How to Save any Screen, so you can review the screen now or later

Device Type	Key combo OR Button combo	Screen image is saved in this folder
Windows	WIN+PRTSCR	Pictures/Screenshots
Macintosh	Shift+CMD+3	Desktop
Android portables	Power+Volume Up	Internal Storage/ DCIM/Screenshots
Apple portables	Home+Volume Down OR Power+Volume Down	Photos

Old and New Nuclear Power Tech

A presentation by

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for PATACS+OPCUG

July 19, 2025

AGENDA

- Inexpensive energy
- Review of the Basics
- Two types of current nuclear reactors
- Weaknesses and accidents
- New nuclear reactor tech … from the 1950s
- Breeders reactors and Thorium
- Companies pursuing new reactor development

My background does not include a nuclear engineering education

- I learned about this topic initially from my son.
- I watched videos and read a book on the topic.
- There are a dozen+ books aimed at a general audience.
- The book by **Alvin Weinberg** is far too technical.
- **Kirk Sorensen** used to do reactor tech presentations for just about anyone who asked, even tiny groups in a home basement. Now he has a full-time executive job.
- So you are stuck with me instead.

Inexpensive Energy is the basis for our Economy and Culture

- Energy heats and cools our homes, powers our transportation, and powers our digital devices and the Internet.
- Energy is also essential for making our digital devices.
- To bring prosperity and reduce conflict around the world, providing inexpensive energy is a key.
- Nuclear energy is cleaner ***and less radioactive*** than coal and natural gas energy fuels.
- Nuclear energy safety can be improved.

Heat, not radiation, is the key concept for reactor safety

- You are about to see a refresher from high school chemistry plus a bit more.
- This helps you to understand how radiation produces heat in a nuclear reactor.
- Heat, transferred to water, produces steam to drive steam turbines to produce electricity.
- Heat MUST be transferred or the heat buildup in a reactor can destroy the reactor.

A review of the Basics

- **Atom:** includes a nucleus surrounded by electrons
- Each **element** nucleus contains a fixed number of protons, equal to the number of electrons. The proton count is called the element's **atomic number**.
- Hydrogen►1, Lithium►3, Carbon►6, Oxygen►8, Silicon►14, Iron►26, Uranium ►92.
- Atoms contain neutrons in the nucleus also, except the most common form of Hydrogen.

A review of the Basics

- Some atoms of an element contain a varying number of neutrons in the nucleus.
- Each atom of an element with a specific number of neutrons is called an **isotope**.
- Isotopes are identified by the **exact number** of protons plus neutrons.

Uranium isotopes

- 99% of all Uranium on Earth is **U-238:** 92 protons and 146 neutrons.
- About 1% is **U-235**. That is the most common fuel for nuclear power reactors. It is rare and costly.
- About 0.0054% is **U-234.**
- Another isotope: **U-233** is not known to exist in nature on Earth. Nonetheless it has been created artificially, evaluated and used. It may play a big role in the future.

What is radioactive decay?

- Some heavy elements spontaneously eject an **alpha ray**, two neutrons and two protons (a Helium nucleus), from the nucleus. That natural process is called **decay**; both an example of radioactivity and of transmutation.
- The rate of natural decay is called **half-life**, meaning the time required for half of the atoms in a sample to decay.
- U-238: half life 4.5 billion years
- U-235: half life 700 million years
- U-233: half life 159,200 years

What is fission?

- Fission is a ***stimulated breakup*** of an atomic nucleus.
- Fission is stimulated by injecting a neutron at low speed into a nucleus. Injection is not a precise action.
- The fission of a U-235 atom releases a couple of neutrons, and a couple of atoms of lesser atomic number, all moving at high speed.
- High speed movement of atoms is also known as **heat.**
- Carbon inside the reactor surrounding each fuel rod slows down neutrons, and many slowed neutrons then reach and are absorbed by other U-235 atoms.

What is enrichment?

- Enrichment is a process of refinement, removing U-238 so that the portion of U-235 is increased.
- Enrichment often uses gas molecules of Uranium Hexafluoride in a gaseous centrifuge. U-235 floats to the top, and slightly heavier U-238 falls to the bottom.
- The typical enrichment for reactor fuel produces Uranium with 5% U-235 and 95% U-238.
- That 5% enrichment may require two or more stages of centrifuge operation.
- Bottom line: enrichment is expensive.

What is criticality?

- Criticality describes a nuclear fission reaction that carries on continuously.
- Criticality is the basis for nuclear reactor operation. It requires a critical density of nuclear fuel atoms such as U-235.
- Technically, criticality describes the situation where the number of neutrons released is equal to the number of neutrons absorbed by nuclear fuel atoms.
- Nuclear fuel that that does not receive enough neutrons to stimulate release of the same number of neutrons is called **sub-critical**.

