SUPER CRITICAL INNOVATIONS: A PRIMER ON FISSION REACTORS

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I. INTRODUCTION

Society faces the growing energy demands of an information-age economy while simultaneously attempting to reduce reliance on fossil fuels to mitigate climate change. This demand for energy is only growing with the introduction of electron-hungry artificial intelligence programs being introduced by many major tech companies. The leading AI chipmaker Nvidia will be making enough high-end chips that society will be adding an additional Netherlands or Argentina worth of energy demand every year.[1] To address these demands, Amazon,[2] Microsoft,[3] and Google[4] have all contracted with nuclear power companies to provide energy to their data centers. This has renewed interest in nuclear fission (the splitting of atoms) as a potential clean-energy technology. Nuclear fission has unique risks compared to fossil fuel power generation, but unique rewards as it can produce large-scale power without external constraints or generating air pollution. This paper will explain the structure of the atom, how atoms undergo nuclear fission, and how that fission is controlled before examining several different currently operating reactor designs. Understanding the basic mechanics of fission reactors can hopefully allay any fears around this potentially transformative technology.

II. FOUNDATIONAL IDEAS

A. WHAT IS AN ATOM?

An atom is made of a nucleus, comprised of protons and neutrons, and an electron shell. The protons and neutrons have more mass than the electrons and are bonded through the "strong nuclear force." This "strong nuclear force" involves the exchange

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[1] Alex de Vries, *The Growing Energy Footprint of Artificial Intelligence*, 7 JOULE 2191, 2192 (2023).

[2] Amazon, *Amazon Signs Agreements for Innovative Nuclear Energy Projects to Address Growing Energy Demands* (Oct. 16, 2024), https://www.aboutamazon.com/news/sustainability/amazon-nuclear-small-modular-reactor-net-carbon-zero [https://perma.cc/8MY8-5L9F].

[3] C Mandler, *Three Mile Island Nuclear Plant Will Reopen to Power Microsoft Data Centers*, NAT'L PUB. RADIO (Sept. 20, 2024), https://www.npr.org/2024/09/20/nx-s1-5120581/three-mile-island-nuclear-power-plant-microsoft-ai [https://perma.cc/56T5-V38U].

[4] Michael Terrell, *New Nuclear Clean Energy Agreement with Kairos Power*, GOOGLE: THE KEYWORD (Oct. 14, 2024), https://blog.google/outreach-initiatives/sustainability/google-kairos-power-nuclear-energy-agreement/ [https://perma.cc/48K8-55NY].

of even smaller particles called gluons.[5] The best analogy is a "blood brothers" promise that children might make on the playground, where they prick their fingers or hands and shake to symbolize their friendship. Some small amount of blood is transmitted in the act. Similarly, some components of the protons and neutrons are exchanged in this bond. This force is strong but incredibly short-range, not even extending to cover an entire nucleus. Therefore, there are no naturally occurring elements on Earth larger than Plutonium (94 protons), as larger nuclei will eject protons and neutrons in radioactive decay until they achieve a stable configuration. Even some isotopes, or varieties of an element with different numbers of neutrons, will undergo radioactive decay as the neutrons are insufficient to bind the number of protons in the atom.

B. FISSION FUNDAMENTALS

Nuclear fission is when an atom's nucleus absorbs an additional neutron and splits into two smaller nuclei and converts a small amount of the atom's mass into energy. This neutron needs to be slow, as the neutron needs to be integrated into the nucleus to disrupt the "strong force" holding the protons and neutrons together. This is best visualized in the "liquid drop" model, where the nucleus begins being stretched past the limits of the short-range strong force and the electromagnetic repulsion between protons begins to dominate.[6] This results in two smaller nuclei with more stable proton-neutron bonds that repel each other until fully separated.

Fission's energy is primarily the speed, or kinetic energy, of the two fission fragment nuclei, which travel into the surrounding atoms and heat them. Think of temperature as the measure of the vibration of constituent atoms;[7] the hotter something is, the more it vibrates. The atoms of your hot coffee are vibrating more than the atoms of your milk from your refrigerator. These fission products rapidly raise the heat of the surrounding material, because they are traveling fast and have a high positive charge after losing their

