What’s in a Nuclear Reactor?

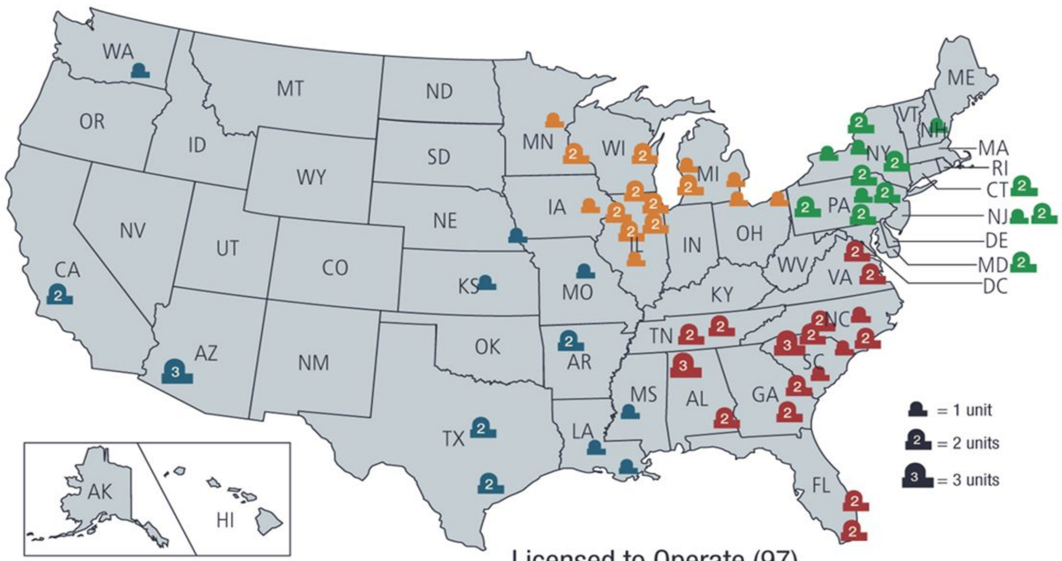
ft. the MIT Research Reactor (MITR-II)

Nuclear power in the US

Nuclear power plants generate ~20% of electricity in the US. There are ~100 commercial reactors and ~35 research reactors.

MITR is one of the oldest (operating since 1958!) research reactors, and the second-largest university reactor.

U.S. Operating Commercial Nuclear Power Reactors



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U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

As of August 2019

Let’s get started..

All matter is made up of things called atoms.

Atoms are the smallest division of something you can get that still behaves the same way. We can break down atoms - in fact that’s what nuclear reactors do! - but the products don’t behave the same as the original.

The center of an atom is called the nucleus, and sometimes when nuclei (plural) react, interesting things happen - hence the name “nuclear reactor”!

What’s in a nucleus?

Nuclei are made up of two types of particles: protons and neutrons.

When nuclei react, they generally do one of two things: split (fission) or combine (fusion).

Nuclear power plants today make use of fission. Fusion can generate much more power (it’s what powers the Sun!) and is much cleaner, but is really, really hard to do.

What kinds of atoms and nuclei are there?

Atoms are classified by the *number of protons* they contain. A type of atom is called an element, and atoms of the same element share most of their chemical properties. Some elements include oxygen, iron and gold.

Nuclei of the same element are classified by the *number of neutrons* they contain. Isotopes of an element are atoms of the element that have different numbers of neutrons in the nucleus. For example, carbon normally has 6 protons and 6 neutrons, but another common form has 8 neutrons.

Where does the energy come from?

You might have heard of Einstein's famous $E = mc^2$.

Every nucleus has a property called a mass defect, which is essentially the difference between the sum of the mass of the protons and neutrons they contain, minus the actual measured mass of the nucleus.

How can this be different? Binding energy - some energy is stored in the bonds between particles. When nuclei break apart, the mass defect/binding energy can change, and excess energy is released.

Ok, now how do we split nuclei?

Some isotopes are stable, meaning that if you leave them for a long time they won't change. Most common materials are this way (otherwise they'd break down and we wouldn't find them...)

Other isotopes are unstable, meaning that they will break down on their own. This is known as *radioactive decay*, and it is a completely random process. Some isotopes decay almost instantly, but others may decay slower. There are three main types of radioactive decay: alpha, beta and gamma.

Ok, now how do we split nuclei?

When we send neutrons into nuclei, sometimes a nucleus will absorb a neutron, causing it to become a different isotope. The incoming energy of the neutron is also absorbed, making this an *excited* nucleus.

