A CONTRASTIVE ANALYSIS OF FOUR CRITICAL NUCLEAR REACTOR CORE SAFETY SYSTEMS AND THEIR HISTORICAL AND FUTURE IMPLICATIONS

By

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PRÉCIS

Nuclear reactors have been a polarizing topic for many years with safety concerns at the forefront of this discussion. Consequently, nuclear reactors have well defined and engineered safety systems meant to directly protect the integrity of the fuel in the event of equipment malfunction, operator error, or natural disaster. Reactor safety systems have existed for as long as reactors have, starting with the SCRAM function which was given its name by Enrico Fermi at the first constructed nuclear reactor, Chicago Pile 1. These safety systems evolved as the nuclear industry grew and reactors became more commonly used for power generation than scientific discovery, creating a different set of challenges to overcome. A few safety systems of note are to be discussed in this thesis, subsequent to a summary of nuclear history and reactor physics.

The SCRAM, an acronym short for Safety Control Rod Axe Man referencing a now defunct job title from the first reactor, has become an industry standard term for a rapid insertion of enough control rods to completely shut down the reactor. Moderators, a component critical to slowing down neutrons so that they may cause additional fission events, were designed for reactor cores in such a way that they would reduce the rate of the reaction upon an increase in temperature, creating an automatic passive safety system to control the chain

reaction. Additionally, methods were implemented to inject emergency coolant should the reactor undergo a rapid and unexpected loss of coolant, ensuring the fuel could be protected in the event of power outages and natural disasters. On the forefront of nuclear engineering, there are those working to design a new type of reactor that functions using molten salt and the fertile material thorium-232. These designs are a marked departure from standard reactor design, containing unique safety systems that allow them to operate both more safely and create less waste than traditional power reactors. The function of each reactor safety system shall be thoroughly covered as well as what events are likely to necessitate its use and what circumstances could lead to a failure of said safety system. Additional commentary cross-analyzing the systems against each other in light of their past and current performances will conclude the paper to illustrate the function and necessity of overlapping safety systems that simultaneously minimize risk.

After spending a significant amount of time at the WSU Nuclear Science Center learning the details of the 1 MW research reactor for the operator licensing examination, I was fascinated by the precise way in which the safety systems were designed to create a web of protection that, together with a trained operator, could prevent any reasonable negative circumstances. It was the natural choice then to complete my thesis on reactor safety systems, choosing two that I was very familiar with at the WSU reactor and two that had different applications in distinct reactor setups to compare and contrast. The goal then became to extensively research and compile information on these four systems as well as surrounding knowledge of the field in such a way to not only tout the substantial safety measures considered standard for the nuclear industry, but also the importance of nuclear in creating and maintaining the modern day technological era we experience.

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Chapter One

Introduction

1.1 On the Significance of Nuclear Reactors

Since the discovery of the possibility of nuclear chain reactions [6], the potential of harnessing energy stored in the strong force bonds of heavy nuclei left behind by supernovae [7, p.1] has offered human civilization the tools to leave behind older forms of electricity production. The fission of a single U-235 nuclei releases 201.92 ± 0.46 MeV of thermal energy [8], which amounts to $8.289 * 10^{10}$kJ per kilogram (see Appendix A for calculation). This immense amount of energy vastly outstrips the energy density of other common sources, while simultaneously lacking the carbon emissions of traditional combustion style power generation. Potential energy of this magnitude is bound to attract some notice, and due to the nature of nuclear power it has simultaneously presented a host of new problems not previously faced.

Critical to the operation of any reactor is the absolute guarantee that the macroscopic benefit of its continuation exceeds any potential persistent or transient negative effects caused by its use. Consequently, regulatory functions are performed by government agencies such as the U.S. Nuclear Regulatory Commission and reactors have to adequately and thoroughly prove the safety of their operation before construction can even begin [9, §50.34]. Safety systems with a proven track record of success are of paramount importance, favoring reliability over novelty, and consequently there are safety systems shared across the majority of reactors; for example, the SCRAM function (to be explained in section 3.2), which results in a rapid shutdown of the nuclear chain reaction, is nearly universally implemented in reactors worldwide.

The urgency to develop safer and more efficient reactors is exacerbated by the omnipresent effects of CO_2 production in electricity generation; in 2018, electric power was the second highest producer of CO_2 emissions, closely following transportation at 27% and 28% of the total production, respectively. Coal and natural gas are largely responsible for this quantity of CO_2, with petroleum consumption constituting the majority of CO_2 creation in the realm of transportation [10, p.2-14]. Even if transportation was to pivot away from petroleum to electric vehicles, power grids would have to scale up to meet increased energy needs. These alarming statistics underline the necessity to grow the capacity of U.S. nuclear energy production, which has remained steady at $\sim$20% of total electricity production in the United States since 1990 [10, p.3-16]. Two large issues that have prevented the scaling up of U.S. nuclear energy production stem from the negative public opinion of nuclear power and the glacial pace with which nuclear regulatory advancements are made. In fact, the U.S. Energy Information Administration has projected that total electrical generation by nuclear reactors will decrease to 12% of total energy production by the year 2050 [11, p.62]. While this is largely due to the growth of renewable energy sources, the projection also shows little decrease in the main culprits of CO_2 production, natural gas and coal. However, recent polls have shown that public opinion on nuclear is taking a turn for the better, with 75% [12] of the population now saying that at least a combination of nuclear power with other renewable energy sources is what they would envision as a better method for power production.

The dangerous nature of radiation and radioactive isotope production presents unique issues for nuclear energy unknown to other fields of power generation. However, the extent of research and work that has been done in the nuclear field has made these reactors among the safest forms of power generation; at the time of writing, there have been no deaths in any U.S. civilian nuclear reactors [13] while even the fields of wind and solar have caused multiple occupational deaths [14]. In fact, it has been predicted that increased utilization of nuclear power could prevent 420,000 to 7.04 million deaths by 2050 due to the reduction of atmospheric CO_2 content [15]. Any technology capable of preventing that many deaths should be seen as a great boon to the world; however, multiple nuclear incidents of the past continue to mar nuclear energy's public image. Despite the current safety standards, a few notable accidents in the nuclear field such as at the Chernobyl, Three Mile Island, and Fukishima power plants have not left the public's mind when it comes to appraising the field's safety. When any accident occurs in a nuclear power plant, it is a notable and significant piece of news due to the political importance of nuclear technology. It is no understatement to say that nuclear technology was pivotal to shaping the geopolitics of the world following WWII, leading into the Cold War and beyond as new nations seek to improve their own nuclear capabilities. Although the checkered past of nuclear technology has led many to dismiss it as a possibility moving forward, countries seeking legitimacy and recognition on the world stage are enthusiastic to grow their nuclear ensemble. In an effort to lead by example, many existing nuclear powers have backed non-proliferation treatises meant to limit the spread of nuclear technology.

Without nuclear reactors, however, the world would find itself at a serious technological disadvantage as the benefits of isotope production have broached many fields, with medicine being among the most notable. Technetium-99m is used as a gamma emitting radiotracer in many medical facilities and must constantly be produced as it has a half life of six hours, which is part of what makes it ideal for these medical procedures [16, p.11]. Additionally, cobalt-60 is used as a source in radiation treatments to destroy malignant tumors within the body that cannot be otherwise removed [16, p.13]. Similar to using a radiotracer in a person's body, certain radioisotopes have been licensed for use by geologists to detect the extents of oil fields in a process called nuclear well-logging [16, p.16]. The uses of nuclear isotopes in different industrial applications go on, and it is important to note that these radioisotopes require special reactors designed to allow samples to be brought close to the neutron flux near the core and then be removed safely. As of May 2020 the U.S. NRC only lists 29 operating research and test reactors in the United States [17]. Electric power generating reactors operate at much higher power levels than research reactors and as a consequence of this it is usually unsafe to have these facilities irradiate samples, as it would require the reactor to power down for removal which is an arduous process for reactors that regularly operate at thousands of MW, compared to the 20 MW of the largest research reactor licensed by the NRC [17]. When seeing the broad importance of the nuclear field in the realms of ecologically friendly power generation, medicine, and technology, the significance of making the best fail-safe systems possible becomes apparent lest the dangers of nuclear power outweigh the extensive benefits.

Nuclear reactors largely face discrimination in the public eye due to a lack of proper understanding of how they work as well as their historic connection to catastrophic and politically charged atomic weaponry. For that reason, before an in-depth discussion of reactor safety systems and the physics that functions behind the scenes can occur, it becomes necessary to explain the whole picture, starting with the discovery of radiation all the way through the Manhattan project and the resultant geopolitical tensions of a Cold War and then post-Soviet era non-proliferation policies. Once an appropriate appreciation of the consequential historic nature of nuclear energy is instilled, only then is it permissible to move on to the in-depth details of what radiation is composed of, what causes it, and why it is important to monitor. The correlation between radiation and cancer is well-known, and so the practices that are observed to minimize dangerous levels of dosages, along with what those dose limits are defined as, will make an appearance in the second chapter. Also pertinent to the discussion of reactor safety systems is a walk-through of the entire process reactor operators use to conceptualize and understand the sustained neutron chain reaction, as references will be made to this section when discussing the effects of different reactor safety systems on the reaction occurring in the core. The discussion on reactor physics will segue into the prompt negative temperature coefficient, the first reactor safety system to be covered and one that is heavily dependent on an understanding of reactor physics. From there, chapter three will move through what a SCRAM is, why coolant injection is necessary for large power reactors, and finally describe the novel safety systems unique to liquid fluoride thorium reactors. Lastly, a cumulative conclusion tying together ideas present throughout will be furnished in such a way to elucidate the collective efforts of each safety system to keep the core and the surrounding areas safe from a host of potential catastrophes, and why this enables nuclear energy to continue to be a prime candidate for clean, ecologically friendly power moving forward.

1.2 Historical Background

1.2.1 Discovery and implementation

In 1903, Henri Becquerel, Pierre Curie, and Marie Curie were awarded the Nobel Prize in Physics for the discovery of a new characteristic of matter: radioactivity [18]. Becquerel and the Curies would refine different isotopes to discover that radioactive elements gave off radiation of varying penetrative qualities, such as the emission from radium, which the Curies' discovered, was much more likely to pass through obstacles than the uranium samples that Becquerel was working with [18]. This would lay the groundwork for understanding different types of reactions that happen in the nucleus, culminating in Lise Meitner and Otto Frisch discovering fission in 1938 and publishing it the following year [19]. Otto Hahn was responsible for the careful and puzzling measurements that piqued Meitner's curiosity, and she consequently used the liquid drop model to interpret how fission could occur in a nucleus with her estimates of the released energy (200 MeV) proving extremely accurate [20]. Otto Hahn would go on to be awarded the Nobel Prize in chemistry in 1944 for his discovery and it is a point of particular disappointment that Meitner's role was not recognized, partly due to the fact that she had been forced to flee from the Nazis due to her Jewish ancestry [20].

The discovery of fission was about to set the world on fire, as soon afterwards H. von Halban, F. Joliot and L. Kowarski would prove that the fission of uranium gave off more neutrons than it absorbed [21], which was additionally confirmed by H.L. Anderson, E. Fermi and H. B. Hanstein [6]. At 3:53pm on December 2nd, 1942, the first nuclear reactor under the direct supervision of Enrico Fermi, dubbed Chicago Pile 1 as it was mostly a pile of graphite bricks, would go supercritical and become a sustained chain reaction [22, p.22]. This evidence was the final key needed to prove to the U.S. government that a self-sustaining chain reaction was possible and the Hanford site in Washington, under the purview of the then Manhattan District, was the result [22, p.16]. The Manhattan project was born as a result of this successful test, and the development that continued under the guidance of General Leslie Groves at sites across the country would lead to the eventual development of the atomic bomb [23, p.13]. Of great interest was the breeder reactor constructed on the Hanford site in Washington state, with construction of the B-reactor starting in August 1943 and by 1945 shipments of refined plutonium were on their way to the bomb construction facilities in Los Alamos, NM [23, p.18]. The Los Alamos laboratory was under the direction of perhaps one of the most famous faces of the Manhattan project, J. Robert Oppenheimer [23] who is widely monikered as "The Father of the Atomic Bomb." Upon the successful detonation of the Trinity nuclear weapons test, the true destructive potential of the atom had been unleashed and it would color the perception of nuclear energy forever.