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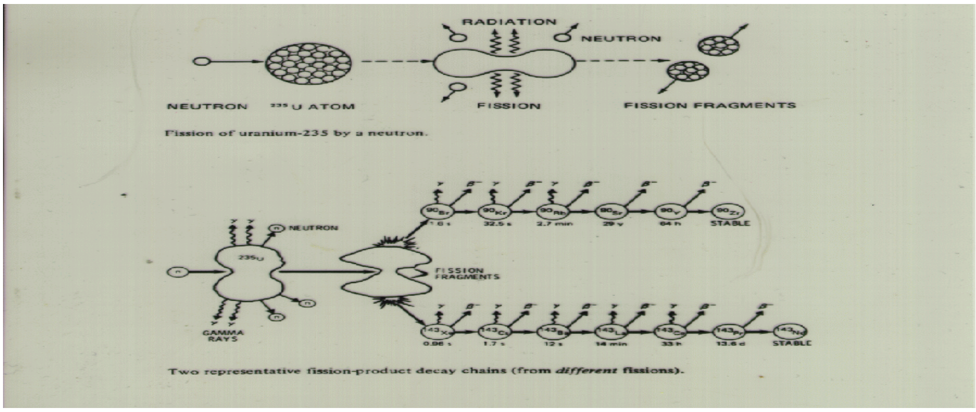
[5] Carl R. Nave, *Gluons*, HYPERPHYSICS AT GA. STATE U. (2017), http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/expar.html [https://perma.cc/H9ES-TL72]; *see also* Lawrence R. Sulak, Residual Strong Force Holds the Nucleus Together, CC104 Lecture 11 at Boston University, https://physics.bu.edu/cc104/rope.html [https://perma.cc/4UCD-Y86K].

[6] Richard R. Sulak, Liquid Drop Model of Nucleus, CC104 Lecture 11 at Boston University, https://physics.bu.edu/cc104/liquid_drop_model.html [https://perma.cc/BVX9-T8TN].

[7] Technically the "average random kinetic energy of a substance."

electrons in the fission reaction, thus imparting a lot of energy to surrounding nuclei. Einstein's famous $E = mc^2$[8] equation quantifies the energy released in these reactions, where small changes in the mass of an atom release tremendous energy in the product nuclei, which impart that to surrounding atoms. The bonding mass, the tiny gluon particles exchanged between protons and neutrons, become the kinetic energy released in the reaction. Even the most minute changes in the mass of protons and neutrons can accelerate the daughter nuclei to high speeds, raising the temperature of the surrounding atoms.

Fig. 1: Fission in Liquid Drop Model Visualized[9]



III. REACTOR DESIGN

How then do we safely contain the energy being released in a sustained fission reaction and channel it to electrical power generation? The best ways are to control the rate of fission reactions, thereby avoiding an uncontrolled chain reaction where each fission triggers multiple other fission reactions and releases unusable and dangerous amounts of energy. A nuclear reactor controls the rate of these fission reactions by controlling the number of neutrons available for fission primarily through the use of A) control rods and B) moderators.

A. CONTROL RODS

The first way a reactor controls the number of neutrons is by actively inserting or withdrawing of control rods,[10] which are

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[8] The equation shows that energy (E) is equal to the change in mass (m) times the speed of light squared (c^2).

[9] Sulak, *supra* note 7.

[10] Referred to as "shimming" the control rods in or out.

made of a neutron-absorbent material like hafnium[11] or cadmium.[12] These rods typically run the length of the fuel element of the core and withdrawing them exposes more fissile material for neutrons to impact and cause fission while inserting them creates a barrier to neutrons and thus slows the rate of fission. The control rods must be able to withstand the heat and pressure of being near these fission reactions. An additional requirement is the ability to rapidly insert the control rods fully into the core in the event of an emergency, in U.S. parlance "scramming" the reactor.[13] To rapidly assure this happens within seconds the control rods will often use a spring to drive the control rods downward and ensure the reactor is fully shutdown.

B. MODERATION AND FEEDBACK

The second method of controlling neutron population relies on the "moderation" of neutrons, slowing them down to increase the likelihood they cause fission when the neutron impacts a nucleus. As discussed above, the neutron needs to disrupt the bonds within a target nucleus to cause a fission reaction, and thus needs to be slower to be absorbed. An example of this is the relationship between moderator density and neutron flux:[14] as a moderator like water[15] (H_2O) heats up the water molecules are spread further apart,

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[11] Preferred by the Naval Nuclear Propulsion Program where superior material properties are more important than cost and nuclear reactors are designed to go decades without refueling to avoid taking ships out of service for extended shipyard periods.

[12] These materials are hungry for neutrons, having a high "neutron absorption cross section," meaning they have a high likelihood of absorbing a neutron that impacts the nucleus.

