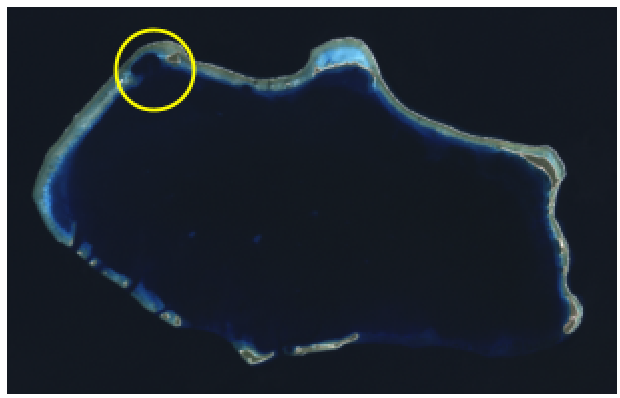
Music blares, urgent and dramatic, as names scroll in Japanese against a black screen. Racing strings and thundering bass, akin to the rumble of an explosion, are occasionally punctuated with a screeching, drawn out roar. The credits give way to peaceful waves, a fishing crew playing instruments and card games on a rocking boat. They are interrupted by a thunderous boom and a flash of light, so bright that the men shield their faces and run. Crew members below deck send out a distress signal as water rushes into their cabin. This is the opening sequence in 1954's *Gojira*, the film to ignite a massive franchise dedicated internationally to the pop culture icon Godzilla. The first scene of *Gojira* pulls directly[1] from a real event, one which happened barely seven months prior to the film's release. On March 1st, 1954, the crew of a Japanese fishing boat[2] (much like that in the movie) was stunned by an unnatural flash of light (much like that in the movie). However, (unlike the movie) their ship wasn't damaged, as the source of this strange display was dozens of miles away. This didn't spare the crew from the white dust that rained down on their boat hours later. The *Lucky Dragon No. 5*, as the boat's name translates to, hadn't been sunk by an enormous monster; rather, it had been showered with the radioactive fallout of *Castle Bravo*, the largest nuclear test ever carried out by the United States to this day. This fallout left the entire ship suffering from radiation sickness. By the time *Gojira* was released in October, one of the crew had died, the rest still confined to the hospital where they would spend more than a year.

*Gojira* Theatrical Release Poster

The connection between Godzilla and the atomic bomb is a common piece of cultural knowledge. The film and the character have been identified as a metaphor for the bombings of Hiroshima and Nagasaki since 1954. The *Castle Bravo* test and the *Lucky Dragon No. 5*, however, are relatively unknown, despite playing a similarly significant part in Godzilla's genesis, both in its production and its reception. Godzilla isn't the only cultural phenomenon to erupt from *Castle Bravo* and the history of U.S. nuclear testing in the Pacific. Bikini Atoll, permanently marked with *Castle Bravo*'s 1.5 km wide crater visible by satellite, is the namesake of the two piece swimsuit, supposed to create an "explosive reaction"[3], as well as of Bikini Bottom, the setting occupied by the sentient aquatic characters in *Spongebob Squarepants*[4].

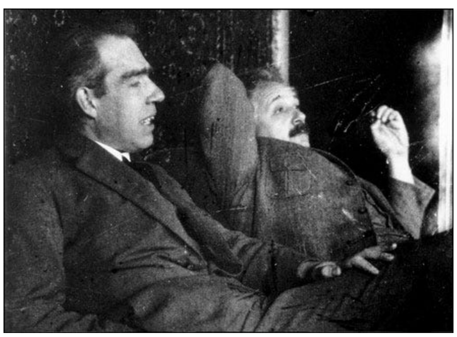
Beyond the cultural niche carved out by nuclear tests, beyond the physical craters left in the Pacific and worldwide, a deep and undeniable scar remains on the lives of many, notably those of the Marshallese communities who continue to be affected by *Castle Bravo* and its ilk to this day. Spectacle and sensation obfuscate trauma and devastation. Pop culture affects the nuclear world just as much as the nuclear world affects it, from playful cartoons painted on the planes that bombed Hiroshima and Nagasaki, to iconography that seems as everlasting as radioactive contamination. These phenomena are conscious, perhaps even intentional distractions from the violent, destructive, and grotesque reality of nuclear weaponry. The truth is far less glamorous, far more objectionable, potentially far more disruptive to the operations of the U.S. government in the ever amplifying arms race. Between crouching under school desks and marveling at monster movies, nobody has the chance to object to the hundreds of nuclear weapons being detonated in the name of "defense".


Bikini Atoll, with the *Bravo* crater circled

With *Castle Bravo* serving as a case study for the lesser known components of nuclear history, this essay will focus on the scientific foundations of nuclear weaponry, testing, and impacts. Explanation and discussion of the science behind nuclear weapons, which is often less complicated than it's proclaimed to be, demystifies a subject where obscurity contributes directly to injustice and violence. We will delve into the design of the *Castle Bravo* device and its detonation, its immediate consequences, and the lasting effects that continue to be studied to this day. However, we must first venture into the fundamentals of nuclear weaponry, of atoms, fission, fusion, and energy, along with the history that led to the transformation of these concepts into application in the most powerful weapons ever created.