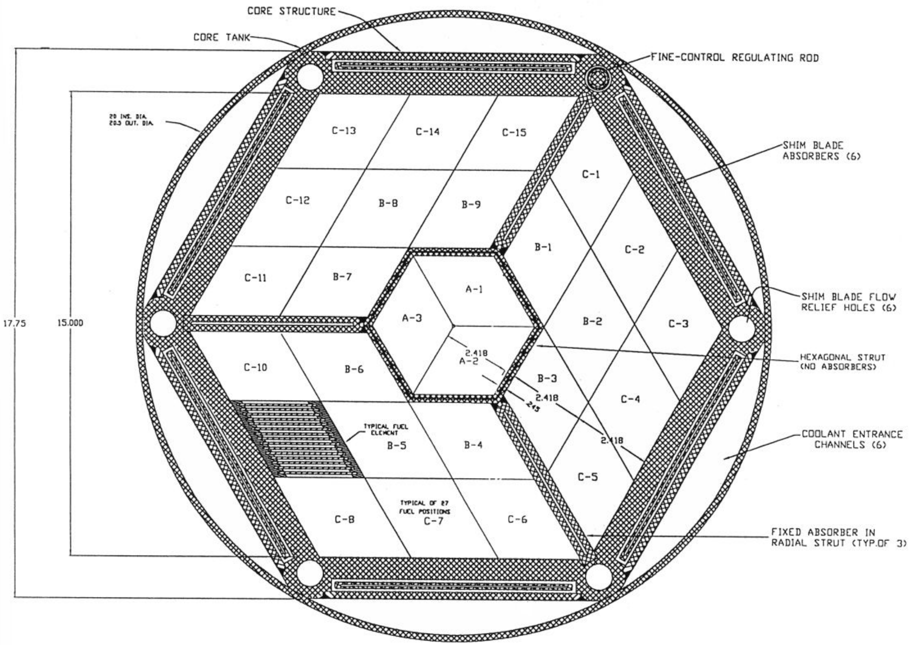
At this point, a couple of different things can happen:

- The nucleus yeets out another neutron.
- The nucleus releases the energy as gamma rays and settles down.
- The nucleus splits into smaller nuclei, releasing some energy and maybe more neutrons. This can cause a nuclear chain reaction.

The core

Holds the nuclear fuel where the magic happens :0

Generally, reactor cores have some number of *fuel elements*, which each hold some nuclear fuel. Usually, this is uranium-235: Uranium is an element with 92 protons, and the 235 indicates 235 total *nucleons*, which are protons plus neutrons. U-235 is an isotope of uranium.



QA# 2014-17

CORE SECTION MITR-II

FIGURE 1.8

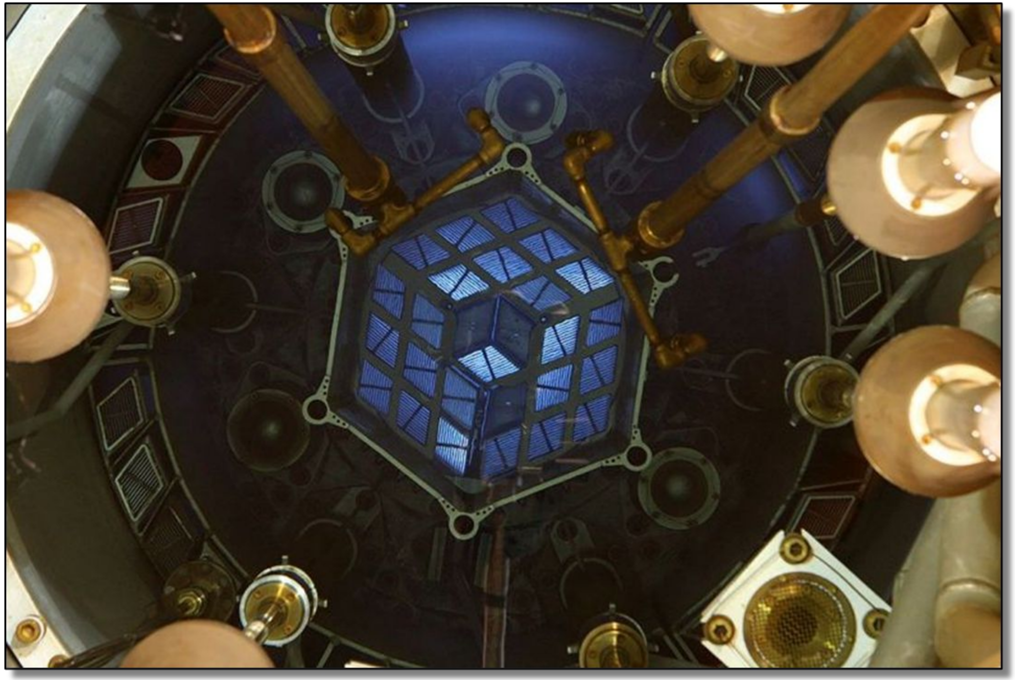
SEPT 2 2014

The core

At the MIT reactor (MITR), the core is surrounded by two tanks of water: the core tank containing *light water*, and the reflector tank containing *heavy water*.