Nuclear reactors produce heat; water heated to steam drives generator turbines

- A reactor vessel contains nuclear fuel, control rods, moderator material (carbon), and water tubes.
- The water tubes warm up, and the water carries heat out of the reactor vessel.
- The main difference is current reactor types is what happens to water inside and outside of the reactor vessel.

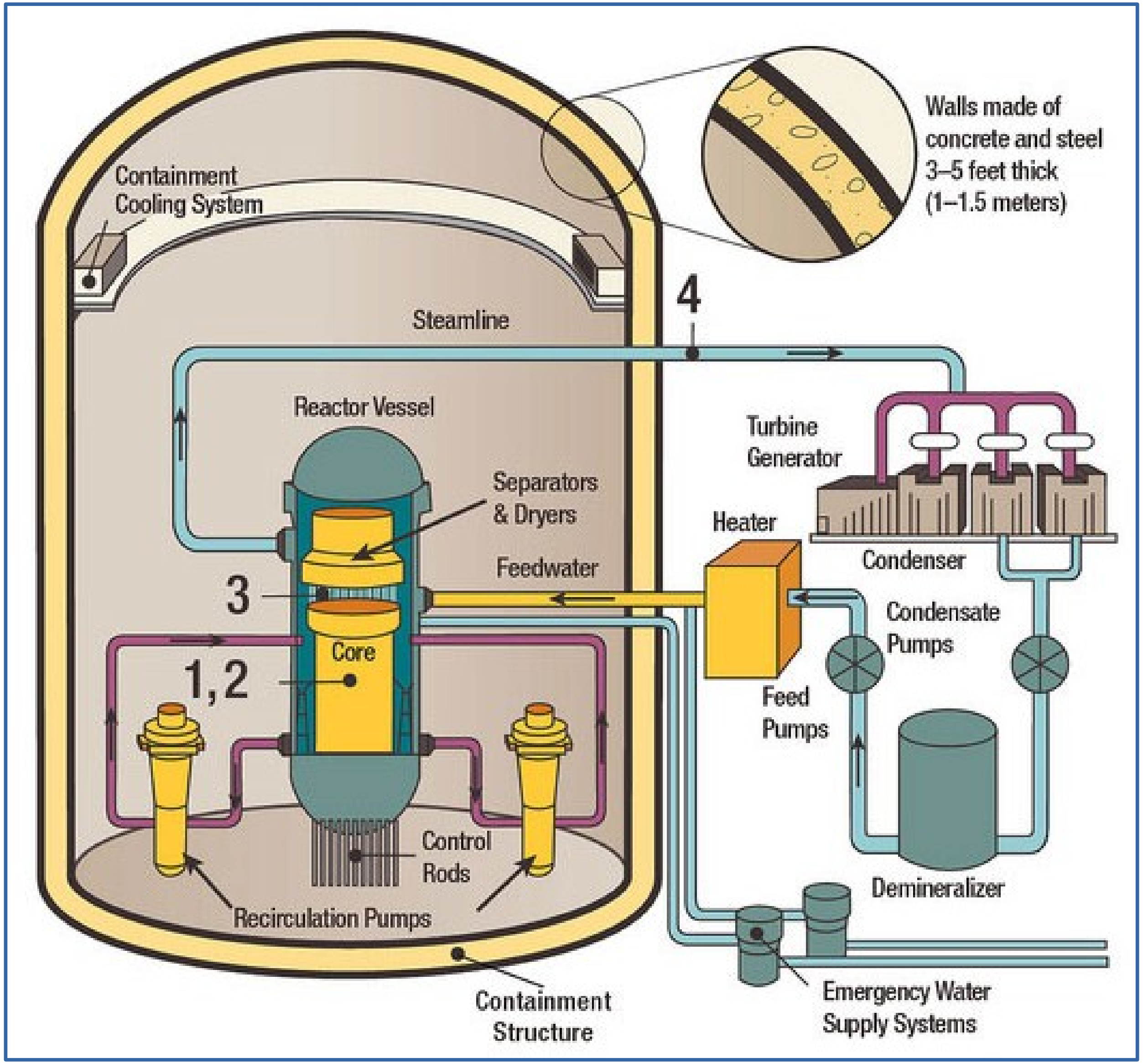
Removing Heat from A Nuclear Reactor is a Major Safety Factor

- Without heat removal, the heat builds up inside the reactor vessel and eventually destroys the reactor and its vessel.
- In severe cases, the reactor building containing the reactor vessel can be damaged.
- In a nutshell, a failure to remove heat caused all three of the famous power reactor failures.