1.2.2 Dangers and accidents

The dangers of nuclear energy are broadly known but can be divided into two categories: radiation exposure and thermal release. The strong nuclear bonds in the relevant isotopes of U-235, U-233, Pu-239, and Pu-241 contain abundant amounts of energy, and the fission of those isotopes in an uncontrolled or rapid manner results in a large release of thermal energy which can result in explosions like those of the Hiroshima and Nagasaki detonations [23, p.

24], or the explosion of the Chernobyl reactor 4 in 1986 when there was inadequate cooling and a spike in reactivity [24] that led to rapid gas expansion and destruction of the reactor core. After the thermal release, however, is when the radiation exposure becomes the primary concern especially in the case of an accident at a reactor as the unstable nature of fission products makes them particularly dangerous to life. It is estimated that 270 million curies of activity were released during the Chernobyl accident, which resulted in 30 deaths from acute radiation sickness and burns from the facility fire, as well as another thousand people who were stricken with complications due to bone marrow and thyroid cancers [24]. While the Chernobyl accident was the result of multiple different synergistic effects that combined to worsen the outcome, there were underlying design flaws that were fundamental to the creation of the catastrophic circumstances [25, p.12-13].

Before the events of Chernobyl, however, the United States had faced its own nuclear disaster at Three Mile Island in 1979. This accident had its own list of complex issues leading up to the eventual core damage and radiation release which was, in comparison to the Chernobyl accident, relatively minor at 13 curies [24] but still served as a wake up call to those who had viewed nuclear reactors with a "Titanic mentality" [26, p.224]. Again, it was a combination of design flaws and operator error that led to the Three Mile Island (TMI) incident, but in this case the lack of proper maintenance also played a role as there was a pressure release valve and a coolant injection valve that both were leaking despite reading as closed in the reactor console. This led to readouts detecting steadily decreasing pressure, and the operators interpreted this as a leak between the primary and secondary cooling systems and to mitigate this issue they throttled down the pumps. However, the water was instead leaking past the stuck open pressure relief valve and creating a minor loss of coolant accident (LOCA). The throttled down primary coolant pumps were unable to adequately cool the fuel within the reactor proper, which resulted in a partial meltdown of the fuel rods or "slump" which was additionally incorrectly interpreted by the operators [27]. The TMI reactor was damaged beyond repair and was decommissioned as soon as it could be safely accomplished.

A more recent nuclear accident occurred at the Fukushima Daiichi power plant in Japan as a result from a powerful earthquake and the resultant tsunami, causing the emergency coolant systems of the different reactor cores to fail when the backup diesel generators were submerged in water. The resultant buildup of heat in the core from decaying fission products resulted in a large hydrogen buildup in the pressure containment vessel of the core itself. In an attempt to release this pressure to the atmosphere, the hydrogen was vented to the above containment building which promptly exploded, uncovering the tops of the immediate containment structure of several of the Fukushima nuclear cores [28]. In addition to the venting of hydrogen from the core mixed with radioactive elements, several cores completely melted through the first containment capsule of the core onto the concrete containment pad below, allowing for further release of radioisotopes into the atmosphere and ground. There were also spent fuel rods stored in pools above the reactors themselves, and these fuel rods were at risk of rupturing and without the containment buildings they could have resulted in a massive release of radioactivity to the environment [28]. The damage resulting from this accident is still under analysis as it has yet to be completely contained and cleaned up but it possessed the potential without corrective action to surpass the events of the Chernobyl nuclear reactor meltdown in terms of curies released. As of now, though, it is still below the environmental contamination levels of the Chernobyl accident by about a factor of 10 [25]. However, each of these accidents created a change in policy and action for each country moving forward and in some cases has been used to educate new restrictions on reactors and in others has been used to condemn the construction of new reactors and hasten the decommissioning of operational reactors before the end of their predetermined lifespan.

1.2.3 Fallout and consequences

Most recently, the immediate fallout from the Fukushima incident led to Japan freezing all plans to construct new nuclear reactors, Germany to shut down its 17 reactors that were previously in operation, along with Switzerland agreeing to slowly decommission its 5 reactors over the span of the next 25 years [29]. There was an overall decrease in the public opinion of nuclear following the Fukushima catastrophe, amounting to a change from a 52.7% approval to a 45.4% approval among 42 different countries that were polled [29]. The Fukushima power reactor was a General Electric design that serves as a basis for multiple U.S. power reactors, and consequently the U.S. NRC used this opportunity to reexamine some of its own requirements for U.S. reactors [28].

With TMI occurring first chronologically, it was the wake up call for nuclear reactor designers and the U.S. NRC sought to make the best out of the disaster, creating a new host of surveillance and design requirements for new reactors and those that were similar to the TMI reactors [27]. There were updates made to console design to reduce the possibility of confusion which proved to be extremely dangerous in the TMI accident. Additionally, the U.S. NRC placed more stringent requirements on the minimum possible accident events that had to be analyzed in the Final Safety Analysis Report (FSAR) of a nuclear reactor. Reactor operators are trained on all analyzed accident events present in the FSAR, so by including more events it would also bolster the training of reactor operators [27].

After the events of the Chernobyl incident and the resultant release of radioactive isotopes to the surrounding region and neighboring nations, there was a great deal of pressure applied to the Soviet Union to rectify the issues present in their RBMK reactors, which had been previously unheard of due to the secrecy and isolation of the Soviet nuclear programs, preventing the invasion of the "safety culture" that was present in many western nuclear programs [25]. The Chernobyl accident remains one of the most well known nuclear incidents in history, as well as one of the most catastrophic. In light of all of these accidents, it has become policy for many of the established nuclear powers to discourage development of nuclear infrastructure in countries that seem likely to repeat past mistakes, namely nuclear accidents and atomic weaponry.

In line with this policy, the U.S. has made continued attempts to prevent other countries from developing nuclear technology, namely those like Iraq [30], India [31], and North Korea [32] which are seen as neither stable nor developed enough to take the appropriate safety and security precautions that are necessary to operate a nuclear reactor possessing high amounts of fissile material for the sole purpose of nuclear energy. Non-proliferation has spread as the method by which different world powers would like to maintain peaceful operations, and countries that are just now entering into their own respective nuclear eras threaten geopolitical stability given their less defined alliances to the traditional world powers. In order to avoid a repeat of the wars of the past century, pressure has been applied to certain countries to maintain political stability rather than advance technologically. The distribution of nuclear technology and weaponry is an ongoing concern especially for those unstable countries in proximity to former Soviet countries, given the tendency for antiquated Soviet technology to find its way into the hands of many insurgent factions in the region. For that reason, any nuclear material is kept under a watchful eye and there are strict regulations in the U.S. in order to prevent the loss of nuclear material. As is with any industry, government regulation increases the cost of building new facilities and has deterred those unwilling to sink the upfront cost into a project that is subject to whims of public opinion. Nuclear facilities spend years in licensing and approval before construction even begins, and changing administrations with different goals do not create an easy environment to complete a nearly decade long process.

Chapter Two

Physical and Mathematical Interlude

2.1 Radiation Essentials

Radioactivity is a property of the nucleus caused by the transition of an unstable nuclei to a more stable state, resulting in the emission of energy in the form of radiation. The exact mechanisms at work to cause this instability are beyond what is necessary to understand the function of reactor safety systems; however, an understanding of what quantifies a stable nuclei will be relevant. Nearly all elements found on Earth naturally are going to be in their stable states, with some notable exceptions being ^{235}U, ^{238}U, ^{232}Th, and ^{40}K [1, p.41]. These isotopes (nuclei that posses the same number of protons, Z, but varying numbers of neutrons, N) have long enough half-lives to still have appreciable quantities left over from the coalescence of Earth from cosmic stardust. At low Z, the most stable isotope of an element will typically have $Z \approx N$, but as the number of protons increases, the ratio of N to Z climbs to maintain stability [33, p.20]. This is partially due to the electrostatically repulsive nature of the positively charged proton, which is overcome by the strong nuclear force between nucleons (protons or neutrons in a nuclei) in stable isotopes. As more positively charged protons are packed into a nucleus, it is necessary for more uncharged neutrons to be present as binding mediators holding everything together. This gives rise to the line of stability seen in Figure 2.1, which can also be used to determine which type of radiation an unstable nuclei

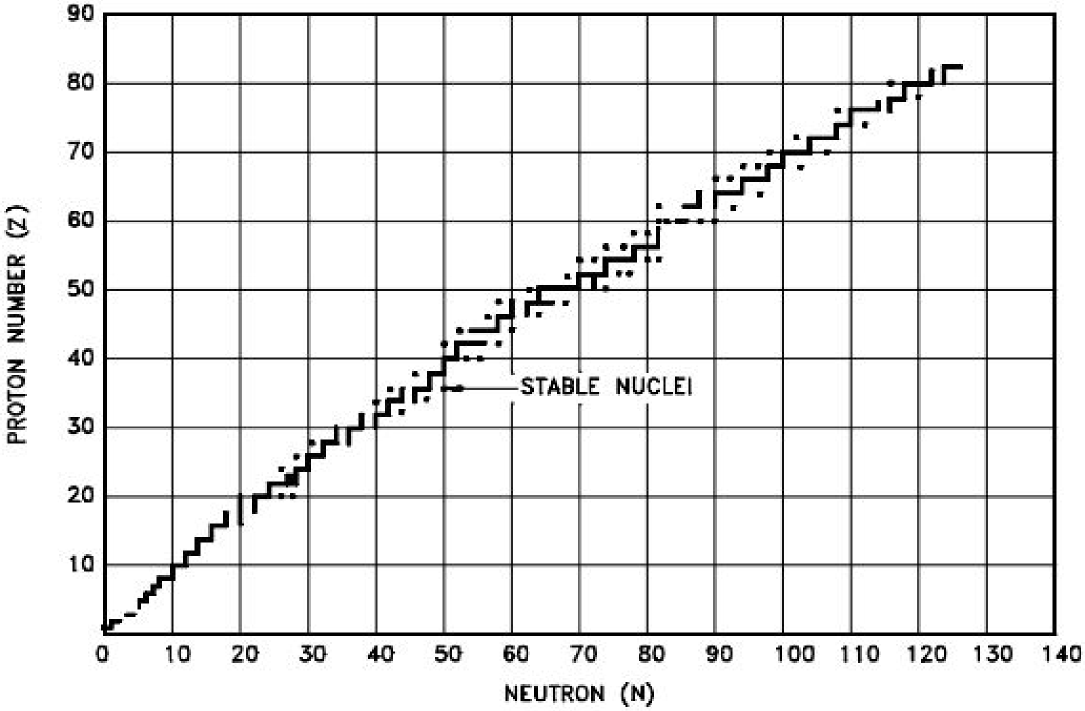

Figure 2.1 The line of stability represented on an N vs Z plot, with the stable nuclei plotted in black [4, p.NP01-14].

is likely to emit. Naturally, isotopes above or below the line of stability will emit radiation that directs them back towards the line of stability.

The rate at which a sample of a radioactive substance decays is a directly probabilistic calculation, stemming from the quantum properties of subatomic particles. In essence, there will exist two states adjacent to each other in an unstable nuclei, separated by some energy barrier which is usually caused by the strong nuclear force. In the bound state, the nuclei is in its original isotopic form, and in the adjacent state the nuclei will exist as some changed form plus some energy/particle emission. Classically, the nuclei does not possess enough energy to broach this energy barrier; however, when represented by wave functions under more quantum mechanical assumptions, there is a chance that the nuclei is indeed found on the other side of the energy barrier in a more stable state [33, p.32]. The chance of this tunneling occurring is related to the energy difference between the states, as well as the width of the energy barrier, but oftentimes all of this information is absorbed into a single relevant physical value: the half-life. The half-life of an isotope is the time at which the probability of finding that isotope in its original state is exactly equal to the probability of finding it in its decayed state, which when used to characterize a sample over time gives an exponential decay expressed by the following equation [4, p.NP01-31].

$$N = N_0 e^{-\lambda t} \qquad \lambda = \frac{ln(2)}{t_{\frac{1}{2}}} \tag{2.1}$$

Here, N_0 represents the initial number of unstable nuclei, N is the quantity of those nuclei remaining after time t passes, and $t_{\frac{1}{2}}$ is the half-life of that isotope. The rate at which a sample decays is defined as the activity and can be mathematically defined as $A = -\frac{dN}{dt}$, which is then given by the following equation.

$$A = -\frac{dN}{dt} = -\frac{d}{dt}(N_0 e^{-\lambda t}) = \lambda N_0 e^{-\lambda t} \equiv A_0 e^{-\lambda t} \tag{2.2}$$

This activity, measured in becquerels (Bq) or curies (Ci), is the direct calculation for the radioactivity of an isotope. Things to note in this equation is the dependence of the activity on the half-life of an isotope: a shorter half-life results in the activity decreasing sooner, but over that time the activity will be much higher than something with a longer half-life. However, the activity level of an isotope is not the sole determinant of the strengths of the effects of the radiation that it emits, as there are four relevant kinds of radiation to be discussed.

