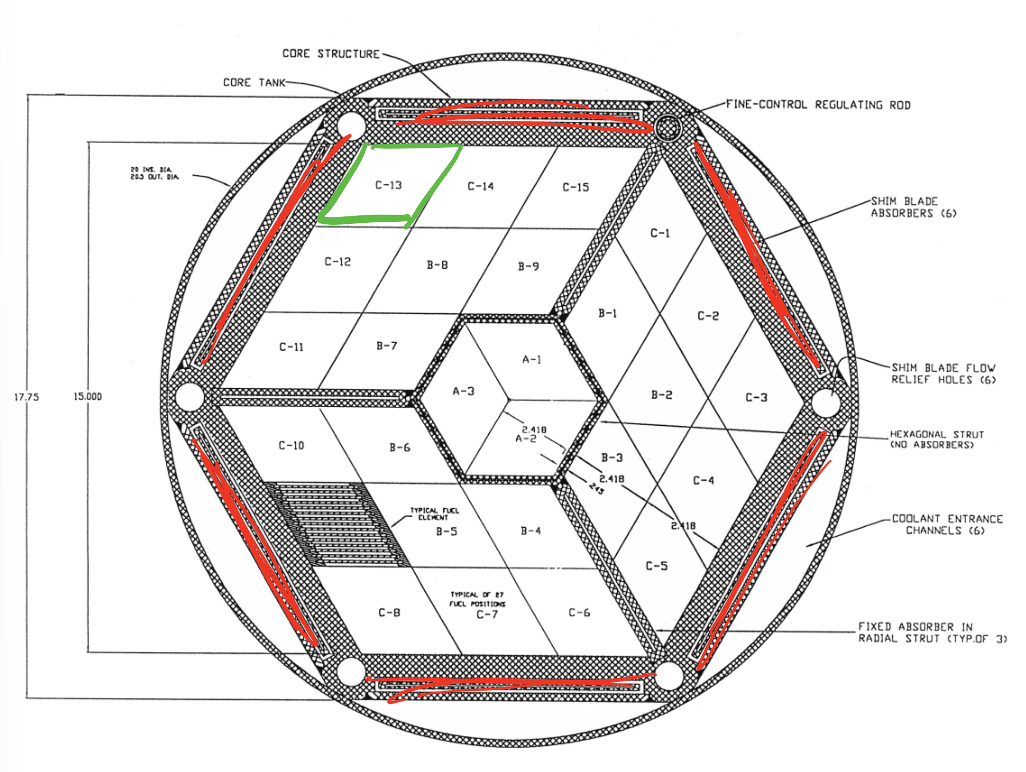
shim blade in/down

We can control how many neutrons are available for the chain reaction by controlling how many neutrons are absorbed. Absorbing more neutrons = (adding <u>negative</u> reactivity), and through calibrations we know how much reactivity each control rod adds or removes.

Reactor control systems are basically neutron-absorbing materials that we can move in or out of the core to change how many neutrons get absorbed.

At the MITR, these take the form of six shim blades (steel with boron) and a fine-control regulating rod (aluminium with cadmium liner).