Two Types of Old Nuclear Reactors in use

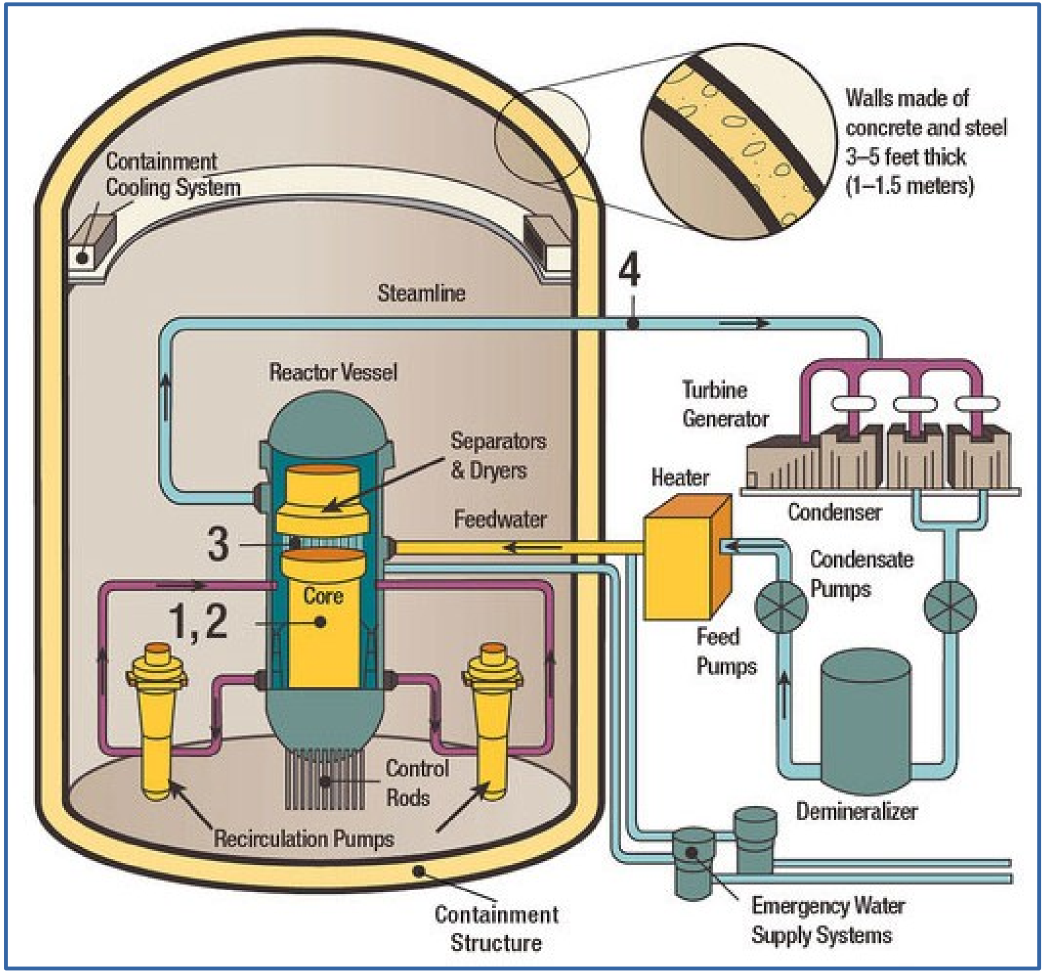
Boiling Water Reactor

- Reactor vessel **3**
- Steam line **4**
- Generator Turbines
- Condenser
- **Water Pumps**