Not all radiation is equal in its composition nor behavior, and it is generally categorized into four main groups: alpha(α), beta(β), gamma(γ), and neutron(n) radiation. Alpha radiation is the most massive of the four, being composed of a $^4_2$He nucleus that is ejected from the original nucleus, resulting in a reaction such as the one below:

$$^{11}_{5}B \rightarrow^{7}_{3} Li + \alpha \tag{2.3}$$

Alpha radiation, having a positive charge of $2e$ and a mass of ∼4 amu, has a very high probability of interacting with the matter in its path and giving off the energy it contains.

Consequently, alpha radiation is easy to block and possesses the highest LET (linear energy transfer, a measure of energy deposited per distance travelled) of the four radiation categories.

Beta radiation is the next type of radiation, and it also bears a resemblance to another familiar particle: the electron. Beta radiation comes in two forms, β^+ and β^-, which are also known as positrons and electrons. To grasp where a beta particle comes from, one has to understand that the proton(p) and neutron are not truly fundamental particles, but are instead made up of quarks [33, p.165], and the process of creating a β^- particle transmutes one quark in a neutron into a different quark that changes the conglomerate particle into a proton. As a slight digression, to conserve a value known as lepton number the transition creates either an electron and an anti-neutrino($\bar{\nu}$) or a positron and a neutrino(ν) for the reverse reaction, which is summarized in the below equations.

$$n \rightarrow p + \beta^- + \bar{\nu} \qquad\qquad p \rightarrow n + \beta^+ + \nu \tag{2.4}$$

Getting back on track, beta particles are also rather easy to shield against as they again have a high linear energy transfer because of their $\pm e$ charge.

Gamma radiation is the next one to cover, and the primary takeaway for this kind of radiation is that a gamma ray is simply a high energy photon, the very same photons that transmit radio frequencies or allow you to read the words on this page. That high energy, though, happens to be the kicker as gamma rays regularly exist in the keV to MeV range, while visible light is typically in the eV range, making gamma rays anywhere from a thousand to millions of times more powerful than visible light. Gamma rays are created in a host of different ways, as they are often a byproduct of other nuclear decays and allow a nuclei to maintain the same N and Z numbers while shedding energy into a more stable state. Oftentimes, when a nucleus decays via one of the other methods, it leaves the product nuclei in an excited state which can be visualized as a state in which the nucleons are 'arranged' in a non-optimal way. From here, when the nucleons shift to their lower energy state, they release a photon typically in the gamma range and this shift is called an isomeric transition [4, p.NP01-26]. Gamma rays can also come from the annihilation of a positron with an electron, creating two photons of 511 keV [1, p.26]. Additionally, due to the electric charge of the electron, when a β^- of sufficient kinetic energy interacts closely with a high mass nucleus, the electron will change its direction and create a photon in the interaction to conserve the total momentum and energy of the exchange, and the resultant high energy photon is called Bremsstrahlung, or breaking radiation [4, p.NP01-66].

Lastly, neutron radiation is perhaps the most critical to understanding how the chain reaction occurs inside a reactor as it is these neutrons that are both the products and the cause of nuclear fission. The main source of neutron radiation is from nuclear reactors, as the reaction of ^{235}U with a neutron creates between 2-3 more neutrons in the consequent reaction, an example of which is given below in equation 2.5.

$$n +^{235}_{92} U \rightarrow X + Y + 3n \tag{2.5}$$

The products, more accurately known as fission products, X and Y are represented by the following distribution in Figure 2.2, where the line labelled 'thermal' is most relevant to the majority of power reactors. The resultant neutron radiation from a sustained nuclear chain reaction is somewhat difficult to block, as neutrons are uncharged and travel until they interact with a nuclei or decay themselves by the reaction seen in equation 2.4 [33, p.27]. However, when a neutron interacts with matter that is rarely the end of the process, as a stable nuclei that absorbs a neutron is oftentimes not stable afterwards and is referred to as 'activated,' and this process is explored more in-depth in subsection 2.1.2. Now, with the different kinds of radiation defined, it is necessary to move on to the approaches radiation workers use to control and minimize the consequences of radiation.

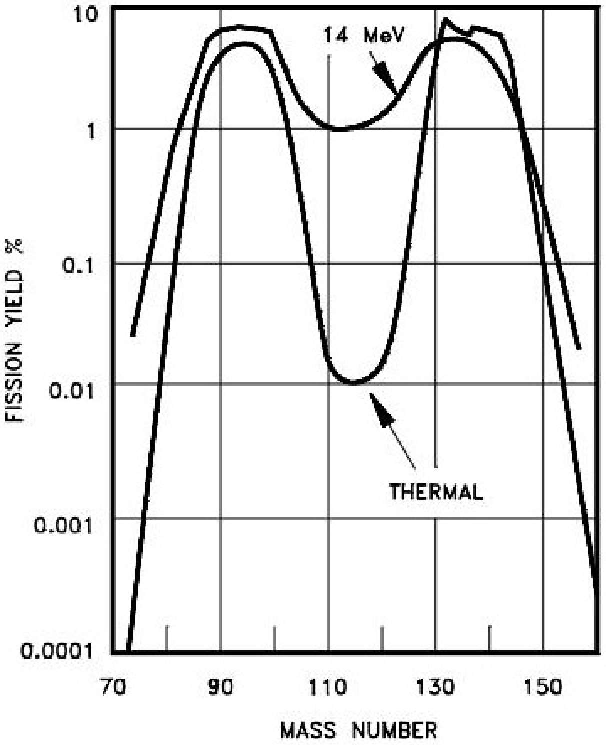

Figure 2.2 The distribution of fission products of ^{235}U for two different energies of neutrons [4, p.NP01-57].

2.1.1 Radiation safety

Radiation is a part of everyday life for every person on Earth, although most people are unaware of the constant dosage they receive from sources like cosmic microwave background radiation or naturally occurring radon leaking from underground uranium deposits, as some estimates put the average dose rate for the U.S. public at 620 mrem/day [1, p.42]. For those unfamiliar with the units of radiation, here is a quick and straightforward rundown: radiation is oftentimes measured by the amount of energy deposited in a unit amount of a substance. Grays (Gy) are the SI unit for measuring energy deposited in mass as a result of radiation, equalling 1 joule of energy deposited in 1 kg of mass, but in the United States the typical scale of measuring is the rad, which is a factor 10^{-2} smaller than a Gray (1 Gy=100 rad) [1, p.38]. Rads are then adjusted into Rems (Roentgen Equivalent Man) by use of Quality factors(Q) which are listed in table 2.1 by the simple formula Rad$*$Q=Rem.

Radiation Type	Q
Alpha	20
Neutron (of unknown energy)	10
Beta	1
Gamma	1
X-ray	1

Table 2.1 Quality factors for relevant types of radiation [1, p.39].

The different kinds of radiation are given the quality factors they have due to the amount of damage they can cause to biological material, which is related to the LET of the radiation type. Alphas are assigned a very high value because they are nearly guaranteed to collide with the objects immediately in their path, and then transfer a lot of their kinetic energy to that object. While nearly harmless outside the body due to the dead layer of skin cells that coat the human body, or the layer of water over the eye, alpha emitters wreak havoc when consumed and the living cells inside an organism are exposed to alpha radiation. Neutrons are on the same scale of mass as alpha particles, and have the only other non-unity value of Q because the amount of energy they can carry in a kinetic form is still much greater than the other kinds of radiation, despite their lack of charge. Now, armed with a sufficient understanding of radiation dose measurement, it is possible to explore the nuclear fields approach to minimizing these doses.

First and foremost among radiation safety principles is ALARA, short for As Low As Reasonably Achievable. This is based on the linear no threshold model of radiation, which in short is saying that there is no threshold below which radiation is no longer potentially harmful [1, p.50]. This approach is meant to be conservative and make every effort to reduce the radiation dose to everyone involved to the minimum possible dose within reasonable limits. In practice, ALARA is composed of three different pillars: Time, Distance, and Shielding. Time, because the shorter the duration you spend in a radiation field, the lower your absorbed dose will be. Distance, because radiation propagates in an inverse r squared relation and so doubling your distance from a radioactive source will decrease your dose by a factor of four. Shielding, because if you can construct shielding in such a way that it does not significantly increase the amount of time that a job in a radiation field will take then it will additionally reduce the absorbed dose of those present. In addition to these, contamination control is important because it prevents the inadvertent spread and/or consumption of radioactive particulates outside of areas that are strictly monitored for radiation dose [1, p.49-53]. When correctly followed, the above tenets are a radiation worker's guide to staying well below their annual dose limit.

At this point, one might be curious as to what a relevant dosage looks like, having covered what the units of dose mean and how to keep that number to a minimum while working around radioactive materials. The annual dose limit for a radiation to receive at their occupation is 5 Rem, and the maximum dosage a member of the public is allowed to receive at a nuclear facility is 200 mrem annually, and in quantities no greater than 2 mrem in one hour [34].

Table 2.2 describes the predicted effects of various dose levels when absorbed in a short period of time, the severity of these instantaneous effects typically is reduced when the dose is absorbed over longer periods of time. However, stochastic (probabilistic) effects are more likely to come into play with any increase of absorbed dose, even absorbed slowly over a long time period. This is where the risk of ingestion comes into play most heavily, as radioactive isotopes will behave chemically identically to other elements in your body and can be absorbed into locations such as the thyroid or bones and continue to irradiate a person from the inside for the entire decay chain of the material or duration of their

Absorbed Dose (rad)	Observable effects
x<25	None
25<x<100	Red and white blood cell levels reduced. Chromosomal mutations. Not externally observable
100<x<300	Nausea, ill-feeling and infection probably. Few weeks to recover
300<x<600	Severe nausea, diarrhea, and infection within hours. Hair loss within weeks, up to year to recover at lower end. Likely fatal above 400-450 rad untreated
x>600	Impaired central nervous system in addition to above symptoms, completely incapacitated above 1000 rad. Survival extremely unlikely

Table 2.2 Observed effects of an acute (short time period) whole body dose [1, p.39].

lifespan, whichever is shorter. Iodine, which can reside in a person's thyroid, is of specific interest due to the fact that an unstable isotope of iodine with a long enough half-life to have the capability of travelling significant distances is a common fission product, which is why the practice of distributing iodine capsules was common practice for nuclear incidents. Additionally, the U.S. Nuclear Regulatory Commission takes the potential release of fission products to the environment very seriously, as it is indicative of degradation of the primary fuel barrier and requires immediate notification of the U.S. NRC [9, §50.72]. The U.S. NRC is dedicated to protecting both populations and the environment from the effects of radiation and consequently, any potential release of radioactive material to the environment is done so through controlled pathways so that conservative limits can be observed, or heavily investigated afterwards in order to prevent future occurrence.