[13] Allegedly named for the "Safety Control Rod Axe Man" at the Chicago Pile, the first nuclear reactor, whose job was to cut the rope suspending control rods above the core, but this has been disputed. *See* Thomas Wellock, *Putting the Axe to the 'Scram' Myth*, NUCLEAR REGUL. COMM'N: NRC HISTORY 101 (Sept. 24, 2021), https://www.nrc.gov/reading-rm/basic-ref/students/history-101/putting-axe-to-scram-myth.html [https://perma.cc/WS7T-UFSZ].

[14] The "temperature coefficient of reactivity": when negative, as temperature goes up reactivity goes down.

[15] Other moderators can be used, such as graphite. However, recent designs eschew graphite moderators after graphite-related phenomena contributed to several nuclear incidents such as Chernobyl and the less famous but still major Windscale reactor fire in the U.K. The risks from graphite partially come from Wigner energy, where neutron impacts distort the molecular structure of graphite by displacing atoms from within the regular matrix structure. This can be best visualized as the neutron impacts compressing a spring, storing up the energy instead of raising

thus reducing the likelihood a neutron impacts that water molecule. The component hydrogen atoms are the “targets” as they have a similar mass to neutrons and a high scattering[16] cross-section. Imagine flicking a ping-pong ball (the neutron) into a basketball (the oxygen atom); the ping-pong ball would retain most of the kinetic energy, bouncing off the basketball at an angle but not slowing down much. Now imagine flicking a ping-pong ball into a golf ball (the hydrogen atom); the ping-pong ball would impart significantly more energy to the similarly sized golf ball. By spreading out the golf balls, the reactor keeps the ping-pong balls traveling too quickly from being absorbed and causing fission.

IV. CURRENT DESIGNS

These fundamental principles are implemented in a handful of broad-design umbrellas that make various compromises between power generation efficiency, potential contamination of secondary components, and nuclear fuel requirements. Decisions weigh the immediate cost of construction with longer-term costs associated with maintenance and repair; a commercial nuclear power plant needs to be online at maximum power for extended periods.

A. GENERATIONS OF REACTORS

It is worth discussing the history of reactor designs as a preliminary matter. Most currently operating reactors are considered Generation II,[17] and the emerging nuclear companies contracting with the tech giants would be considered Generation IV reactors. Although there are few clear demarcations, Generation I comprises the earliest non-commercialized reactors. Generation II is considered the early commercial reactors of the mid-1960s to the mid-1990s, the period most current reactors were designed and

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temperature immediately after the neutron impact. This stored energy creates the potential for significant heat when the graphite is heated to the point of annealing, when the crystalline structure is restored. This adds extra thermal energy as the reactor is heating up, which can potentially exceed safe limits, as they did in the U.K. Windscale reactor fire in 1957. *See* William Penney, Basil F J Schonland, J. M. Kay, Jack Diamond & David E. H. Peirson, *Report on the Accident at Windscale No. 1 Pile on 10 October 1957*, 37 J. RADIOLOGICAL PROT. 780, 780 (2017).

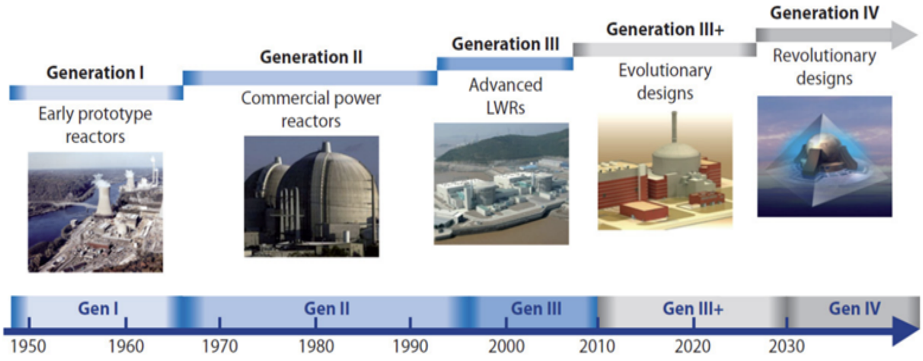
[16] Scattering is when a subatomic particle like a neutron impacts a nucleus and bounces off, instead of being absorbed into the nucleus.

[17] Pablo Fernández-Arias, Diego Vergara & José A. Orosa, *A Global Review of PWR Nuclear Power Plants*, 10 APPLIED SCI. 4434, 4440 (2020).

built. Generation III was coined to describe the designs of the late 1990s which will be constructed before 2030.[18] Finally, Generation IV describes the designs "likely to reach maturity" before 2030, in an international initiative the US Department of Energy began in 2000.[19] These designs may be built on an aggressive schedule before 2030, but delays are endemic in the field of nuclear power.