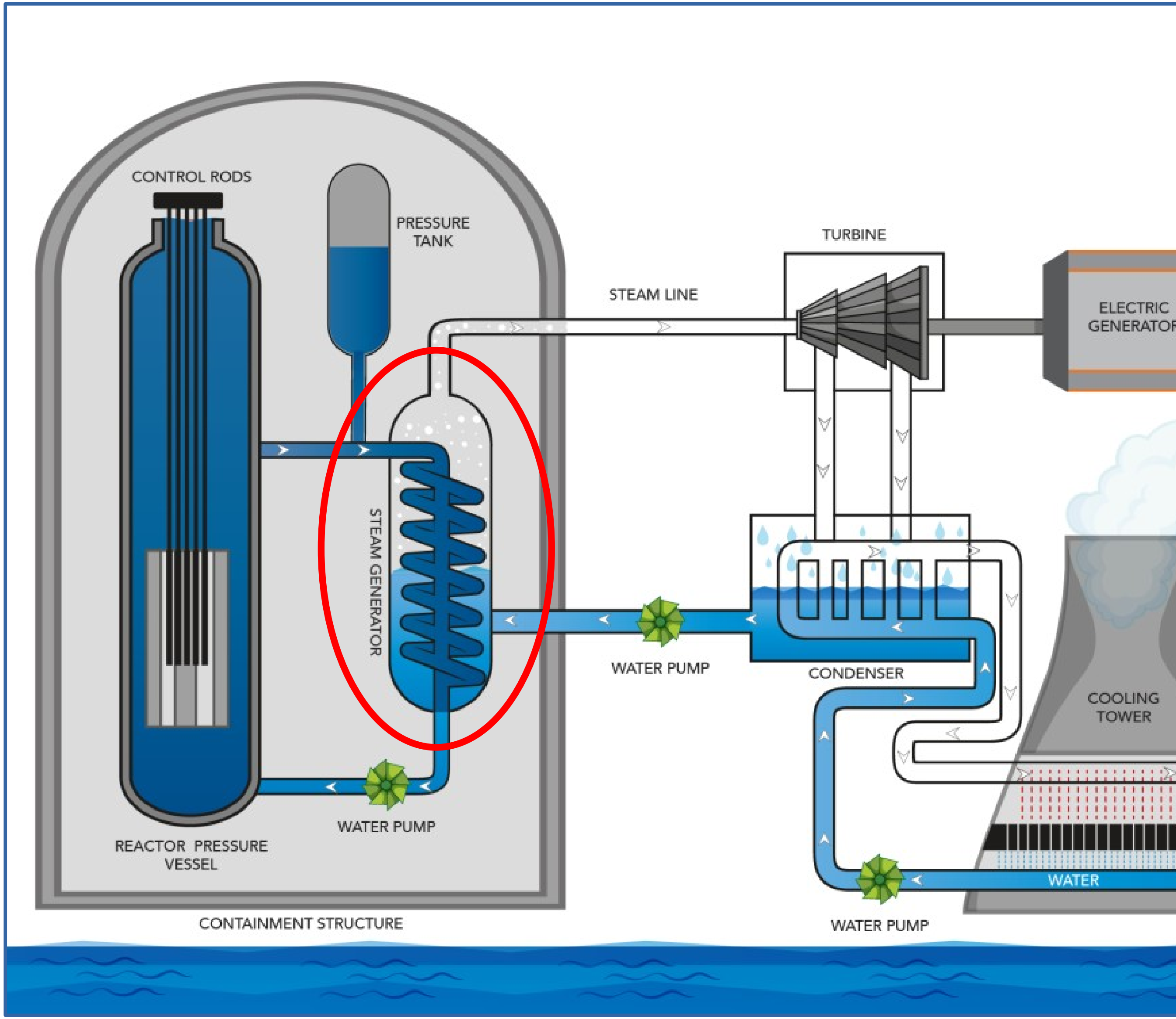
Boiling Water Reactor (BWR)

- Water pipes inside the reactor vessel 3 heat up. Hot water turns to steam.
- The pipes 4 carry steam to spinning steam turbines, and then to a condenser to cool steam to its liquid state.
- Water returns to the reactor vessel via the feedwater line to repeat the cycle.