Light water acts as a coolant and neutron moderator.

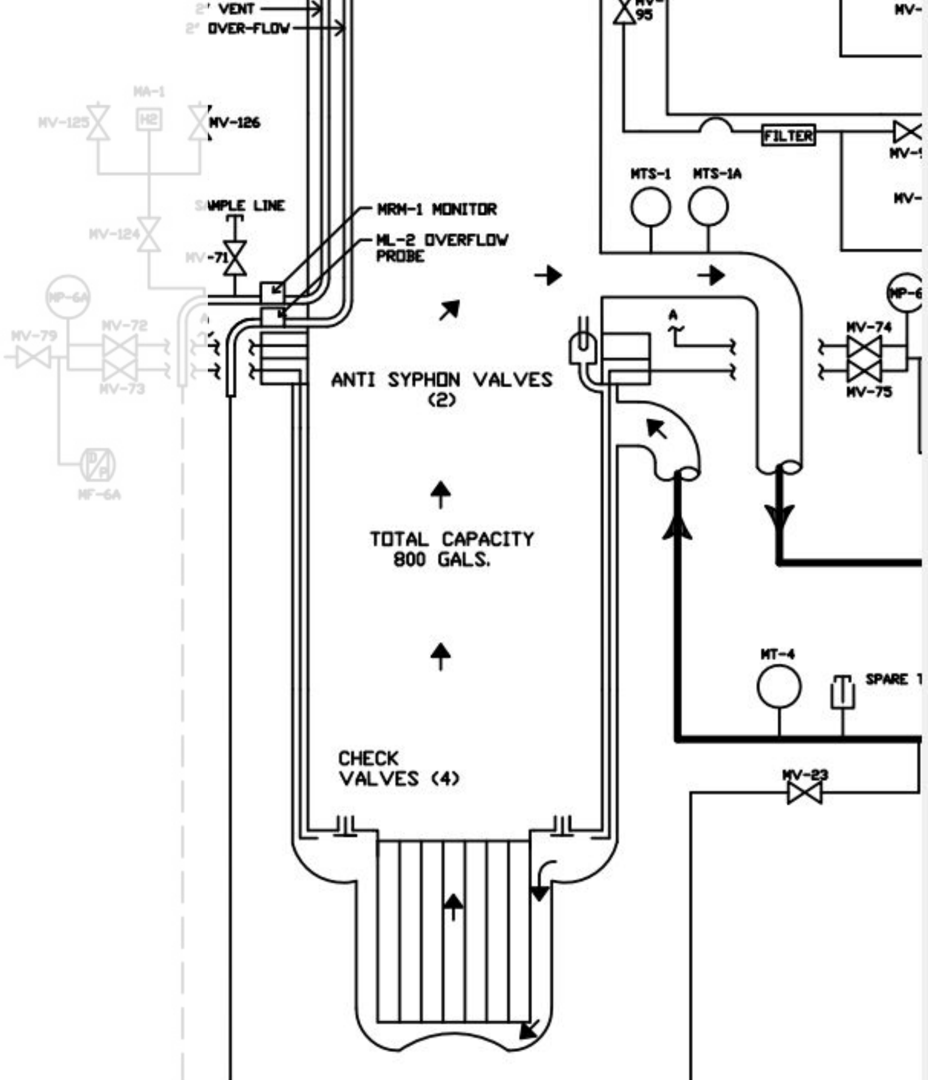
Heavy water acts as a neutron reflector.