Control systems



CORE SECTION MITR-II

FIGURE 1.8

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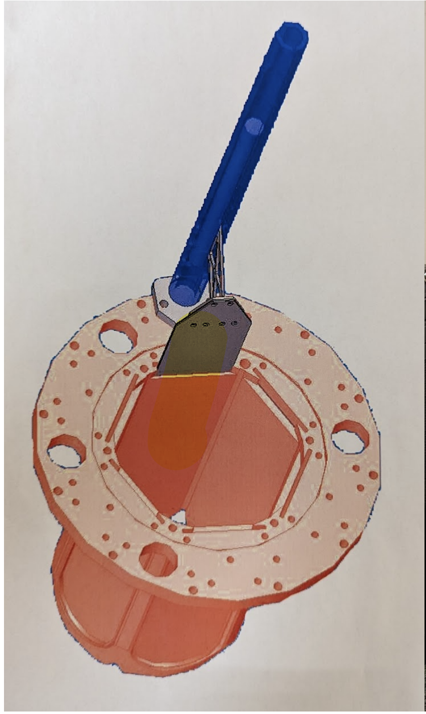
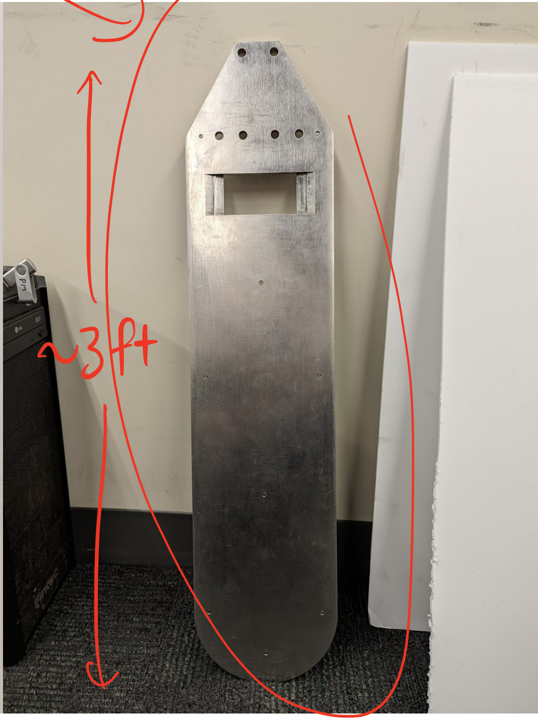




The six shim blades are located in a hexagon around the core, and are normally used for larger power adjustments.

Operating the reactor

Lots of parameters need to be monitored to ensure the reactor is in a safe condition.

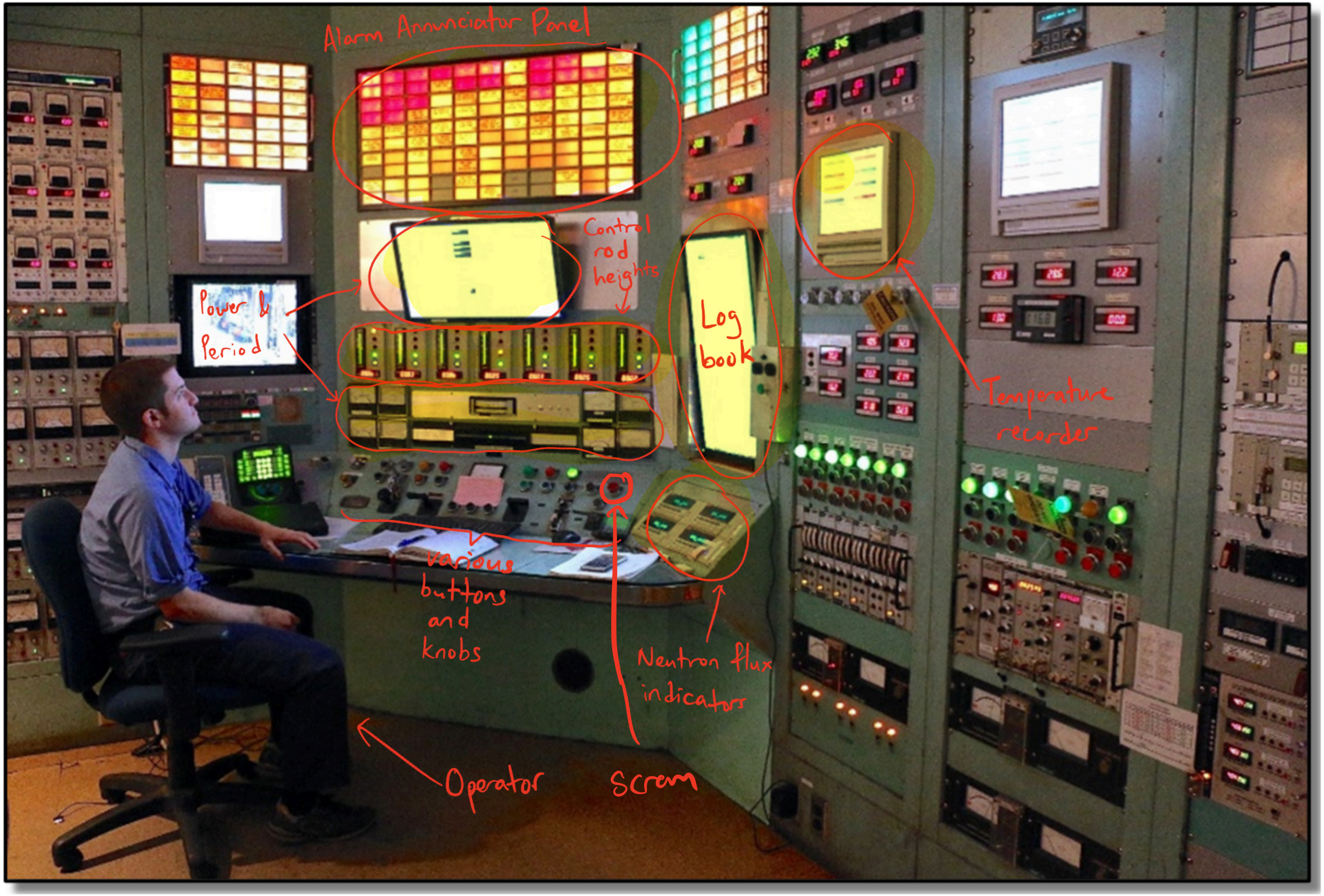
Examples include: reactor power, coolant temperature, pressure and flow, tank levels