2.1.2 Neutron interactions

Neutrons have the unique property in radiation interactions of being able to activate a target they in-elastically collide with. The probability of this collision is fundamental to the isotope in question, and this property is given the name cross section and the symbol σ, which has units of barns or $10^{-24}cm^2$. Cross section varies with the kinetic energy of the neutron, but in general the thermal cross section of an isotope is the most relevant. A thermal neutron is one that is at equilibrium with its surroundings, and in other words its kinetic energy is on the order of $\frac{3}{2}k_bT$. This is a result of elastic scattering of the neutrons with its surroundings; materials that are used for the express purpose of slowing down neutrons to thermal levels are called moderators, which subsection 2.2.1 covers in more detail. When a neutron combines with a nucleus, the resultant nucleus has an increased mass and N value, which may remove it from the line of stability or possibly move it closer to it. Lighter isotopes upon activation tend to have short half lives due to the $\frac{N}{Z}$ ratio being easily shifted away from unity with the addition of a neutron, which can cause the product to decay immediately or pass through a meta stable state on its way to stability.

$$A' = N\sigma\phi(1 - e^{-\lambda t})e^{-\lambda t'} \tag{2.6}$$

The above equation calculates the activity A of a sample of N particles with cross section σ in a neutron flux ϕ for t time. In the equation, λ represents the decay constant of the activated product, equal to $\lambda = \frac{ln2}{T_{1/2}}$ where $T_{1/2}$ is the half life, and t' represents the time since the end of the irradiation [1, p.79]. Table 2.4 contains some example values of neutron cross sections that will be important to demonstrate later concepts.

When a substance is present in a nuclear reactor that is capable of absorbing neutrons, thus removing them from the chain reaction, it is known as a neutron poison or simply poison. Listed in Table 2.4 is ^{135}Xe, which is a neutron poison with an extremely high

Isotope	Thermal Neutron Absorption Cross Section (barns)	Reaction type
^{235}U	582.6 ±1.1	(n,fission)
^{238}U	11e-6 ±2e-6	(n,fission)
^{113}Cd	19852 ±400	(n,γ)
^{10}B	3837 ±9	(n,α)
^{135}Xe	2.65e6 ±1.1e5	(n,γ)
^{1}H	0.3326 ±0.0007	(n,γ)
^{1}H	20.491 ±0.014	(n,elastic)
^{2}H	3.390 ±0.012	(n,elastic)

Table 2.3 Thermal neutron cross sections for various relevant isotopes for the desired reaction [2].

neutron absorption cross section so it is extremely likely to absorb a neutron, significantly more so than ^{235}U. ^{135}Xe is also created within the fuel by the fission of uranium and the decay of other fission products, and so it has a significant and noticeable effect on reactor operation as it provides a transient poison within the core that will continue to affect power level until an equilibrium state of equal amounts being created and removed is reached.

2.2 Reactor Physics

In a generic nuclear reactor there is an array of fuel rods contained in some sort of cladding, stainless steel for example, that are in either a rectangular or vaguely circular arrangement with enough space between the fuel rods to allow water to pass through. The water serves many important purposes, such as shielding, cooling, and moderation. Around the edges of the core there may be reflectors designed to contain neutrons within the core better and increase the efficiency of the reaction. Additionally, interspersed throughout the core there will be rods or blades of a neutron absorbing material, such as boron or cadmium, that are linked to mechanisms that are remotely moved to control the chain reaction. Lastly, there have to be some detectors which provide real time output to the operators for data such as the neutron flux level and fuel temperature. There are a great number of factors at play that affect the efficiency of a neutron reaction, and some engineered inefficiencies in place that increase the overall safety of the core.

From earlier sections, it was explained that nuclear fission of ^{235}U releases between two and three additional neutrons that can then go on to cause additional fission events. However, those neutrons are moving much too fast with average kinetic energies of 2 MeV and need to undergo the thermalization process before they will make good candidates for other ^{235}U nuclei to absorb them [4, p.NP02-23]. This thermalization process is the purpose of moderators, which the next section will explain.

2.2.1 Moderation

Moderators are one of the most important components of a reactor, as they are necessary to slow down fast neutrons to thermal speeds which can then be absorbed by the fuel to continue the chain reaction. Ideal moderators have high neutron scattering cross sections, low neutron absorption cross sections, and masses approximately equal to that of the neutron. To visualize it simply, imagine neutrons as high velocity billiard balls launched towards some target, with the goal being that the neutron will be returned at a lower velocity. If the target is made of clay, it is akin to having a high absorption cross section and you will lose many of your neutrons as they stick to the target. Additionally, if the target is something akin to a bowling ball, your billiard ball will be returned at nearly the identical velocity it left with which creates an inefficient moderator (See Appendix B). The ideal moderator, then, is hydrogen as it is of a comparable mass to the neutron at $\sim$1 amu, and has a high neutron elastic scattering cross section compared to its absorption cross section (see Table 2.4). The process of moderating neutrons is not instantaneous and can require multiple collisions to reach thermal energies, and there are various events that can occur that prevent a neutron from successfully reaching thermal energies. All U.S. reactors are undermoderated, for reasons that will be discussed in section 3.1, but for now it is adequate to know that the efficiency of a moderator is dependent on the temperature of the moderator.

2.2.2 Neutron life cycle

The neutron life cycle is described by the empirical six factor formula in equation 2.7,

$$k_{eff} = \varepsilon \pounds_f p \pounds_{th} f \eta \tag{2.7}$$

where the following table gives the definition of each value of the equation [3, p.NP03-10].

Variable	Definition
k_{eff}	$\frac{n \text{ produced in one generation}}{n \text{ absorbed in prev. gen.} + n \text{ leakage in prev. gen.}}$
ε	$\frac{\text{fast } n \text{ from all fissions}}{\text{fast } n \text{ produced by thermal fissions}}$
$\pounds_f$	$\frac{n \text{ produced in one generation}}{n \text{ absorbed in prev. gen.} + n \text{ leakage in prev. gen.}}$
p	$\frac{n \text{ that reach thermal energies}}{\text{fast } n \text{ that begin thermalization}}$
$\pounds_{th}$	$\frac{n \text{ produced in one generation}}{n \text{ absorbed in prev. gen.} + n \text{ leakage in prev. gen.}}$
f	$\frac{n \text{ absorbed by fuel}}{n \text{ absorbed by all reactor materials}}$
η	$\frac{\text{fast } n \text{ produced by thermal fissions}}{n \text{ absorbed by the fuel}}$

Table 2.4 Definitions of each variable within the six factor formula [3, p.NP03-10].

How the six factor formula works is that it characterizes the behavior of a single generation of neutrons within the reactor, and despite these steps all happening simultaneously within the core, the math still is functionally relevant to the probabilities that each neutron undergoes and thus scale-able for any size of neutron generation. Starting with the fast fission factor,

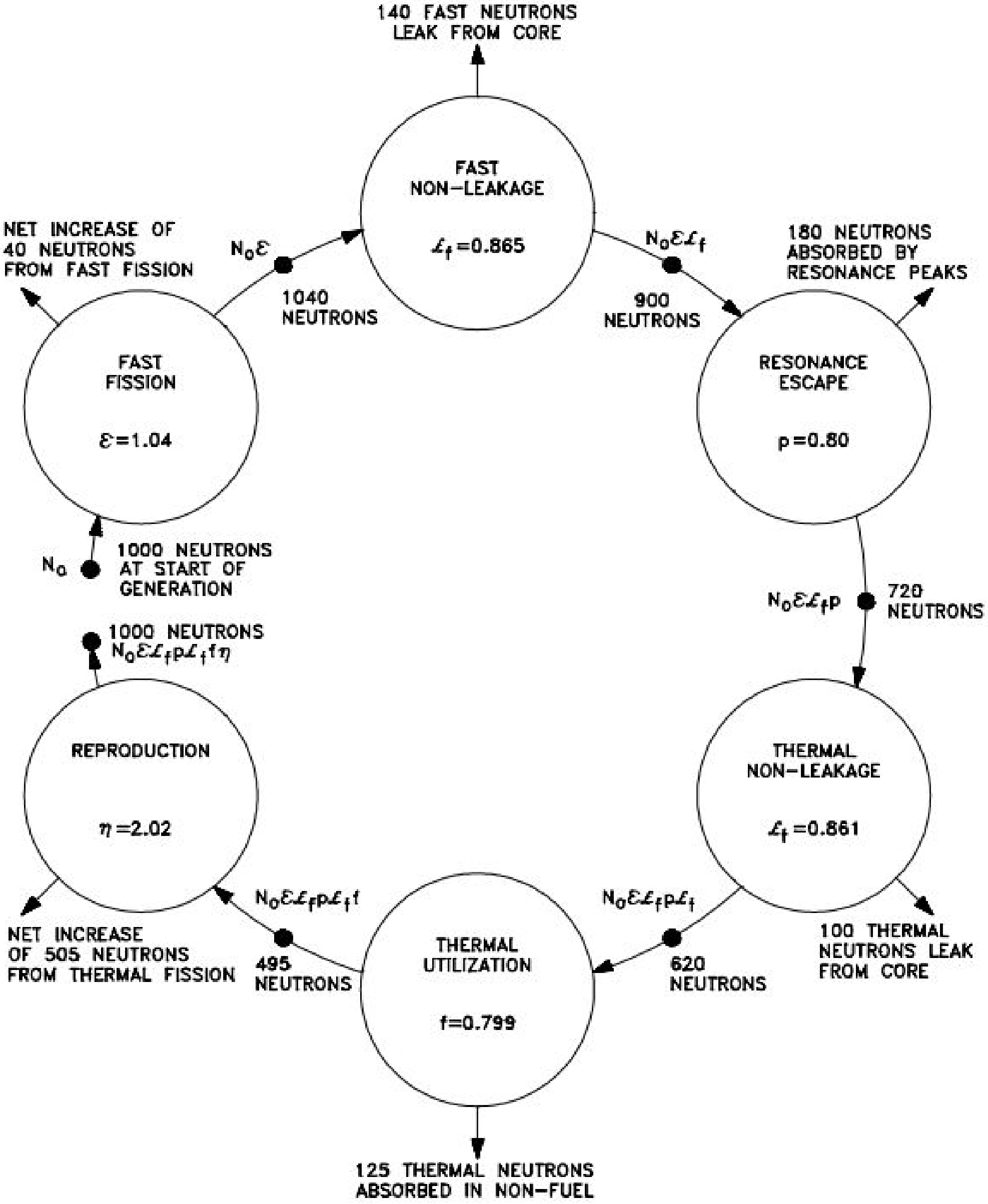

Figure 2.3 A graphical representation of the six-factor formula at work, with typically values inputted [3, p.NP03-11].

ε, here is where we see an increase in the number of neutrons due to the fast fission of ^{238}U in the fuel before any of the neutrons from the previous generation have been able to begin thermalization. Fast fission is the term used for fission that is caused by neutrons above thermal energies, as some isotopes in the core such as ^{238}U are considered fissionable, meaning they can fission with neutrons of sufficient energy. These isotopes differ from fissile isotopes, which are isotopes that will fission with neutrons of thermal energies.

After fast fission neutrons are added to the generation, the next factor chronologically to be applied is the fast non-leakage factor $\pounds_f$ which simply defines the ratio of neutrons that do not escape out of the core immediately into the shielding beyond the core. Increasing the amount of reflectors - which are made of elements such as carbon which have high neutron scattering cross sections and higher masses than moderating materials to bounce neutrons back in more effectively - will increase the fast non-leakage factor by preventing additional neutrons from escaping the core. Once the neutrons begin thermalization, they are susceptible to being absorbed by the resonance peaks present in ^{238}U and this is where the resonance escape factor, p comes into play. Figure 2.4 illustrates what resonance peaks

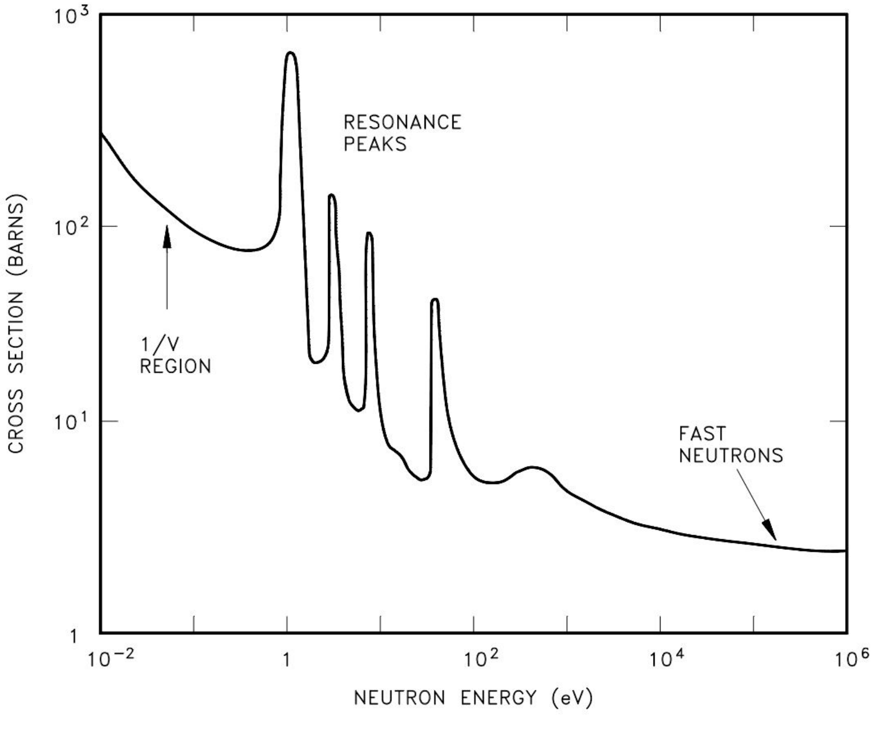

Figure 2.4 A typical neutron capture cross section [4, p.NP02-9]

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will look like, as rapid increases in the absorption cross section when related to the energy of the incident neutron. When a neutron is being moderated, it has to pass through the energy levels of these peaks and avoid being absorbed at the resonance peaks of ^{238}U specifically to reach thermal energies. By decreasing ^{238}U concentration in the fuel you can increase the value of p; similarly, increasing the amount of moderator to decrease the amount of time the neutrons spend near these energy peaks will have a similar effect.