Cooling systems

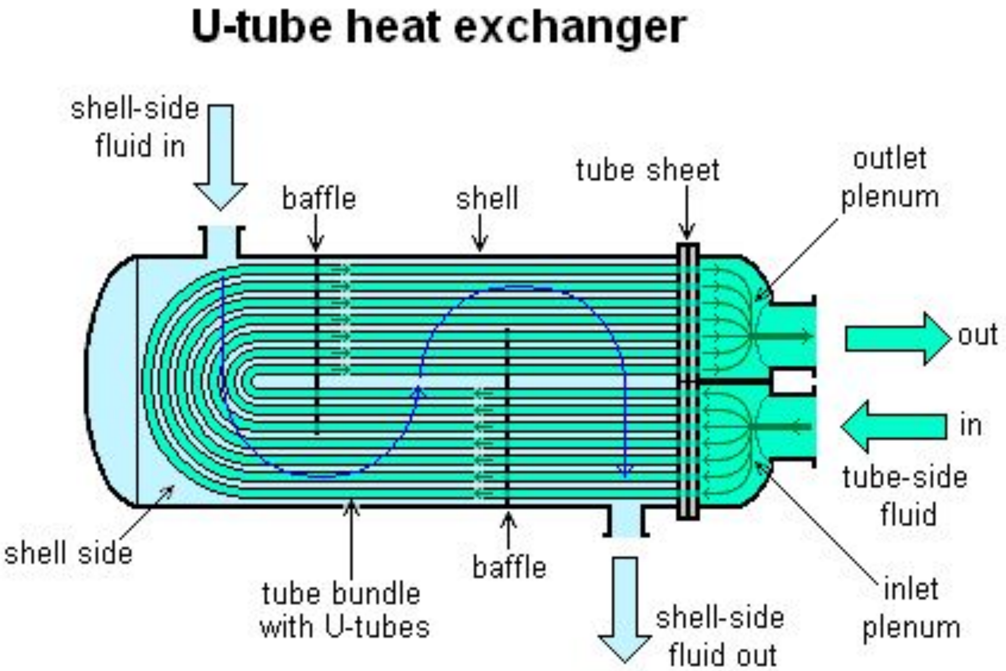
Nuclear reactions release much of their energy as heat.

Primary coolant is the coolant that is directly in contact with the core. It’s what removes heat from the core itself to prevent fuel from melting.



Cooling systems

Secondary coolant meets the primary coolant (but doesn't mix!) at a component called a heat exchanger. It removes heat from the primary system and exhausts it to the environment.



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Control systems

Fission chain reactions need to be controlled to be useful - if they’re uncontrolled, we get explosions, and explosions bad.

When U-235 splits, it releases two or three extra neutrons. If each of those splits another U-235, we get between 4 and 9 new neutrons, which then split more U-235 to get 8+ neutrons, and so on…

In reality, this doesn’t happen - not every neutron splits a nucleus, and many neutrons escape the reactor core or are absorbed.

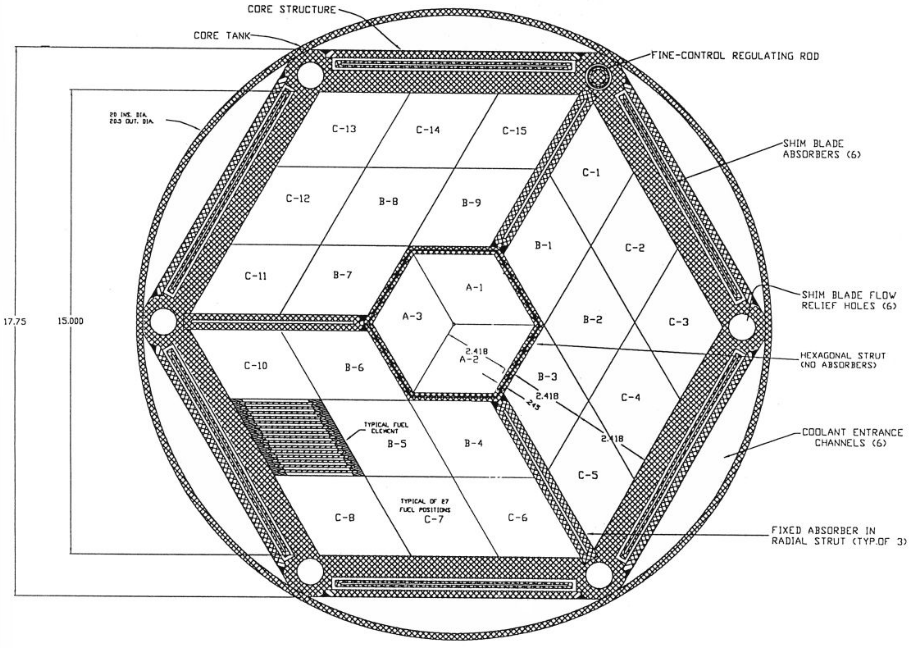
Control systems

We can control how many neutrons are available for the chain reaction by controlling how many neutrons are absorbed.