We also have an automatic controller!

A closer look

Here are some of the most important instruments in the control room.

Conveniently, they're all right in front of the operator :)

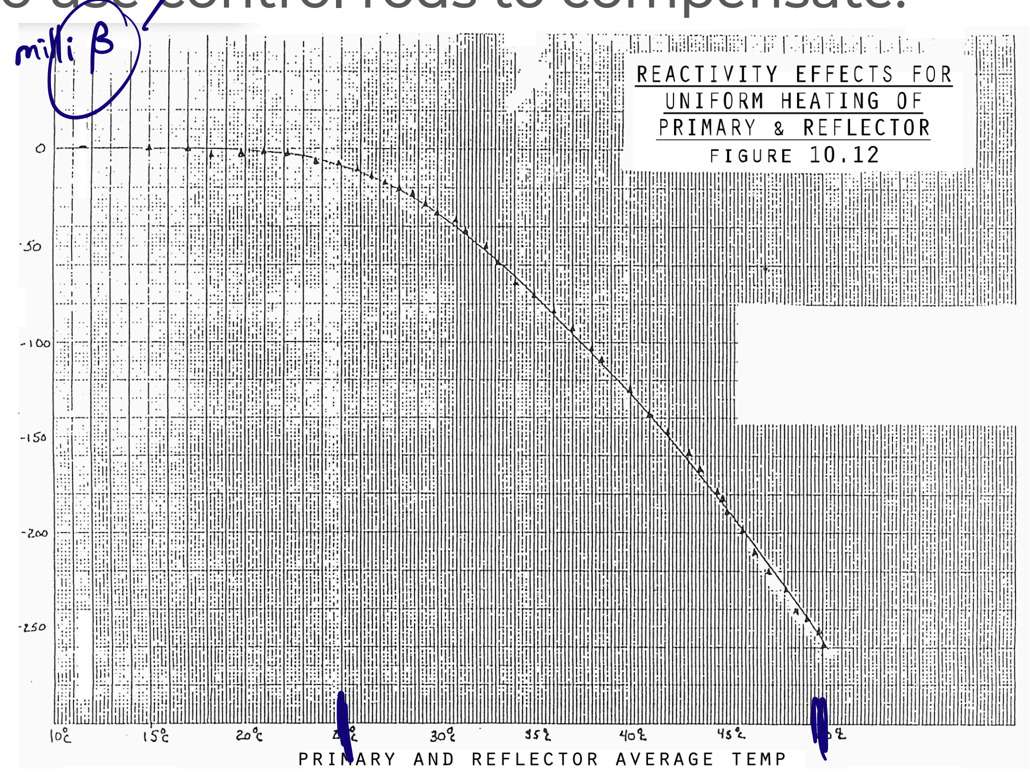


Reactor feedback mechanisms

delayed neutron fraction

There are a number of ways the reactor responds during operation which affect reactivity, requiring us to use control rods to compensate.