Fig. 2: OECD Nuclear Energy Agency for the Generation IV[20]

Figure ES.1: Generations of nuclear power: Time ranges correspond to the design and the first deployments of different generations of reactors



B. PRESSURIZED WATER REACTOR

The Pressurized Water Reactor is constructed of two circuits: one primary coolant loop that runs through the reactor itself and then passes through a heat exchanger that heats a secondary loop, boiling water and spinning a turbine. The pressurization and two-step design reduces the efficiency of the reactor but has some counterbalancing safety and design advantages. Only the primary section is radioactive, minimizing the irradiation of the turbines and other components. Additionally, keeping the primary loop as a fluid minimizes the risks of boiling in the core and thus maintains

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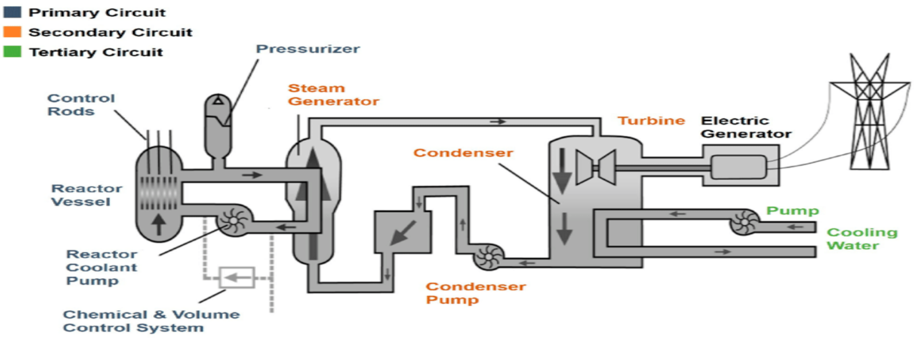
[18] Ann MacLachlan, *CEA chairman pleads for EPR order, calls wait for Gen IV 'unrealistic*', NUCLEONICS WEEK (Sept. 25, 2003), https://wrlc-gulaw.primo.exlibrisgroup.com/permalink/01WRLC_GUNIVLAW/1adkk5q/cdi_proquest_reports_202961521 [https://perma.cc/K48K-DGKV].

[19] Frank Carré & Gian Luigi Fiorini, *Status of the Generation IV Initiative on Future Nuclear Energy Systems*, EUR. NUCLEAR SOC'Y (Apr. 21, 2004), https://web.archive.org/web/20110317125012/http://www.euronuclear.org/info/generation-IV.htm [https://perma.cc/VX4W-ZBDG].

[20] *Figure ES.1* (illustration), *in* TECH. ROADMAP UPDATE FOR GENERATION IV NUCLEAR ENERGY SYS. (Jan. 2014), https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf [https://perma.cc/4MJ4-PSJD].

efficient heat transfer through the actual reactor, as convection heat transfer is much better at removing heat than the radiative heat transfer that happens to a gas. Think of a beach or pool, it is much easier to cool down from immersion in the water than to heat up in the sun. Similarly, it is easier for atoms to heat up by absorbing the vibrations of other atoms than by a ray of light.

Fig. 3: A Sample Pressurized Water Reactor[21]



C. BOILING WATER REACTOR

A contrasting design is the Boiling Water Reactor. Water goes through the reactor, boils, then spins the turbine, is condensed and re-fed into the reactor. A major downside to this design is the contamination of the turbine, condenser, and other components as the steam directly passes through the core, carrying some level of radioactivity with it. However, these designs are more efficient, as the reactor is directly boiling the water to turn the turbine, which enables these reactors to use less enriched nuclear fuel. Many commercial reactors use this design, as they can achieve lower costs to generate large amounts of energy and have fewer, but more significant, points of failure.

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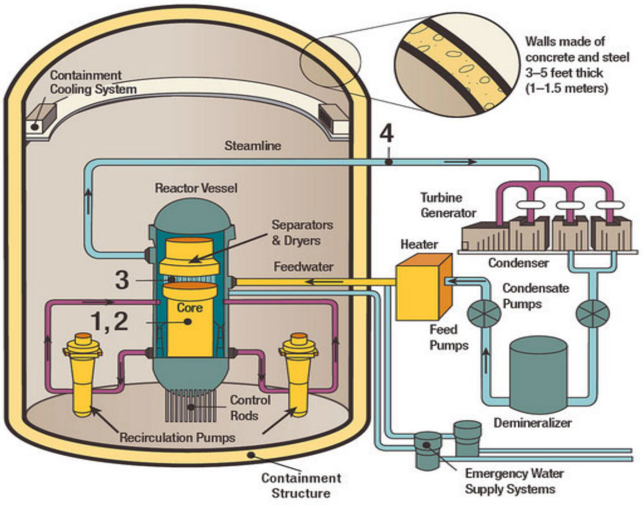
[21] Arias, et al., *supra* note 18, at 4440.