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* and a *fine-control regulating rod*.

Control systems



CORE SECTION MITR-II

FIGURE 1.8

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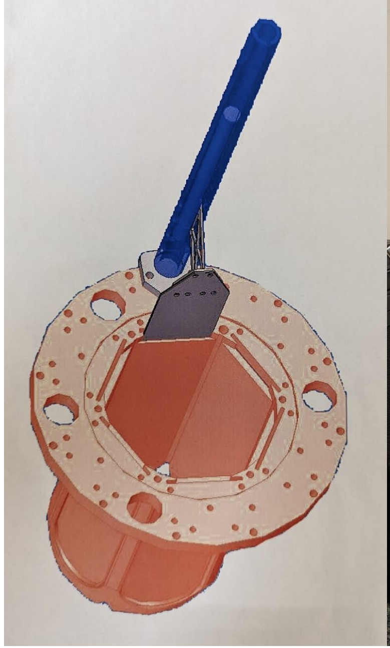

The six shim blades are located in a hexagon around the core, and are normally used for larger power adjustments.

Operating the reactor

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

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

Shielding

Radiation can be very dangerous to both living and non-living things, as we’ll talk about later. Shielding the reactor helps to make sure it doesn’t release excess radioactivity.

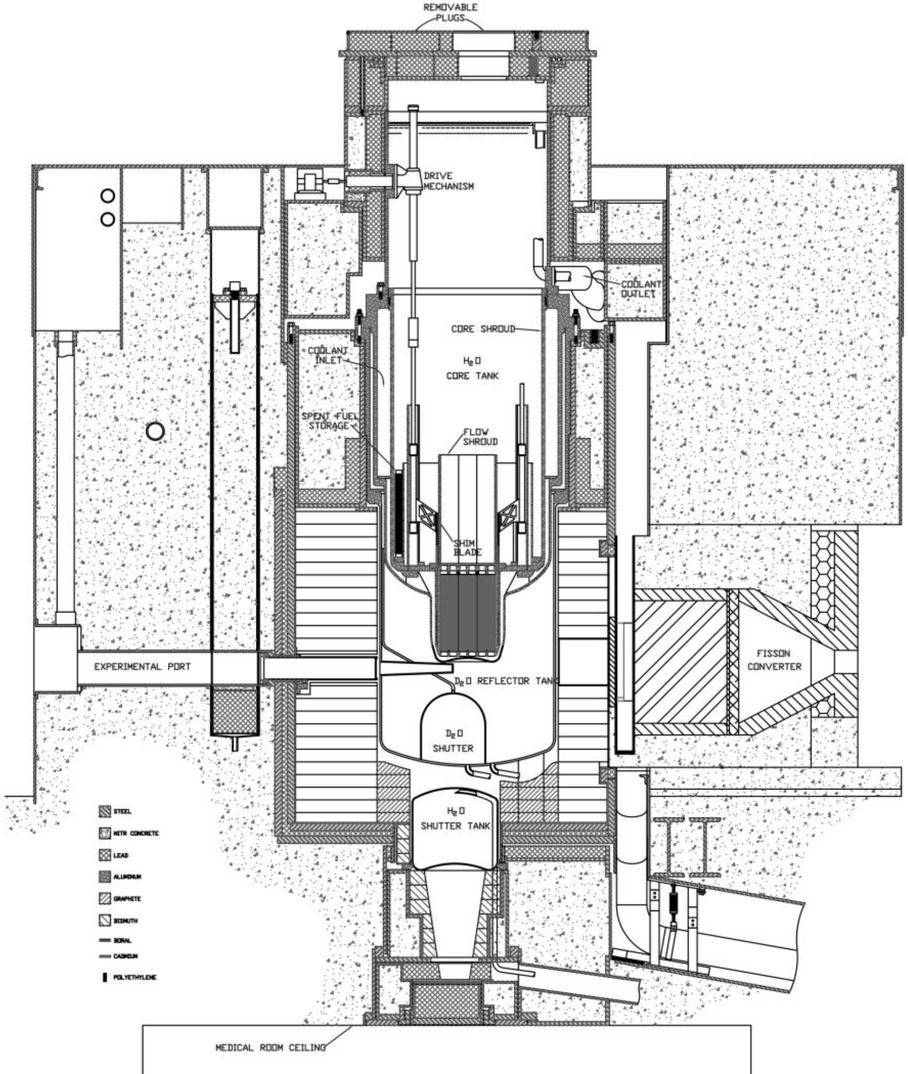
There are several things to shield against:

- Alphas and betas don’t travel far.
- Gammas are shielded by heavy elements like lead.
- Neutrons are shielded by light elements like the hydrogen in water.