Next is the thermal non-leakage factor, $\pounds_{th}$, which is defined similarly as $\pounds_f$, except that the neutrons have now completely thermalized and this factor represents the ratio that are left to be absorbed by the core. All of the neutrons from this point on then have to be absorbed by the core, and the thermal utilization factor f is used to describe the ratio that are absorbed by the fuel specifically versus all of the neutrons that are absorbed by the core. The most relevant non-fuel structures in the core are the control elements, and so the thermal utilization factor is the most easily manipulated of the six factor formula by an operator in order to arrive at different criticality states. Lastly, the reproduction factor is where the traditional understanding of a fission reaction occurs, as the fuel absorbs the thermalized neutrons and produces additional neutrons to start the next generation. This last factor is largely dependent on the enrichment of the fuel, as more ^{235}U will result in a larger reproduction factor [1, p.103]. All of these factors combined give k_{eff}, known as the effective multiplication factor which determines the growth or shrinkage of the neutron count with each successive generation. Values of k_{eff} above unity result in a supercritical reactor, while values below give a subcritical reactor. When $k_{eff} = 1$ the reactor is said to be exactly critical, with power level maintaining a constant position [1, p.100].

Reactivity, which is defined as the departure of a reactor from criticality, and mathematically calculated with equation 2.8, is an important measure in a reactor as different actions can either add or subtract reactivity to affect the chain reaction.

$$\rho = \frac{\Delta k_{eff}}{k_{eff}} = \frac{1 - k_{eff}}{k_{eff}} \tag{2.8}$$

The concept of reactivity can be referred to as positive or negative rather interchangeably depending on the mechanism at play, as it is easier to think of neutron poisons building up in the core as adding negative reactivity, while removing fuel will be removing positive reactivity. These both push the value of k lower despite their different phrasings, and so care should be taken to prevent any confusion when mentioning reactivity. Reactivity is oftentimes given in units of dollars ($), which is given by the equation $\$ = \frac{\rho}{\beta_{eff}}$ where β_{eff} is a scaling constant equal to the fraction of delayed neutrons present in the core [1, p.117]. As delayed neutrons are necessary to control reactor power, what this translates to is that a positive reactivity excursion of 1$ at $k_{eff} = 1$ is enough to take the reactor prompt critical, and so to maintain control of the chain reaction during normal, non-transient operations the reactivity value above what is necessary for exact criticality must remain below this point.

2.2.3 Subcritical multiplication

Subcritical multiplication occurs when a reactor is neither critical nor supercritical, leading to an exponential decay of each generation of neutrons which after some amount of time would lead to an extremely low number of fissions occurring in a core. However, reactors often have one other mechanism present not discussed in the previous sections: a neutron source, which is usually some combination of elements that when irradiated is provoked into releasing neutrons at a steady and predictable rate. The purpose of a neutron source is to never let the number of neutrons in the core approach zero, largely so that the neutron count stays above the minimum detectable rate from power detectors. The neutron source is akin to a car's battery, because it 'charges' during operation of the reactor, and then is used to maintain a low and steady power level after shutdown which can then be drawn on to jump start the reaction when operation is to begin again. This steady and low power level is a result of the source neutrons being multiplied by the subcritical reactor, as each generation is born the same size and then slowly decreases over time. The resultant sum of each successive generation converges into a geometric series, leading to the following equation [1, p.106].

$$C = S(\frac{1}{1 - k_{eff}}) \tag{2.9}$$

Here, C is the number of neutrons present in the core at any point after the reactor has been shut down for long enough to decay down to this steady value, and S is the number of neutrons produced by the source. If the source were ever removed, the neutron count would continue to exponentially decay related to the value of k_{eff}.

As one can imagine, this delay between control blade insertion rendering the reactor subcritical, and its actual eventual arrival at its lowest power level has been influential in all three of the aforementioned nuclear power reactor accidents. In both the Fukishima and Three Mile Island accidents, the cores melted down after the control rods had been fully inserted [28] [27]. As for the Chernobyl nuclear accident, the melted core material dubbed the "elephant's foot" is still active to this day in a lavalike state, continuing to create its own heat and undergo chemical changes [35].

Chapter Three

Reactor Safety Systems

Now, with a sufficient understanding of the background physics occurring within a nuclear reactor established, it is possible to move onto the main features and describe the functions of several different reactor safety systems and analyze their shortcomings, successes, and how combinations of them function to reach an acceptable level of safety. Within any reactor there are typically two major kinds of safety systems at work (using safety systems broadly, to describe any engineered property or mechanism meant to prevent or minimize the risk of one or more potential catastrophes). Passive safety systems work without the initiation of a signal given by the reactor operator or monitoring systems, while active safety systems are initiated by either an operator or when predetermined conditions are met causing an automatic initiation of the active safety system. The first passive safety system to cover is common to all U.S. reactors and stems from physical properties of the core's design: the prompt negative temperature coefficient.

3.1 Prompt Negative Temperature Coefficient

All U.S. reactors are purposefully under moderated in order to create what is known as a prompt negative temperature coefficient (PNTC), which results from different effects that temperature has on the efficiency of moderating material [1, p.142]. In general, moderators decrease in efficiency as the temperature increases when the effects described in the following subsections take hold. As revealed in Figure 3.1, the ratio of the amount of fuel to the amount of moderator in a reactor core has drastic effects on the value of K_{eff}, as when there is too much moderator the value of K_{eff} decreases due to the poison effects of the moderator absorbing neutrons. However, the neutrons that are not absorbed by the moderator thermalize more quickly, decreasing the number that are absorbed by the different resonances they pass on the path to thermalization and leading to the value of the resonance escape factor, p, to increase. The top line of Figure 3.1 is the product of the two below lines as well as the other four factors which are held constant over the x-axis for the purpose of this visual. Where temperature comes into play in this graph is that the ratio of moderator to uranium fuel given by N^m/N^u is inversely proportional with temperature over the relevant temperature ranges, with some notable exceptions that will be covered in later in the section. Consequently, for under moderated reactors an increase in temperature results in a leftward shift of the moderator to fuel ratio and a decrease in K_{eff}, giving rise to the titular effect of this section, the prompt negative temperature coefficient. As a result, any increase

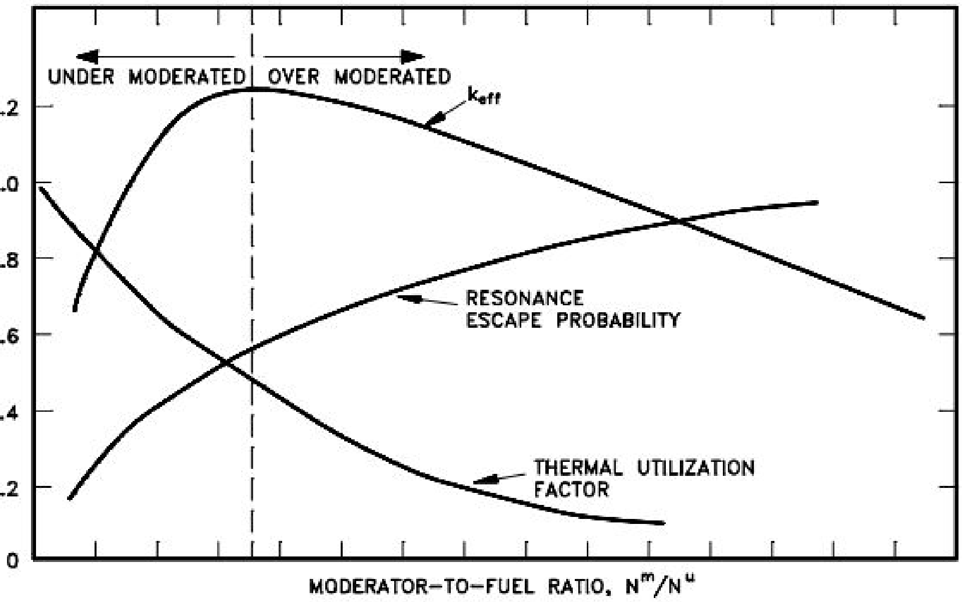

Figure 3.1 The effects of the moderation to fuel ratio on two different values of the six factor formula [3, p.NP03-25].

in a moderating material's temperature results in a reduction of reactivity combating this increase in power and creating a more inherently stable chain reaction that is resistant to sudden temperature excursions [3, p.NP03-26]. Composing PNTC are four main physical effects that combine to create the overall temperature coefficient: the cell effect, void coefficient, Doppler broadening, and thermal expansion, to be elaborated on in the next four subsections.

3.1.1 Cell effect

The cell effect exists largely due to the vibration of moderator molecules due to thermal excitation, and is significant in its magnitude compared to the other effects when applicable. Neutrons are thermalized via the process described in sub-section 2.2.1, and when the heat of the moderating material increases so does the frequency of the oscillations within its molecules. A neutron is described as thermal when it is in equilibrium with its surroundings, and via the equipartition theorem we can say that this places the neutron's kinetic energy at $\sim \frac{3}{2}k_BT$ and its average speed between 2700-3900 m/s for temperatures in the 300K-600K (27°C-327°C) range (see Appendix C for calculation). The cell effect is largely important when the main moderator for the fuel undergoes temperature changes alongside the fuel, and the moderator is composed of low mass elements (usually hydrogen) that have a velocity distribution similar to neutrons. Consequently, this effect is limited to a small subset of reactors, specifically the TRIGA research reactors located in the U.S. due to the hydrogen-zirconium matrix that is distributed among the fuel meat of TRIGA fuel [1, p.145]. However, tests have shown that the uranium-zirconium-hydride matrix of these types of fuels could be scaled up to the level of power reactors while retaining large PNTC values with some small changes to the composition of the fuel [36]. Reactors moderated by water or graphite are less susceptible to these effects as water has a relatively high specific heat, and graphite being composed of carbon has a smaller change in velocity over the same temperature ranges presented above. As a result, the following three effects are much more noticeable and pertinent to the discussion of power reactors but even these will vary in importance based on reactor design as they are variable characteristics inherent to each design.

3.1.2 Void coefficient

When water is present within a core, the void coefficient corresponds to the steam pockets that form when operating above boiling temperatures and create holes within the fluid. This effect is much more important in power reactors, whose primary purpose is to harness the thermal energy from the chain reaction via boiling water and then use this to drive a turbine which generates electricity or other forms of energy to be utilized. However, whether the effect of the void coefficient is positive or negative depends on how the core is moderated. For instance in the graphite moderated Russian RBMK reactors like the ones that operated at Chernobyl, an increase of the voids in the water present in the core increased reactivity by reducing the total amount of water in-core which had a poisonous effect on the neutron chain reaction, and this effect was so great that it led to the core itself having a prompt positive temperature coefficient, and with little imagination one can imagine the risk of this synergistic effect between temperature and positive reactivity excursion [37, p.2-3]. The cause for this positive void coefficient can be traced to the fact that due to the graphite moderation of the core, the core did not require water in order to complete moderation and allow for the chain reaction to continue and as a consequence the poison effects of having water in the core dominated the interactions of neutrons with the water. Therefore, when the amount of water molecules would decrease by forming less dense steam bubbles, the poison effects of the water would actually decrease and increase the reactivity of the core.