Fig. 4: A Sample Boiling Water Reactor[22]



D. HIGH-TEMPERATURE GAS-COOLED REACTORS

High-Temperature Gas-Cooled Reactors (HTGR), which use helium or other inert gases as a coolant, combine higher thermal efficiency while minimizing the production of radioactive material, as helium is not activated from exposure to neutrons while passing through the reactor. The downside of HTGR is the component design requirements for these high temperatures and the direction of gas flow being more likely to reverse inside the core than a liquid. Ensuring the direction of flow is important to ensure the coolant goes to where heat can be adequately removed before being cycled through the core again. These reactor types also show promise for commercial clean-hydrogen production and other industrial applications requiring "process heat."[23]

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[22] Illustration of a Boiling Water Reactor *in Boiling Water Reactors*, U.S. NUCLEAR REGUL. COMM'N (Feb. 9, 2023), https://www.nrc.gov/reactors/power/bwrs.html [https://perma.cc/E4C4-URZX].

[23] J. M. Beck & L. F. Pincock, *High Temperature Gas-cooled Reactors Lessons Learned Applicable to the Next Generation Nuclear Plant*, IDAHO NAT'L Lab'y 3 (Apr. 2011), https://inldigitallibrary.inl.gov/sites/sti/sti/5026001.pdf [https://perma.cc/G97B-WRF8].

Fig. 5: A Sample HTGR, Pennsylvania's Peach Bottom Reactor[24]

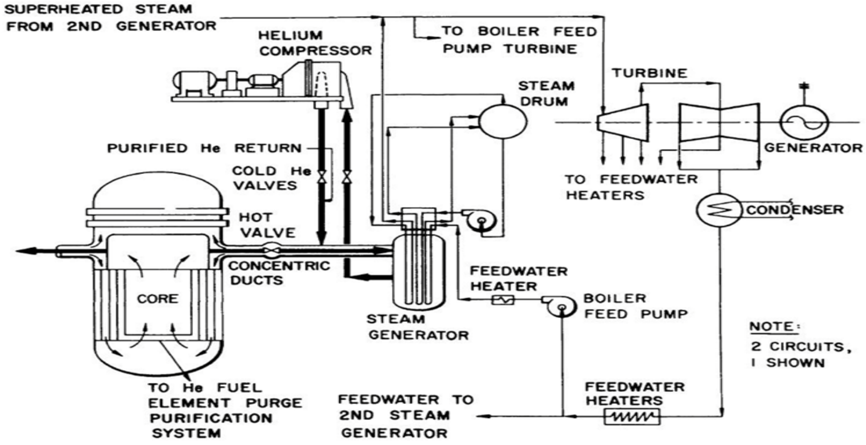

Figure 4. Flow diagram of Peach Bottom's primary circuit.[5]

E. CONTRASTING PRESSURIZED WATER, BOILING WATER REACTORS, AND HIGH-TEMPERATURE GAS REACTORS

Reactor Type	PWR	BWR	HTGR
Pros	Safer: heat transfer from the reactor to coolant is more assured, the core is safe as long as water is in the primary loop No contamination of turbine or secondary components	Higher Efficiency and therefore can use less-enriched fuel. Can be smaller, as it does not require a secondary loop.	Higher efficiency: can heat the gases in primary loop more than water Utility in clean hydrogen and other "process heat" uses No contamination of secondary components
Cons	Lower efficiency, heating water to boil other water to turn a turbine. More complex as it requires a pressurizer and secondary loop	Potential problems from water to steam phase change in the reactor core Contamination of turbines and secondary components	High metallurgical requirements for high temperature gases Potential of flow reversals in the core meaning no heat is being transferred

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[24] *Id.* at 8.

V. CONCLUSION

The testing and construction of nuclear reactors have been stagnant for decades, while the possible options available to safely utilize atomic power have grown with advances in materials sciences. Understanding how nuclear fission produces heat to boil water to turn a turbine hopefully reduces the mystique and therefore fear around a technology that holds promise in a carbon-neutral future.