Shielding

The MITR’s shielding has several layers:

- core and reflector tanks,
- graphite absorbers,
- lead thermal shielding and
- concrete biological shielding.

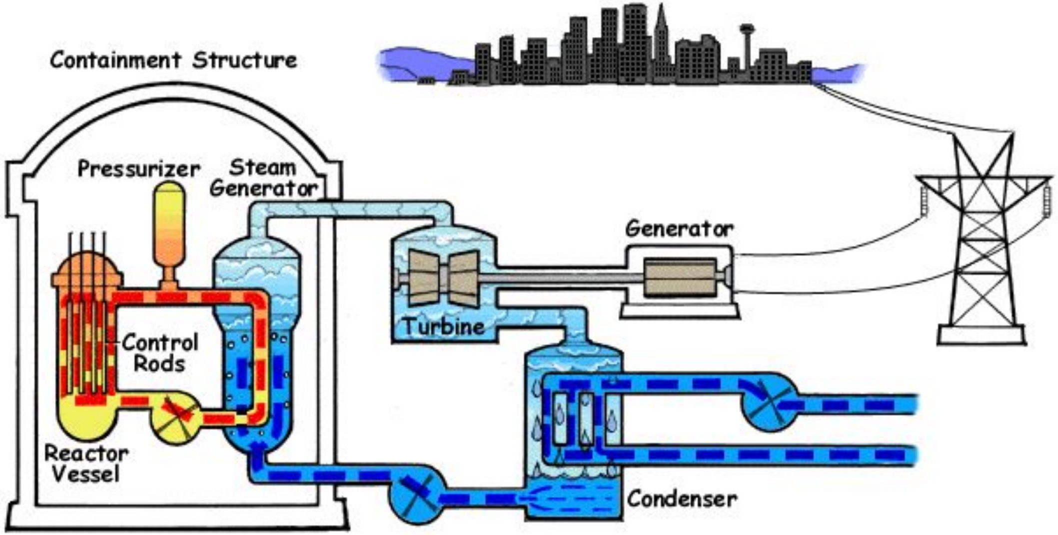


Generating power!

Pressurized water reactors (PWRs) are the most common reactor type in modern nuclear power plants.

PWRs have high-pressure water as their primary coolant (to prevent boiling).

Secondary coolant turns to steam and drives a turbine to generate electricity.



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The dangers and downsides

GRAPHIC IMAGE WARNING!

The dangers and downsides

Radiation can be very harmful to living beings. Large doses will damage cells by causing mutations, making them unable to function properly. This presents as *acute radiation syndrome (ARS)*, with a list of symptoms ranging from vomiting, diarrhea and blistering to hair loss and seizures.

Even small doses can be dangerous, as the mutations they cause can lead to increased risk of cancer or birth defects in children.

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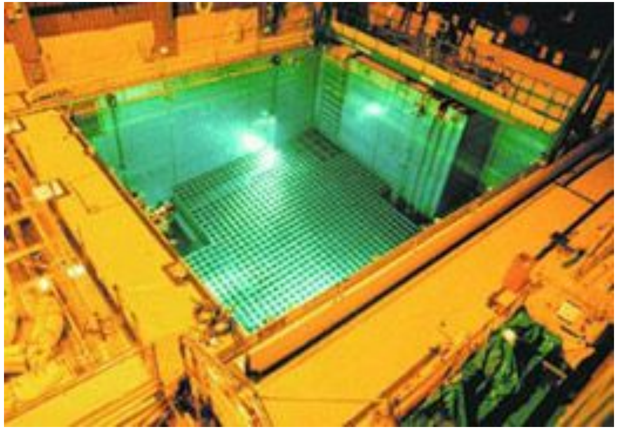
The dangers and downsides

Fission reactors generate large quantities of radioactive waste, like the products of the splitting of U-235. These are often highly radioactive and have to be stored carefully for a very long time. Currently, most waste is stored in “spent fuel pools” or “dry casks”.

Some waste is buried deep underground (see the Yucca Mountain repository), but the site has to be chosen carefully to make sure that the space will not collapse in the next few thousand years.