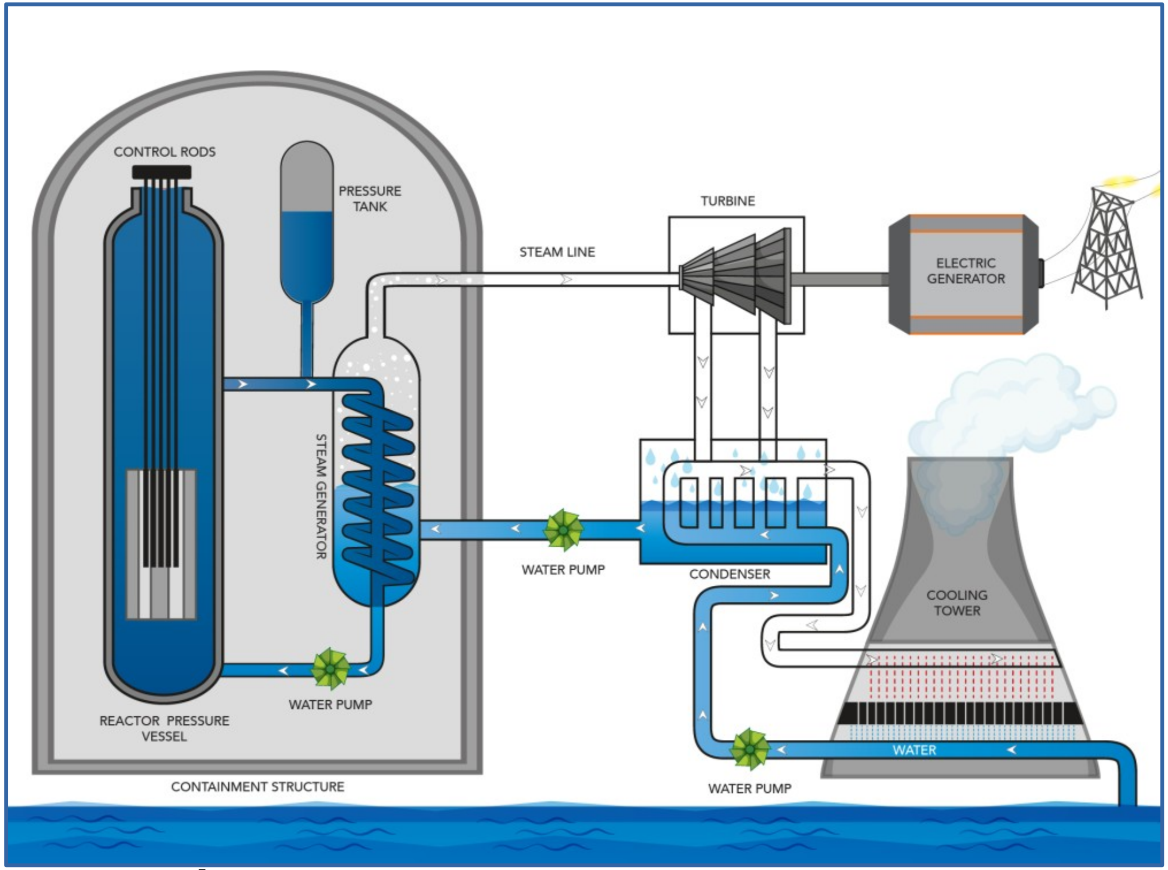
Pressurized Water Reactor

- **Two** cooling loops.
- **Heat exchanger** (circled) hands off primary water loop heat to secondary water loop.
- Exchanger heats second water loop to steam.



Pressurized Water Reactors (PWRs)

- The pressurized primary cycle water flows through a heat exchanger, cools, and then goes back into the reactor vessel.
- After spinning the turbine, steam heats incoming water from a river or lake and then is released through a cooling tower.



- Pumps (green) keep water moving.

US Nuclear Power Reactors

- About 65% of nuclear power reactors in the US are PWRs.
- Those include the Surry (1.6 GW) and North Anna (1.892 GW) plants in Virginia, and the Calvert Cliffs (1.79 GW) plant in Maryland.
- About 35% are BWRs.
- Both types use condensers to turn steam back into liquid water and pumps to keep the circulation moving.
- Condensers need cool water in large quantity, usually from a river or large lake.

Weaknesses of PWRs and BWRs

Weaknesses of Nuclear Tech

- **Fuel inefficiency:** each fuel rod is spent when only 2% of its 5% U-235 has fissioned. This is both an economic inefficiency and a long-term safety issue.
- **Water Pumps can fail:** when pumps stop, water in pipes sits in the reactor vessel too long, overheats, and can destroy a reactor vessel and part of the building around it.
- Pump power supplies are redundant because of the pump failure risk. That can include power from outside the power plant.

Analyses of Nuclear Power Reactor Failures

The Three Mile Island failure

Three Mile Island

- A PWR. The secondary water pumps failed, so the heat exchanger did not cool the primary cycle water.
- The primary cycle water overheated in the reactor.
- Inside the reactor vessel, the nuclear fuel and related materials overheated and partly melted. The melted fuel did not melt through the containment building floor. There was no explosion.
- A tiny bit of radioactive gas was released, not enough to exceed background radiation levels in the closest homes.

The Chernobyl failure

Chernobyl

- A BWR. The **water pumps were shut off** by a poorly-trained test crew.
- The reactor had been partly shut down. It eventually heated rapidly to 3x its designed max operating wattage.
- The steam overheated. Steam pressure burst its pipes inside the reactor vessel.
- In the high heat of the reactor, water molecules broke up into H_2 and O_2.
- Heat or a spark caused explosive combustion, which burst the reactor vessel ***and the containment building.***

Chernobyl

- Years earlier, the reactor vessel, fuel and other parts were lowered into the containment building.
- A frustro-conical concrete cap sealed the roof after that. The cap weighed over 100 tons.
- The hydrogen explosion threw that cap into the air.
- The cap flipped and landed on the roof off-center and upside-down.
- A gap between the cap and the roof allowed hot radioactive gas to rise in the atmosphere and scatter on the winds.