In a properly undermoderated, water moderated core however, the void coefficient will be negative due to the lessening efficiency of the moderator as it is in its less dense gaseous form. Here it is important to create the distinction between the two major reactor types in the U.S.: boiling water reactors (BWRs) and pressurized water reactors (PWRs). The difference is evidenced by their names, as a boiling water reactor boils the water directly in core, containing a mixture of both gas and water in the containment barrier and using the created steam to drive the turbine outside of the containment barrier. A pressurized water reactor works slightly differently in that the water within core is kept in a liquid state at all times and reaches temperatures well above the standard boiling point of water. This water is then piped out and used to boil water that is not kept pressurized in a heat exchanger, and then this steam goes on to drive the turbines. From this analysis, it is then clear that the void coefficient is much more relevant to boiling water reactors than pressurized water reactors [3, p.NP03-27]. In other reactors where boiling conditions are not met, or where the steam is quickly removed from the core via its own buoyancy, the value of the void coefficient is much reduced in magnitude.

3.1.3 Doppler broadening

As established during the discussion of the six factor formula in subsection 2.7, specifically p the resonance escape factor, during the thermalization process the neutrons pass through energy resonance peaks of different elements and can be consequently absorbed at these peaks (see Figure 2.4). Doppler broadening occurs due to the relative motion of ^{238}U in the fuel with incoming neutrons, taking the peaks shown in Figure 2.4 and broadening the energy range of neutrons that they can absorb and remove from that neutron generation, which is demonstrated by Figure 3.2. The best way to visualize this effect is to imagine the absorbing nucleus on a spring, oscillating at a frequency that is dependent on the temperature. For that nucleus to absorb a neutron that collides with it, it must collide with a specific energy. When the oscillating nucleus is at low frequencies, its energy contributes minimally to the collision and we have a sharp absorption peak. However, when the oscillation frequency increases, this contribution becomes much more significant and it is easiest to understand the collision by comparing two different reference frames: the normal or 'lab' frame, where the neutron is viewed as moving with some velocity and the absorbing nucleus is oscillating on its spring, and the frame of reference in which the absorbing nucleus is holding still. For non-relativistic neutrons, Galilean relativity is sufficient enough to explain that the results from the viewpoints of either frame of reference should be identical at the moment of collision. Therefore, our neutron of velocity v and our oscillating nucleus which has a velocity range bounded by $\pm\Delta V$ collide and the relative velocities between the two falls within the range of $v \pm \Delta V$, and so as ΔV increases so does the range of energies that the absorbing nucleus sees, and consequently the probability of colliding at the exact required energy for absorption is increased. This effect then contributes to the magnitude of the prompt negative temperature coefficient and will exist in nearly every core that contains some amount of ^{238}U, which is one of the main isotopes contributing to the resonance escape probability.

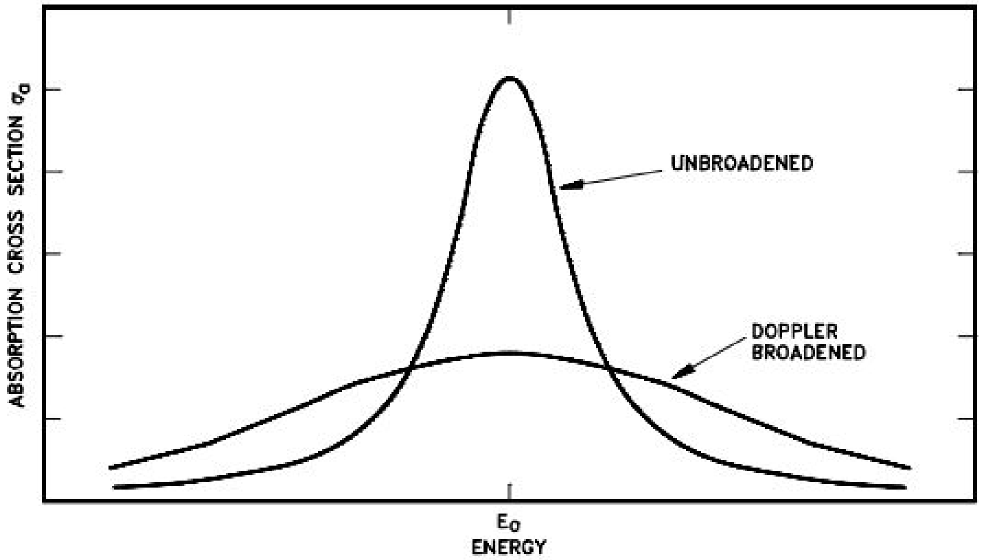

Figure 3.2 A demonstration of the change in a resonance absorption peak during Doppler broadening [3, p.NP03-27].

3.1.4 Thermal expansion

Commonly the smallest contribution to PNTC is the thermal expansion of the materials used as both moderators and fuel. Water only varies by $\sim 4\% \frac{\#}{V}$ over its entire fluid phase at 1 atm [38], so the effects of thermal expansion in a water moderated reactor are bound to be small but empirically noticeable. For PWRs, the pressure of the moderating water is also a factor but is also a minor one due to the immense amount of pressure that it takes to appreciably change the density of water. Consequently, the thermal expansion and high pressure compression of the moderating material is very small compared to other temperature related factors affecting reactivity such as the void coefficient and Doppler broadening [3, p.NP03-27].

3.1.5 Shortfalls

The prompt negative temperature coefficient of a reactor is useful as a balancing force when raising the temperature of a core, providing a mechanism to prevent runaway reactions during controlled startups. However, reactor cores have to be designed with a PNTC and have enough built in excess reactivity, or reactivity above what is necessary to reach criticality, to overcome it such that they can continue to operate at full power when the temperature is at elevated but still normal operating levels. Consequently, a steady insertion of reactivity, or a loss of coolant accident could be enough to damage the core in such a way that the intrinsic PNTC would not be able to prevent damage to the core. Additionally, in cases where the cladding of the fuel fails or the reactor melts down into a composite material known as 'corium,' the structurally engineered PNTC of the fuel can be altered or negated entirely. As a result, the PNTC provides an important mechanism for controlling reactor power but is not enough to provide adequate levels of safety in large reactors that have a higher volume of fuel and oftentimes reduced magnitude PNTCs.

3.2 SCRAM

The SCRAM function is one common to many reactors, as it is perhaps the simplest and most straightforward way to reduce reactor power. Reactor power is typically controlled by insertion or removal of neutron-poison containing control rods/blades (rods and blades are used interchangeably, ofttimes regardless of geometry), and a SCRAM is designed to rapidly insert the rods back into the core in such a way to shut down the nuclear reaction very quickly. In the first reactor designed by Enrico Fermi, the rods were made of cadmium which he likened to "a pipe of cold water running through a rubbish heap; by keeping the temperature low the pipe would prevent the spontaneous burning" [22, p.30]. While the origin of "SCRAM" is disputed [39], a common story repeated among reactor operators is that in the first reactor, Chicago Pile 1, there was a large cadmium plate hanging above the core by a rope that was run over a pulley and mounted to an accessible location. A grad student of Fermi's was then given an axe and the title Safety Control Rod Axe Man with the instructions to cut the rope should Fermi determine the reaction was getting out of control, and SCRAM entered nuclear reactor vernacular as an acronym of this title. Interesting anecdotes aside, the idea of using gravity to let a control rod drop into a reactor core is a common feature of nuclear reactors as it is a reliable and calculable source of force that is immune to mechanical error.

3.2.1 Construction details

Control rods are typically constructed of neutron absorbing materials like boron or cadmium (see Table 2.4) and can utilize a variety of systems to be raised and lowered into the core. For the Reed TRIGA reactor [1], as well as the WSU research reactor [40], reversible electric motors are connected to rods that have strong electromagnets on the end. These electromagnets, when engaged, then connect to plates at the top of long rods that extend down to the core and connect to the neutron poison blade that is located inside the core itself. The motors can be used to raise and lower the blades at a controlled speed into and out of the core, with potentiometers attached to give the operator a real time position reading. When a SCRAM is initiated or electricity is lost to the building, the current to the electromagnets is cut and the blades are dropped into the core via the force of gravity, free falling nearly the entire length until a dashpot assembly using viscous damping slows the descent for the last ∼1in so that the entire weight of the blade is not dropped on the bottom of the core structure. For the small size of both the WSU research reactor and the Reed reactor, this rate of insertion is well within what is required of the facilities governing documents. Once a SCRAM is completed and the rods are fully inserted, the reactor is in a subcritical state but it will still take time to dissipate the built up thermal energy from operation. Additionally, the fission products created during operation will continue to decay and release neutrons as some of these are known as delayed-neutron precursors, the longest half-life of which is 55.72 seconds [1, p.117]. Consequently, after an initial power drop the reactor power decrease will reach a steady exponential decay until it reaches the neutron count that is created from the multiplication of neutrons from the source (see subsection 2.2.3). For a small research reactor, this may take several days and in a large reactor it may take weeks during which the cooling systems still need to be operational.

Larger scale power reactors have additional systems to be concerned with in the event of a SCRAM, mainly the cooling systems due to either the high pressure in the containment capsule of a PWR or the creation of steam in a BWR. The necessity of these cooling systems is tantamount in a power reactor that can produce hundreds of megawatts of thermal energy, and so a combination of pressure and flow sensors work in tandem to either warn the operator(s) of insufficient cooling capacity or initiate automatic protective action themselves. PWRs have blades inserted from the bottom of the core [41, p.251], due to the nature of their design, and so they do not rely on gravity for blade insertion but instead a pressurized hydraulic system that forces the control blades into the core upon the initiation of a SCRAM or loss of power. Overall, the concept of the SCRAM is the same for most light water reactors: control blades are moved to the position which maximizes the magnitude of their negative reactivity insertion with a speed greater than what would be used during normal operation or shutdown operations. In terms of the six factor formula, insertion of the control blades is going to decrease the value of f the thermal utilization factor by decreasing the number of neutrons that are absorbed by the fuel, instead absorbing them into the core structure which includes control blades. Reactors are designed such that a SCRAM will lower f by a large degree such that the reactor can be made subcritical from any operating conditions [42, B 3.1.1-1] [43, B 3.1.1-1], which is built into the definition of shutdown margin (SDM) for all U.S. reactors. Present in the technical specifications of a nuclear reactor is a limit on the minimum shutdown margin allowable, which has the added safety of requiring that this limit be met with the highest reactivity blade in the fully withdrawn position so that no matter what, even if one blade fails to insert, the core can be made subcritical via means of a SCRAM.

3.2.2 Extra considerations

A variety of factors determine the effectiveness of a SCRAM, such as the location of the control rods relative to the flux, speed of insertion, as well as the possible reduction of the void coefficient due to decreasing temperatures [41, p.258]. Additionally, larger reactors will take longer to cool down as delayed neutron precursors continue to create new neutrons in the core for some time after the core is rendered subcritical. In power reactors with cooling systems forcing water through the core, it is important to carefully control the temperature decline of the core to prevent thermal distortions, and so a maximum cooldown rate is implemented via the cooling system pressure and flow rates to prevent temperature shock [43, B 3.0-3]. Additionally, one historically large shortfall of the SCRAM function occurred at the Chernobyl power plant in Ukraine, as the rods were completely withdrawn and were not constructed of homogenous materials along their entire length. Consequently, when they were all rapidly reinserting following the initiation of a SCRAM, the carbon capped ends of all the rods entered the core first and pushed the already uncontrolled power increase, caused by a prompt positive temperature coefficient, past the tipping point [37, p.16]. This failure highlights the necessity of having multiple overlapping safety systems that can all work together to return a reactor to safe conditions should a dangerous situation develop. Had the SCRAM function of Chernobyl been designed such that the poison section of the blades entered first, or if the core was designed with a prompt negative temperature coefficient it is possible that the catastrophe would have been mitigated or of a reduced severity.