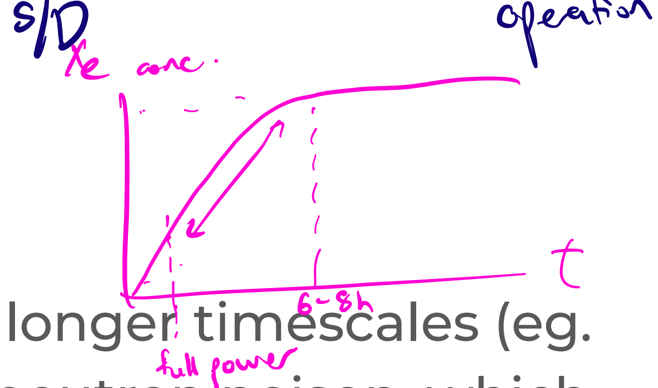
<u>Moderator temperature</u> is the fastest such mechanism. As the reactor operates, the light water which serves as both coolant and moderator heats up. As water becomes less dense, it becomes a worse moderator and also allows more neutrons to leak out.



REACTIVITY EFFECTS FOR UNIFORM HEATING OF PRIMARY & REFLECTOR

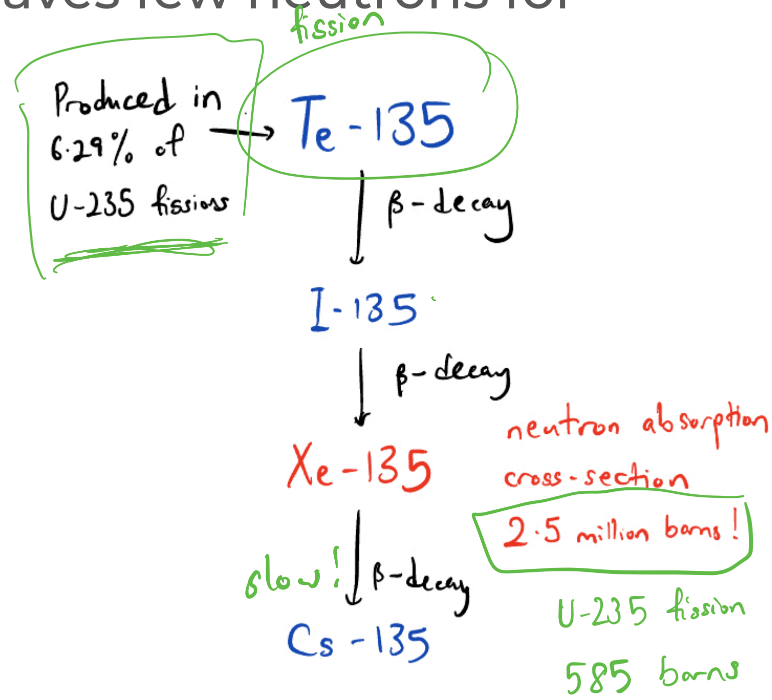
FIGURE 10.12

Reactor feedback mechanisms



Xenon concentration becomes important over longer timescales (eg. hours of operation). Xenon-135 is a very strong neutron poison, which means it absorbs neutrons very easily - this leaves few neutrons for U-235 and effectively kills the chain reaction.

Unfortunately, Xe-135 is a natural product of the decay of some of the most common fission yields (elements produced from U-235 fission), so its production in a reactor is unavoidable. As Xe-135 builds up, we need to bring out the control rods to counteract the negative reactivity effect.



neutron absorption cross-section
2.5 million barns!

U-235 fission
585 barns