The Fukushima Daiichi failure

Fukushima Daiichi

- A BWR. An earthquake knocked out local operator controls, and knocked down power lines carrying backup electric power for pumps from another power plant.
- Each reactor had a backup diesel generator in the basement to power water pumps.
- The reactors were near the Pacific and the diesel generators were close to sea level.
- The quake created a tsunami that flooded the diesel generators so they could not power the pumps.

Fukushima Daiichi

- Steam in one reactor vessel overheated and burst its pipes.
- Steam in the high temperatures of the reactor vessel broke down to H_2 and O_2.
- Heat or a spark causes explosive combustion, which burst the reactor vessel and damaged the containment building.
- Some radioactivity from the reactor vessel fuel did escape into the air and the Pacific.

Common Threads

- **Pumps failed or were shut down**. Water overheats in the reactor vessel. Fuel rods overheat in the reactor vessel.
- Overheating in all three incidents melted part of the reactor fuel.
- At Fukushima Daiichi and Chernobyl, water pipes burst, steam contacted hot fuel rods, and steam broke up into H2 and O2, the same gases that powered the Space Shuttle Main Engines.
- Explosive combustion of H2 and O2 burst the reactor vessel and the reactor building at Fukushima Daiichi and Chernobyl.

Another Common Thread

- In an emergency, the nuclear fuel remains in close proximity and sustains criticality.
- There is no way to separate or remove nuclear fuel to eliminate the criticality and its heat.
- Control rods are designed to absorb neutrons and eliminate criticality. Some of those literally broke apart when lowered too fast at Chernybl.

New nuclear reactor tech originated in the 1950s

Alvin Weinberg

- Scientist and leader at Oak Ridge National Laboratory
- Named inventor in PWR tech patents.
- Built and tested **liquid-fuel reactors** at Oak Ridge.
- Shown in 1959 between Senators Kennedy and Gore at Oak Ridge.

Alvin Weinberg

- The US Air Force wanted nuclear power aircraft to keep aircraft aloft for weeks. US Navy reactors were too big.
- Weinberg led a team developing a super-compact **liquid-fuel reactor (LFR)** using Uranium Fluoride salt as a fuel, also known as a **Molten-Salt Reactor (MSR)**.
- The team built and operated two liquid-fuel reactors at Oak Ridge.
- Weinberg concluded ***liquid-fuel reactors were much safer than BWR and PWR***. Later you will find out why.
- The Air Force lost interest, but Weinberg and his team published every detail of the liquid-fuel reactor.