3.3 Emergency Core Cooling Systems

One of the most catastrophic disasters possible in a water-cooled nuclear reactor is a loss of coolant accident (LOCA), as the heat will weaken the structure of the fuel rods and possibly cause them to rupture, releasing fission products into the void left where the primary coolant used to be. Three fundamental safety functions are crucial to the design of any nuclear core: control of reactivity; removal of heat from the core; and confinement of radioactive material [44, p.4]. In a LOCA, cooling capabilities have the potential to be reduced below acceptable safety levels, which can then lead to a release of radioactive material if the core melts down and breaks containment. Emergency core coolant systems (ECCSs) are then required by the NRC in PWRs and BWRs using uranium oxide pellets within zircaloy cladding in order to meet several goals in the event of a LOCA, one of which is to keep the peak temperature of the fuel cladding below $2200°F$ [9, §50.46]. Left uncooled, the swelling of rods due to internal gas pressures and possible cladding ruptures can reduce the total effectiveness of the coolable geometry by as much as 100%, exceeding what is speculated to be coolable by an ECCS [45, p.501]. Consequently, an ECCS needs to be able to effectively cool the core in a short timescale and at a high enough rate to overcome the maximum possible LOCA, which is defined as a break equal in size to a double-ended rupture of the cooling system's largest pipe [9, §50.46]. Then comes the considerations necessary for the differences between PWRs and BWRs, as a PWR will require the possibility of pressurized water injection, and both will need to have mechanisms to prevent the escape of any steam or gasses from the core that may interchange places with the inserted coolant. In terms of complexity, coolant injection exceeds the SCRAM function by far and introduces another degree of freedom for reactor manipulation by the operator, one that has to be carefully applied or risk serious consequences for the core integrity.

3.3.1 ECCS components

ECCSs are typically manually deployed systems designed to add more coolant to a core in the case of a LOCA to prevent exceeding the temperature safety limits of the core fuel and possible fuel element damage. Within an ECCS four systems are present to return the core to safe conditions: high pressure core spray system (HPCS), automatic depressurization system (ADS), low pressure core spray system (LPCS), and low pressure coolant injection (LPCI). In a maximum analyzed LOCA, these systems would be deployed sequentially to first cool the core at high pressures via the HPCS while the ADS is working to reduce the internal pressure of the containment vessel. Once pressures have been sufficiently equalized, the LPCS can then aid the HPCS in spraying a mist of water into the core until it is safe to deploy the LPCI system and flood the core with water, all of which is predicted to occur in less than 3.5 minutes [46, p.544-9]. Continued cooling is necessary past the 3.5 minutes but once the core is flooded with water there is enough time to reevaluate and proceed with a course of action which shall maintain fluid flow until such a point that the leak can be fixed and primary coolant systems reengaged, or additional actions to reduce the consequences of an LOCA can be taken.

While cooling may be the primary concern during a LOCA, being able to shut down the source of the thermal energy to a greater degree will be of benefit to the safety of the entire system and that is the purpose of boron additives in the ECCS. As ^{10}B is the isotope responsible for neutron absorption in most control rods, it is straightforward to understand why the addition of boron during the HPCS and LPCS phases of cooling after a LOCA would be beneficial in shutting down the reaction and keeping excessive heat from building up in the core. This addition of negative reactivity, which can reach values of 20\$, is enough to offset the potential positive reactivity changes resultant by adding more cool moderating material (water) to the core which would decrease the void coefficient [47, p.168]. Overall, the ECCS system is designed in such a way to cool the core without introducing additional hazardous conditions that would elevate the dangers of the LOCA.

3.3.2 Analysis

The design criteria of any ECCSs are sufficient enough to allow for total re-submersion of the core into water in a short time scale, and without introduction of too great of a temperature transient by means of the sequential spray and flooding systems that it would seem equipped to handle nearly any predictable level of coolant loss. Add onto this the insertion of dissolved boron in the emergency cooling system, which can be thought of nearly as a liquid SCRAM, and plant safety is seemingly assured. However, it is important to recognize that one of the accidents marring the past of the nuclear field at Three Mile Island was due to both failures in the reactor coolant system as well as operator actions which exacerbated the mechanical failures [27, 33]. Consequently, what this highlights is not only the importance of training for operators at the controls, but proper diagnostic equipment so that the source of an accident may be correctly identified and mitigated using the established steps for that situation. In essence, a safety system is only as strong as its weakest link and when readouts return confusing or seemingly contradictory data, it makes it nigh impossible for a trained operator or an electronically deployed safety system to beneficially take protective action.

3.4 Liquid Fluoride Thorium Reactors

Liquid fluoride thorium reactors (LFTRs) function fundamentally differently than a standard uranium PWR or BWR and have yet to see broad adoption globally. However, they contain promising engineered safety systems that could render them completely immune to meltdown situations. Additionally, thorium reactors can be designed to produce less waste than traditional reactors because of the liquid fuel design. By having fuel unconfined by rigid cladding, chemical separation can take place during power operations which allows molten salt thorium reactors to avoid costly and time consuming fuel swap outs [5, p.308]. Additionally, thorium is abundant in amounts approximately four times greater than uranium in the Earth's crust, and is more easily refined as it does not require the enrichment that traditional uranium fuels do [5, p.306]. However, before proper discussion of the distinct safety systems unique to LFTRs one has to grasp the differences in the design of one of these reactors that permits these features.

3.4.1 Thorium reactor design

Thorium reactors take advantage of the fact that thorium-232 is a fertile isotope, meaning it can be transmuted under neutron irradiation to produce ^{233}U which is fissile. This is done by using a multi-layered structure in which the outer containment shell is filled with a blanket of ^{232}Th which surrounds the chain reaction of the enriched ^{233}U in the central chamber. After the initial chain reaction is begun using a source, the ^{233}U is capable of maintaining the chain reaction in the central chamber, with some neutrons escaping to irradiate the ^{232}Th in the outer chamber. The blanket of molten fluoride salt is continuously being cycled through the outer chamber, leaving the core to have the transmuted ^{233}U chemically separated via introduction of fluorine gas. The purified ^{233}U is then redirected to the central chamber to serve as additional fuel for the chain reaction [5, p.307]. Additionally, the central chamber material is cycling out of the core and undergoing chemical separation

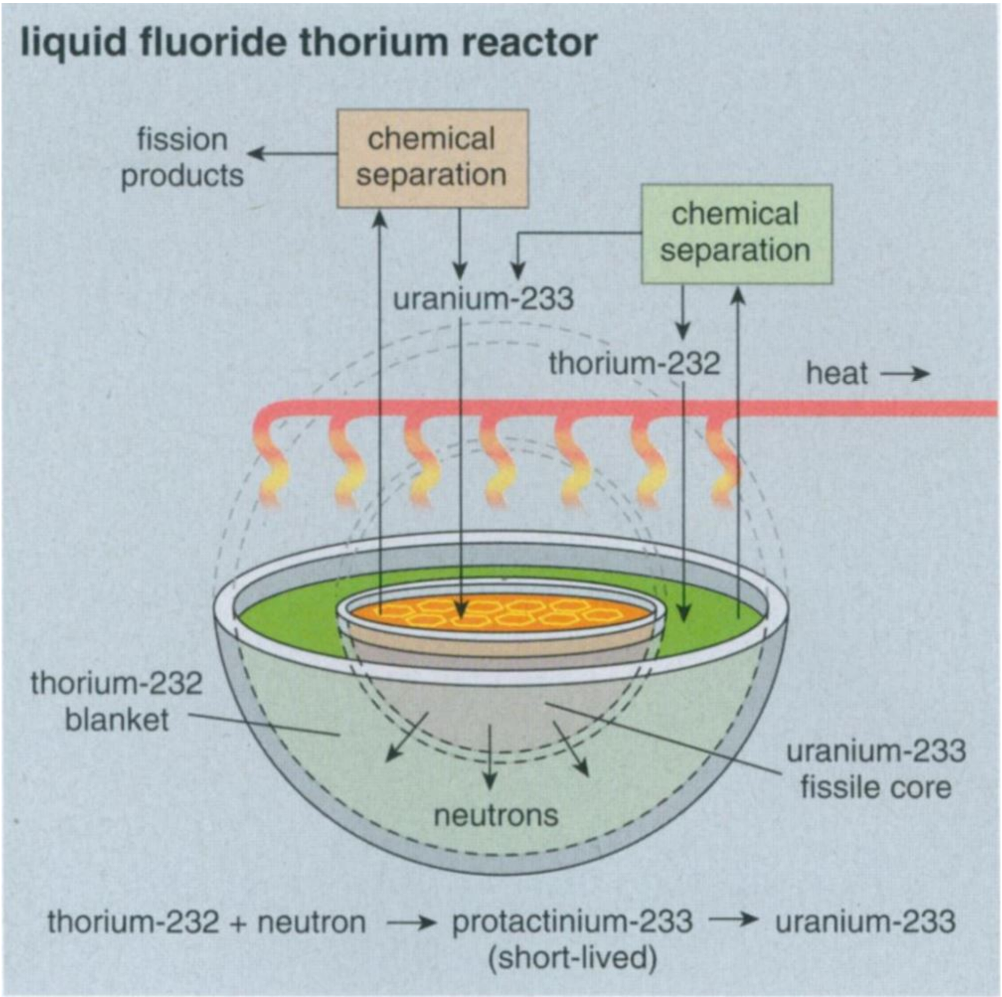

Figure 3.3 An abstract image of a potential design of a LFTR, demonstrating the separate chambers and irradiation process [5, p.307].

in which the neutron poisons formed via fission products, with ^{135}Xe being of note, are removed before they can reach significant concentrations. What this amounts to is that a LFTR functions as a reactor, fuel enrichment and reprocessing center all within the same complex with the end result being a vast reduction in the amount of nuclear waste byproduct created per unit of energy generation, at an estimated ten to 100 times less than a light water reactor [5, p.308] [48, p.337]. As the molten fluoride salt does not boil until $1400°C$, it is not necessary to pressurize the chamber and heat can be exchanged from the apparatus either by the pumping of the fuel medium through a heat exchanger or a system of pipes running through and around the core itself [5, p.310]. By separating the coolant from the fuel even further, the explosive dangers of pressurized capsules and boiling water are reduced to a greater degree than in standard PWRs and BWRs.

3.4.2 Safety features

Besides the removal of volatile steam from the reaction, the most exciting safety feature of liquid fluoride thorium reactors is the salt plug designed into the bottom of the pool of liquid fuel. This plug is kept below the freezing point of the salt by means of a fan, and if the electricity is ever cut or the core becomes too hot, the salt plug will melt and the liquid fuel will be removed from the core and moved to auxiliary tanks that are outfitted to cull the chain reaction quickly [5, p.310]. By including this feature, the core material has become essentially immune to meltdown as an overheat situation will lead to an outcome in which the fuel is entirely removed from its reactive arrangement and into holding tanks that can be specially designed to both mitigate the chain reaction and the heat of the molten fuel mixture. In addition to this, LFTRs possess similar capabilities to light water reactors for an engineered PNTC, which can preclude ever needing to utilize the salt plug safety feature.

On top of all of these safety features, one more fact is important to consider; due to the constant reprocessing and refining of the fissile/fertile isotope inventory in the core, in the unlikely event that there is some sort of containment breach the amount of potentially dangerous radioactive isotopes that can be released from the core is at a reduced magnitude than reactors arranged with fuel encapsulated by cladding. In essence, the fission products can be continually diluted and removed during operation of the reactor and moved to safe storage, whereas in standard reactors all of these fission products are removed alongside the spent fuel at the end of a fuel cycle. So not only is a thorium reactor unlikely to breach containment, but in the occurrence that such an event occurs the risk posed to the surrounding area by release of fission products is greatly reduced.

3.4.3 Looking forward

There are currently no commercial fuel reprocessing facilities in the United States, and so the fact that LFTRs have the capabilities to refine ^{233}U from their irradiated thorium mixture is a matter of concern from a licensing standpoint, as it would require overcoming the tendencies of both the U.S. NRC and established power utilities to avoid risk by using more established design techniques [5, p.313]. At one point there was a prototype LFTR operating at Oak Ridge National Laboratory that contained many of the systems that would be necessary to implement one today; however, it was shut down in 1969 when the program was terminated and little additional research has been done since then [5, p.313] [48, p.339]. However, for developing countries across the world without access to vast uranium resources, such as India, the promise of LFTRs is enticing considering that it allows for the usage of clean nuclear power without needing to develop expensive fuel enrichment and large waste containment facilities that drive up the initial costs of developing nuclear infrastructure [5, p.305].