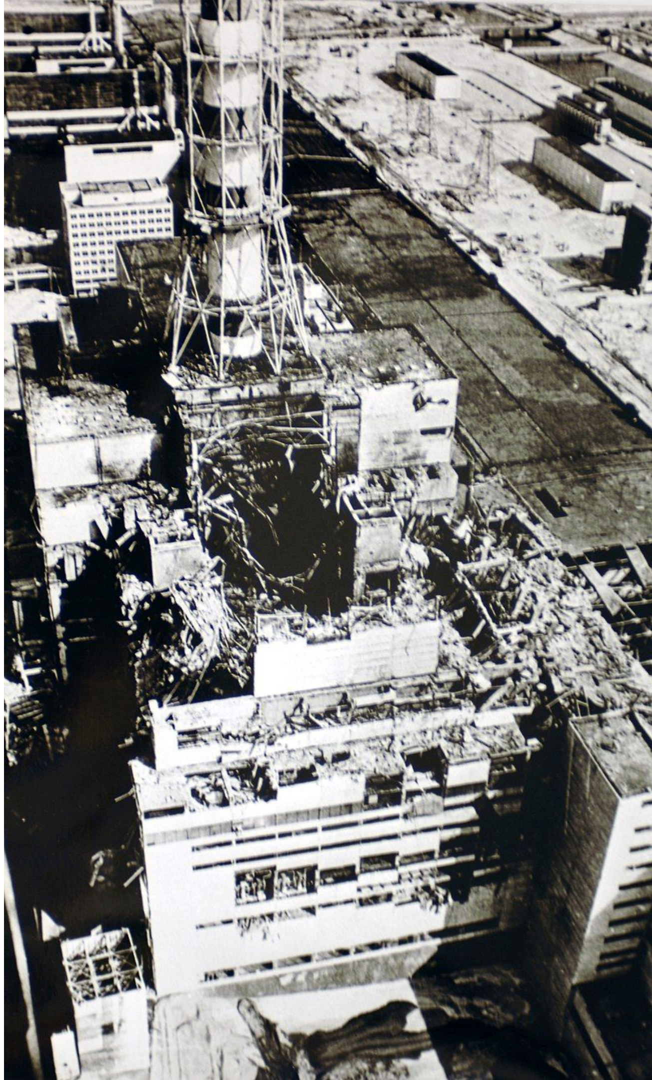


By NRC, https://www.nrc.gov/waste/spent-fuel-storage.html

The dangers and downsides

There is a risk of nuclear accidents, which can result in the release of radioactive materials. The most famous such accidents are Chernobyl (1986) and Fukushima (2011), each requiring hundreds of thousands of people to evacuate.

These were International Nuclear Event Scale (INES) *Level 7* accidents: major release of radioactive materials with widespread health and environmental effects.



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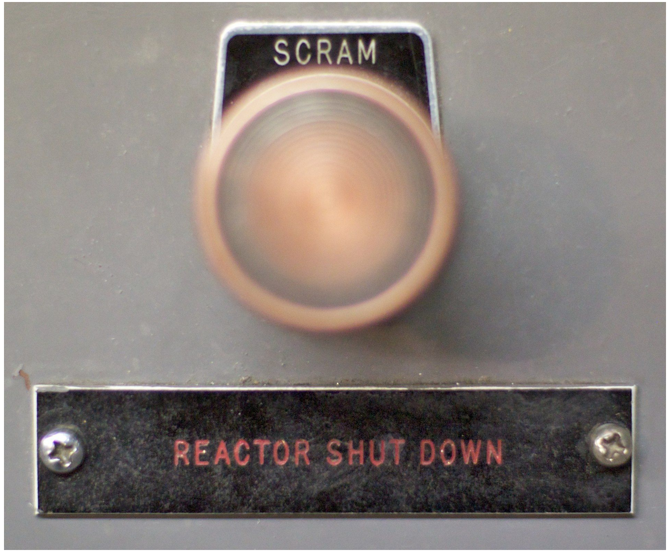
Safety in a nuclear reactor

One of the safety mechanisms in nuclear reactors is called a *scram*. Essentially, a scram inserts all the control elements, absorbing lots of the neutrons and stopping the nuclear chain reaction.

Lots of dangerous conditions will trigger an automatic scram (at MITR, there are 30+ of these conditions!), such as rapidly increasing power or high coolant temperature.

There's also usually a "big red button" that an operator can use to scram the reactor.