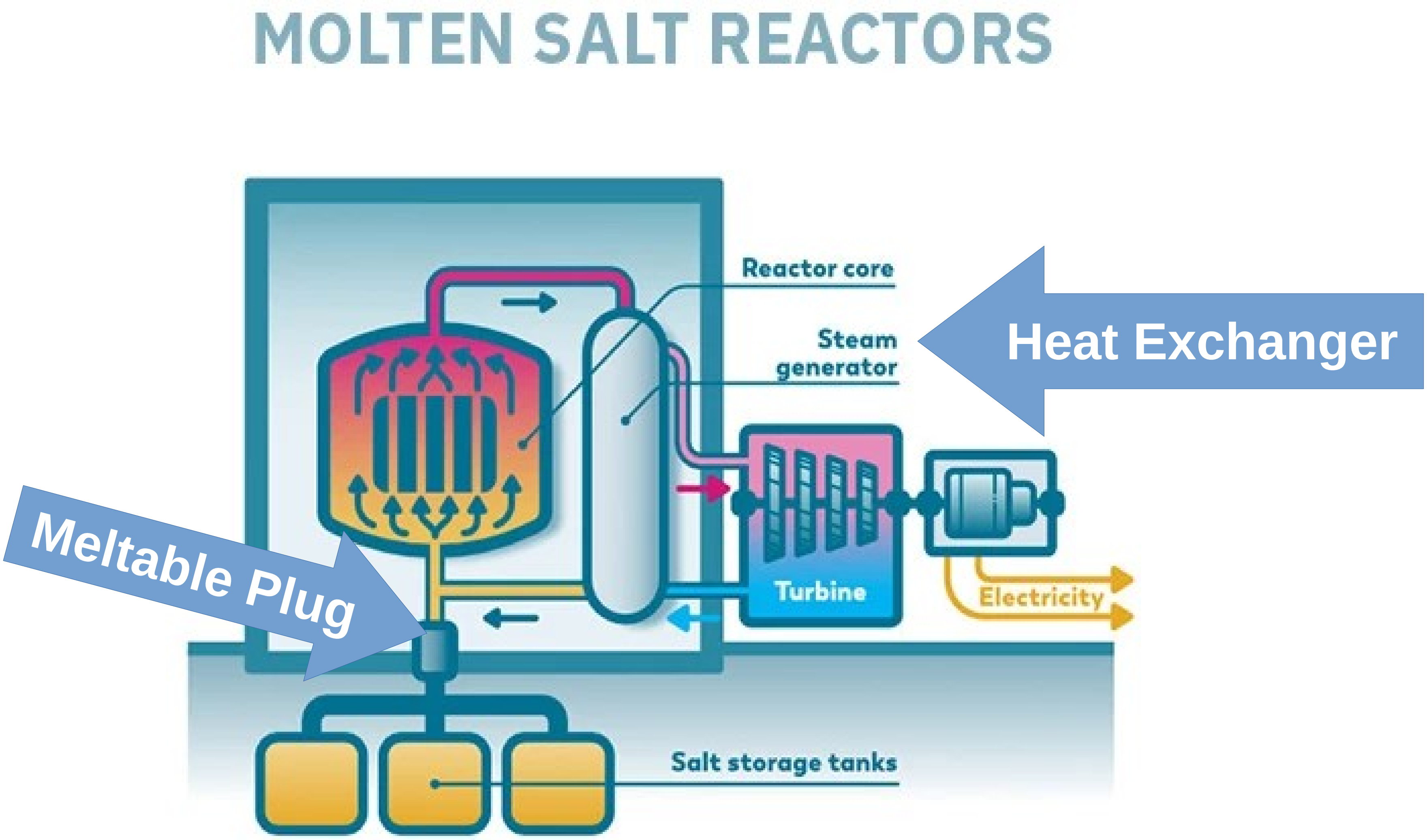
LFR: advantages

- Very compact reactor vessel because liquid fuel achieves criticality at lower physical volume than fuel rods.
- Liquid fuel is its own coolant, flowing between the reactor vessel and a heat exchanger.
- The fuel flow loop outside the reactor vessel is sub-critical due to lower volume pipes.
- Like a PWR, the heat exchanger heats a secondary cycle water to steam for powering a steam turbine.
- Uranium fuel in liquid salt form is 100% fissioned in the reactor. No depleted fuel storage or disposal needed.

LFR: advantages

- Uranium tetrafluoride fuel salt is a liquid at temperatures well below the melting point of Uranium metal.
- Pumps keep the fuel moving through pipes.
- The fuel pipes include a lowest point with a **meltable plug.** Below the plug is one or more wide shallow containers.
- If the fuel overheats, then the plug melts, and the liquid fuel falls into the wide shallow container(s).
- When the fuel is spread out, criticality is not possible. The fuel will cool and will not melt through the container.

LFR diagram


MOLTEN SALT REACTORS
Reactor core
Steam generator
Heat Exchanger
Turbine
Electricity
Meltable Plug
Salt storage tanks

What is a breeder reactor?

- The normal reactor vessel is surrounded by a heavy element that is not nuclear fuel but is **fertile**, meaning it can be transmuted to a nuclear fuel.
- U-238, 99% of all Uranium, can be transmuted by fast neutron absorption into Plutonium, atomic number 94, another nuclear reactor fuel.
- A few US reactors are fast breeders, turning U-238 into Plutonium.
- The U-238 is wrapped around the fuel inside the reactor vessel to absorb fast neutrons. That wrap is called a **bed**.

Thorium

- Thorium, atomic number 90, has a half life of 14 billion years. Pure Thorium does not produce enough radiation to harm you.
- Thorium is common on Earth, about 500 times more common than U-235.
- In a breeder reactor bed, Thorium can be transmuted to **Protactinium**, atomic number 91.
- Protactinium is not itself nuclear fuel, but decays on its own over a few months into **U-233, which is a nuclear fuel**.

U-233 downside

- U-233 is more hazardous than most nuclear fuels.
- U-233 spontaneously emits **gamma rays**, very high-frequency light, more energetic than x-rays.
- Earth's atmosphere protects us from gamma rays originating in space.
- Reactors containing U-233 fuel require **gamma ray shielding** to protect people.
- Protactinium storage for its slow decay to U-233 require **gamma ray shielding** to protect people.

LFR economics

- Consider using say ten LFRs, each with 160 MW capacity:
- The ten might occupy the acreage of one PWR.
- The total wattage might equal the wattage of a PWR.
- A failure of one LFR would only take 10% of the total wattage offline.
- One or two LFRs might be affordable in smaller countries that cannot afford a PWR or BWR.