Chapter Four

Conclusions

It is vividly apparent that an alternative energy source to reduce greenhouse gas creation is necessary; when Kharecha A. Pushker and James E. Hansen of NASA's Goddard Institute for Space Studies and Columbia University's Earth Institute, respectively, published that a transition to nuclear power could save an estimated 420,000 to 7.04 million lives by 2050 [15], that statistic is shocking enough to make even the most staunch nuclear critic hesitate. What is necessary then is a suite of safety systems and designs that assure regulatory agencies as well as the public that placing their faith in the nuclear industry is not misguided and that it truly is the most compact solution to growing energy needs. The technology for the growth of the nuclear industry already exists; the regulatory framework is underway, and the issue of nuclear waste is being actively discussed in the scientific community. Between the four safety systems discussed inside this article, the framework for a safe reactor acceptable to all reasonable parties is within reach.

With the implementation of the prompt negative temperature coefficient, as well as the potential to increase PNTCs in power reactors to values that were previously only achievable in small research reactors [36], it should be possible to design a conventional nuclear reactor that is markedly safer due to its inherent nature alone. This, in conjunction with a reactor operator's abilities to react to a transient accident situation or equipment failure via the SCRAM and emergency core cooling systems can further ensure that no likely severity of accident is capable of damaging the radioactivity control systems to the point that the environment is affected. In a recommendation report to the NRC, Brookhaven National Laboratory developed the criteria that any event which could be construed into leading to catastrophic fuel damage with an expected likelihood of greater that 10^{-7} per reactor-year (1 in 10 million chance per year of operation, per reactor) should be analyzed and properly regulated [47, p.162]. This further stresses the atmosphere of safety present in the nuclear field, and so cautious and slow progress is the norm of every development and change. By implementing previously tried and true systems such as the SCRAM and ECCS, the regulatory work of passing qualifications for redundancy and safety considerations can be reduced significantly.

However, it is within previously bypassed designs such as the LFTR that the true potential for long term nuclear power resides, as not only does it produce vastly less waste, it also uses a much more commonplace and less labor-intensive naturally occurring isotope to fuel its reaction in the long term, something that would allow LFTR plants to operate for their entire lifespan nearly uninterrupted by the refueling cycle that reduces average yearly outputs of other reactors. Primary to this though is the innate safety of the LFTR system, combining the safety of the PNTC and SCRAM systems with its own unique variant in the salt plug. This reliance on fundamental physical laws, like the melting point of a salt plug or thermal expansion for the PNTC, can nearly extinguish the possibility of mechanical failure in a reactor. Through careful combination of these attributes, it should be sufficiently demonstrable that the right design would be immune to nearly every accident scenario short of regionally catastrophic natural disaster or deliberate sabotage. Previously unmentioned, the creation of LFTRs is much safer to promote in countries which are seen as at risk for nuclear proliferation, as the ^{233}U breeding cycle in LFTRs is significantly distant from the fissile isotopes of plutonium (atomic mass 239 and 241) which are the isotopes of highest concern when it comes to the creation of atomic weaponry. The same cannot be said for standard uranium reactors, whose high concentrations of fertile ^{238}U in the low enriched uranium possesses the capability to be re-enriched into appreciable quantities of ^{239}Pu, the same method by which the Manhattan project produced its plutonium resources.

When taken together, the presented information creates a elucidating argument for the necessity of nuclear power, alongside the ever-growing demand for safety that has characterized the field in response to past accidents. It may never be possible to totally eradicate the possibility of radioactive release and the nuclear field will likely never return to the "Titanic mentality" it once possessed [26, p.224], which can be seen as a beneficial outcome of the tragic events of the past half century. The nuclear field will continue to learn and adapt and it is important that it is given the chance to, because the potential of nuclear power is too great to ignore when faced with the growing issues of greenhouse gas release and climate change.

APPENDIX

Appendix A

Unit conversions:

$$E_{fission} = 201.92MeV * \frac{10^6 eV}{1MeV} * \frac{1.6022 * 10^{-19} J}{1eV} = 3.2352 * 10^{-11} J \tag{A.1}$$

$$M_{^{235}U} = 235.04amu = 235.04\frac{g}{mol} * \frac{1mol}{6.022 * 10^{23}} * \frac{1kg}{1000g} = 3.9030 * 10^{-25} kg \tag{A.2}$$

Calculation of energy per mass:

$$\frac{E_{fission}}{M_{^{235}U}} = \frac{3.2352 * 10^{-11} J}{3.9030 * 10^{-25} kg} = 8.2890 * 10^{13} J/kg \tag{A.3}$$

Appendix B

Simplified diagram from before and after the collision:

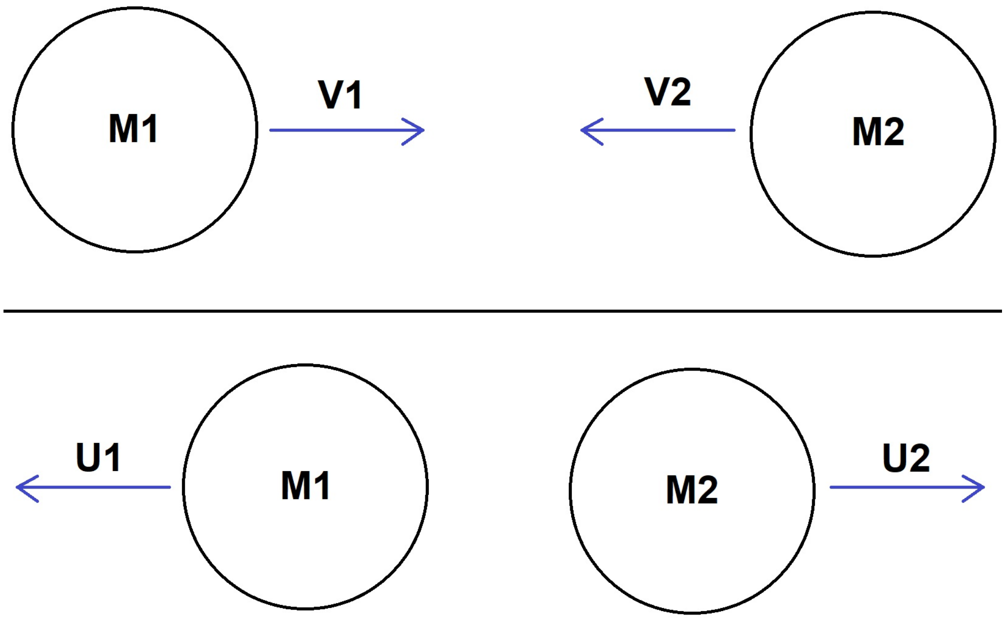

Figure B.1 A simple drawing of an elastic collision with labelled velocities and masses.

Assumptions:

- Non-relativistic velocities
- Momentum is conserved
- One dimensional
- Mass is conserved
- Perfectly elastic collision i.e. kinetic energy is conserved

Energy conservation equations:

$$E_{1,i} = \frac{1}{2}M_1V_1^2 \qquad E_{2,i} = \frac{1}{2}M_2V_2^2 \qquad E_i = E_{1,i} + E_{2,i} \tag{B.1}$$

$$E_{1,f} = \frac{1}{2}M_1U_1^2 \qquad E_{2,f} = \frac{1}{2}M_2U_2^2 \qquad E_f = E_{1,f} + E_{2,f} \tag{B.2}$$

$$E_i = E_f \qquad \frac{1}{2}M_1V_1^2 + \frac{1}{2}M_2V_2^2 = \frac{1}{2}M_1U_1^2 + \frac{1}{2}M_2U_2^2 \tag{B.3}$$

$$M_1V_1^2 - M_1U_1^2 = -M_2V_2^2 + M_2U_2^2 \tag{B.4}$$

$$= M_1(V_1^2 - U_1^2) = M_2(-V_2^2 + U_2^2) \tag{B.5}$$

$$= M_1(V_1 + U_1)(V_1 - U_1) = M_2(U_2 + V_2)(U_2 - V_2) \tag{B.6}$$

Momentum conservation equations:

$$P_{1,i} = M_1V_1 \qquad P_{2,i} = -M_2V_2 \qquad P_i = P_{1,i} + P_{2,i} = M_1V_1 - M_2V_2 \tag{B.7}$$

$$P_{1,f} = -M_1U_1 \qquad P_{2,f} = M_2U_2 \qquad P_f = P_{1,f} + P_{2,f} = -M_1U_1 + M_2U_2 \tag{B.8}$$

$$P_i = P_f \qquad M_1V_1 - M_2V_2 = -M_1U_1 + M_2U_2 \tag{B.9}$$

$$M_1V_1 + M_1U_1 = M_2V_2 + M_2U_2 \tag{B.10}$$

$$= M_1(V_1 + U_1) = M_2(V_2 + U_2) \tag{B.11}$$

Combine equations B.6 & B.11:

$$\frac{(B.6)}{(B.11)} = \frac{M_1(V_1 + U_1)(V_1 - U_1)}{M_1(V_1 + U_1)} = \frac{M_2(U_2 + V_2)(U_2 - V_2)}{M_2(U_2 + V_2)} \tag{B.12}$$

$$V_1 - U_1 = U_2 - V_2 \tag{B.13}$$

$$U_2 = V_1 + V_2 - U_1 \tag{B.14}$$

Insert B.14 into B.11:

$$M_1(V_1 + U_1) = M_2(V_2 + V_1 + V_2 - U_1) \tag{B.15}$$

$$\frac{M_1}{M_2}V_1 + \frac{M_1}{M_2}U_1 = 2V_2 + V_1 - U_1 \tag{B.16}$$

$$\frac{M_1}{M_2}U_1 + U_1 = -\frac{M_1}{M_2}V_1 + 2V_2 + V_1 \tag{B.17}$$

$$U_1(\frac{M_1}{M_2} + 1) = 2V_2 + V_1(1 - \frac{M_1}{M_2}) \tag{B.18}$$

$$U_1 = \frac{2V_2 + V_1(1 - \frac{M_1}{M_2})}{\frac{M_1}{M_2} + 1} \tag{B.19}$$

Define mass ratio $\alpha \equiv \frac{M_1}{M_2}$

$$U_1 = \frac{2V_2 + V_1(1 - \alpha)}{1 + \alpha} \tag{B.20}$$

Limiting cases:

- $\alpha = 1$ (equivalent masses)

$$U_1 = V_2 \tag{B.21}$$

- $\alpha \ll 1$ (M_2 is very large)

$$U_1 \approx 2V_2 + V_1 \tag{B.22}$$

- $\alpha < 1$ and $V_2 = 0$ (M_2 is large and stationary)

$$U_1 = V_1\frac{1 - \alpha}{1 + \alpha} \lesssim V_1 \tag{B.23}$$

Appendix C

Equipartition theorem:

$$\langle KE\rangle = \frac{3}{2}k_BT = \frac{1}{2}m_n\langle v^2\rangle \tag{C.1}$$

Algebra steps:

$$\langle v^2\rangle = \frac{3k_BT}{m_n} \tag{C.2}$$

$$v_{rms}(T) = \sqrt{\langle v^2\rangle} = \sqrt{\frac{3k_BT}{m_n}} \tag{C.3}$$

Unit conversion:

$$m_n = 1.001amu = 1.001\frac{g}{mol} * \frac{1mol}{6.022 * 10^{23}} * \frac{1kg}{1000g} = 1.662 * 10^{-27}kg \tag{C.4}$$

Numerical calculations at relevant temperatures:

$$v_{rms}(300K) = \sqrt{\frac{3 * 1.381 * 10^{-23}J/K * 300K}{1.662 * 10^{-27}kg}} = 2735ms^{-1} \tag{C.5}$$

$$v_{rms}(600K) = \sqrt{\frac{3 * 1.381 * 10^{-23}J/K * 600K}{1.662 * 10^{-27}kg}} = 3867ms^{-1} \tag{C.6}$$

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