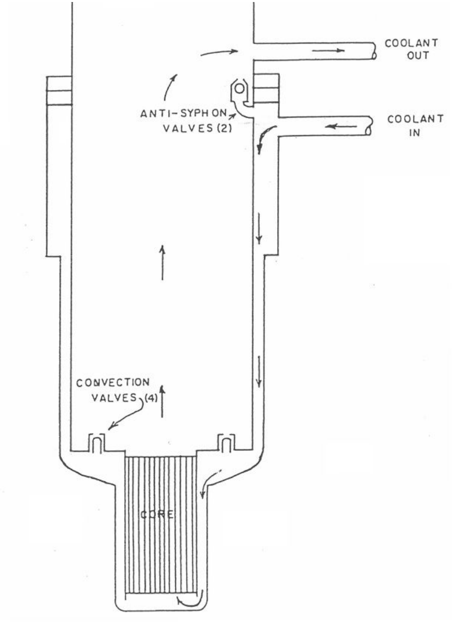


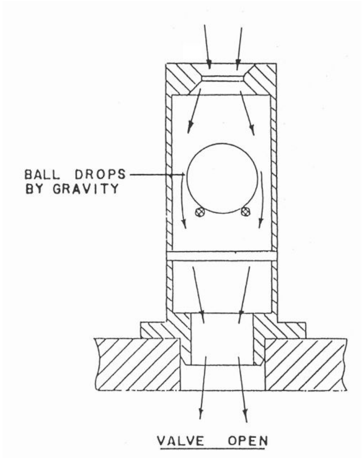
Safety in a nuclear reactor

Even after shutting down (whether normally or via a scram), the core still produces some *decay heat*, because the core is radioactive!

In a scram condition, the primary coolant pumps may not work, but the core still needs cooling. All reactors have an *emergency core cooling system* to ensure the core remains within safe temperature ranges.

At MITR, decay heat can also be removed by natural convection.

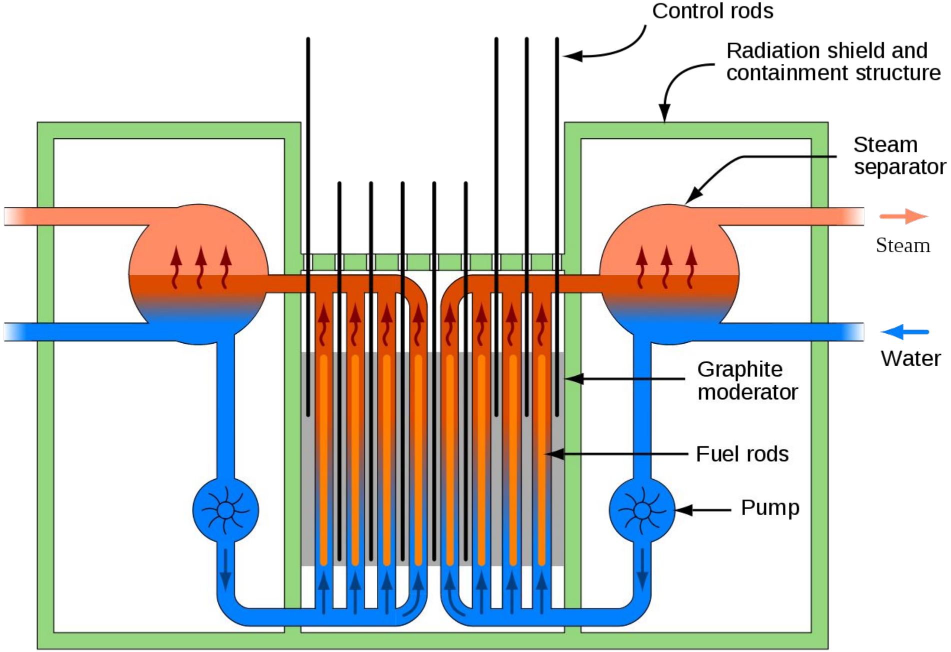




Safety in a nuclear reactor

If all else fails, most reactors have a passive safety feature: they have *negative reactivity coefficients*. This means that as certain values (fuel temperature, coolant and reflector temperatures, void coefficient) increase, the reactor becomes less reactive.

The design of the Chernobyl reactor, which did not have negative reactivity coefficients, contributed to the disaster.



By Fireice~commonswiki, Sakurambo, Emoscopes - Own work based on: Magnox reactor schematic.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3579057

Some links before we leave...

MIT Nuclear Reactor Lab: nrl.mit.edu

US Nuclear Regulatory Commission's Basic References:
https://www.nrc.gov/reading-rm/basic-ref.html

International Atomic Energy Agency's Nuclear Explained:
https://www.iaea.org/newscenter/nuclear-explained

Or shoot me an email at S15510-teachers@esp.mit.edu!