Liquid-fuel reactor (LFR)

- Start-ups such as **Flibe** (US) and **Copenhagen Atomics** (Denmark) want to factory-build LFRs.
- Both argue that the factory approach will allow tighter quality control and lower costs.
- Both are enthusiastic about make LFRs to breed Thorium into U-233. They call such breeders Liquid Fuel Thorium Reactors (**LFTRs)**.
- But LFTRs are not specifically limited to U-233.
- Weinberg used U-235 as fuel in his LFR.
- He built that first LFR as a breeder reactor.

Copenhagen Atomics

- As of July 2025, this company plans to ship its first production liquid-fuel reactor to the Swiss National Nuclear Lab in 2027 in a truck, and operate it there with the Lab as safety guarantors and system verifiers.
- The company plans to own every reactor they build and ship, and offer electrical power as a service.
- The company hopes to undercut the price of conventional nuclear power, wind power, solar power, coal power, oil power, natural gas power, and even hydropower.
- **www.copenhagenatomics.com**

Flibe

- Flibe, founded by Kirk Sorensen, designs LFRs but as of February 2025 has no customers and no US Department of Energy approvals.
- Kirk Sorensen is featured in numerous YouTube videos describing LFRs. He is a very convincing advocate.
- He is good at explaining how to scrub the liquid fuel using electrochemical methods for removal of valuable medical isotopes, and to pull Protactinium out of the liquid breeder bed and isolate it until it turns into U-233.
- Kirk Sorensen video, one of many: **https://www.youtube.com/watch?v=KfWB4CsQwyw**

Natural Private Markets for compact LFRs

Think of energy-intensive businesses:

- Data centers,especially for AI and bitcoin-mining (25% of Virginia’s electricity supply is used by Data Centers)
- Chemical makers, especially ammonia and chlorine
- Oil refineries
- Chip makers
- Metal makers, especially aluminum

Terrapower

- Funded by Bill Gates, this company is building a Small Modular Reactor in Wyoming. It appears to be building-size, not shipping container size. **www.terrapower.com**.
- The primary loop coolant is liquid metal at low pressure, not water. It won’t turn into metal steam.
- The reactor uses a dual cooling cycle like a PWR. It appears to use liquid fuel, but the fuel itself does not circulate through a heat exchanger.
- If the reactor being built operates safely, its type may get regulatory approval before any compact LFR does.

Economics and Regulation

- The U-235 fuel companies providing enriched U-235 fuel for BWRs and PWRs may fight hard to capture the fuel market for LFRs.
- Thorium breeding produces pure U-233. Commercial enrichment does not produce pure U-235.
- Liquid U-235 as fuel may be good for starting up a Thorium breeder LFR. Think of U-235 as analogous to kindling wood for an LFR.
- The U-235 fuel companies may become a powerful ally of Flibe and other LFR builders in terms of regulatory advocacy at US Department of Energy and its agencies.

US DOE Regulators are behind the technology evolution curve

- This has been true for years in the US Department of Energy.
- It may be even more aggravating now due to the current mania for federal government layoffs.
- The DOGE-diminished DOE staff must focus on what they know about the existing BWRs and PWRs tech and the regulations for that tech.
- I do not think that Flibe and its competitors will see LFR acceptance by US regulators before 2030.

What locales are best for LFRs?

- Good sources of water for secondary cooling and steam turbine operation.
- Good distribution network lines to carry power to customers.
- This sounds like every locale of a power plant, since steam is always needed to drive steam turbines and cool water helps recondense the steam to water for recirculation.
- Possibly the most demanding customers are data centers. Some LFRs might be put to work as dedicated power plants for a group of data centers, if water is abundant.

Summary

- Solid-fuel PWRs and BWRs cannot avoid overheating when water pumps fail, and that causes catastrophic failures.
- Liquid-fuel LFRs use the fuel itself to transfer heat to a secondary steam-water loop for driving steam generators.
- When a pump fails in an LFR, the liquid fuel heats, melts the bottom plug, and drains into the lower shallow holding tanks where the spread-out fuel cannot sustain criticality and cannot melt its surroundings.
- LFRs consume 100% of their liquid fuel. PWR and BWR solid fuel rods are inherently wasteful.
- LFRs are compact and may be on-site power sources.

NuScale: another US company

This slide was added after the 7/19/2025 meeting.

- Describes its reactors as a Small Modular Reactor (SMR). Modular and factory-built, yes. Small, not so much.
- Reactor is 77 feet long and 17 fee at widest diameter.
- Its solid fuel PWR design is approved by US Department of Energy. Its design includes the same negative safety impact of solid fuel in full-size PWRs and BWRs.
- Its reactor is factory built without an included steam turbine and generator, unlike Copenhagen Atomics.

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THE END