In August of 1945, just before dawn, an incredible flash lit up the sky for miles above the New Mexico desert. The *Trinity* test, the world's first nuclear detonation, was successful, releasing 78 trillion Joules of energy[5]. *Trinity* was the culmination of the efforts of some of the world's preeminent physicists, working together in the top-secret laboratories of the Manhattan Project. But *Trinity* was not merely the result of those four years of government-funded research (although 2 billion dollars certainly helped), but also of centuries of physics and chemistry, of theory and experimentation in the constant journey towards understanding the world we live in. The amount of seemingly disparate concepts and subjects that can be tied back to nuclear science is broad and immense, but a few topics serve particularly well to map out the path to *Trinity*.

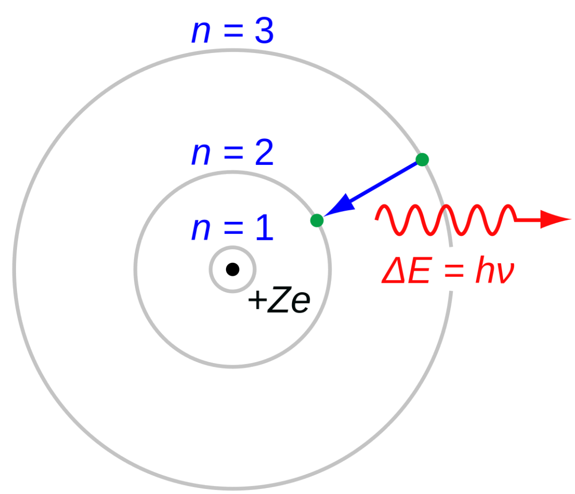
One of the most influential scientific developments that contributed to the harnessing of nuclear energy began, it seems, as far from atoms and particles as possible. The work of Albert Einstein is usually associated with concepts like time and space, with the speed of light and space travel, not with neutrons and nuclei. However, the application of Einstein's theories to atomic properties is perhaps the most impactful result of his work. The immense energy released in nuclear reactions traces directly back to $E = mc^2$, which dictates that a small amount of mass corresponds to great amounts of energy. This theory promised an incredibly lucrative source of energy at great efficiency. If only there were some way to readily convert mass into energy, scientists thought. The primary suspect for this great source of energy was the atom, still elusive and mysterious at the time Einstein published his theory of relativity. Fortunately, Einstein's work opened the door for rapid strides in the understanding of the atom.



Niels Bohr and Albert Einstein

While Albert Einstein himself was highly skeptical of the newly born field of quantum mechanics, it was his theories that allowed for the groundbreaking conclusions of physics superstars like Niels Bohr and Wernher Heisenberg. From Einstein's assertion that light existed in individual particles (later called photons), Bohr adapted the same principle, that of quanta, to problems in the model of the atom. Instead of miniature solar systems with freely orbiting electrons, Bohr proposed that electrons instead occupied quantized, stable states[6]. The Bohr model of the atom explained a vast range of chemical phenomena, laying the foundation for **molecular orbital theory (core concept #1, MO theory)**. The periodic table as it appears today is a direct consequence of the Bohr model, which clarified the existence of transition metals and lanthanides as separate groups, an idea proposed by chemists like Alfred Werner in prior decades without the theory to support it yet.

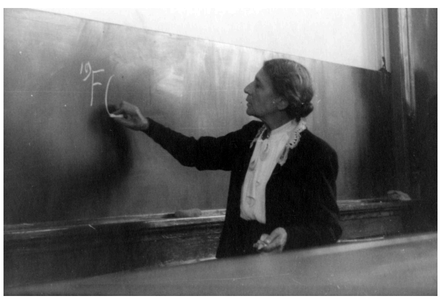
Quantum theory greatly advanced the understanding of molecular bonds and chemical reactions. It also led to the understanding and harnessing of nuclear reactions. Despite their vast differences, the commonplace chemical reaction and the extraordinary nuclear reaction share many broad traits. Both rely on the fundamental **structure of the atom (core concept # 2, atomic structure)**. The properties of elements and molecules are the product of the subatomic makeup of each element. Protons inside the nucleus distinguish the elements, and determine the number of electrons that lie outside the nucleus. These particles are the building blocks of chemical reactions, which are ruled over by interactions between electrons, positive and negative charges, and geometric arrangements dictated by orbitals. Neutrons play a minor role in chemistry, their influence isolated to molar masses and the helping hand that isotopes lend to different types of spectroscopy. Energy arises from the stability of molecular and atomic arrangements, the strength of bonds, and the rates of reactions. In an exothermic chemical reaction like the combustion of hydrogen and oxygen, 242 kJ/mol[7] of thermal energy is released when energy (much lower than the output) is supplied to split dioxygen into the highly unstable, and therefore highly reactive, singlet oxygen. Reactions like this are essential to countless processes in the modern world, allowing the energy stored in molecular bonds and charged particles to be manipulated and harnessed for fantastic benefits. In contrast, a fission reaction involving uranium-235 yields around 1.8 x $10^{10}$ kJ/mol[8]. Both reactions require an initial input of energy, both involve the energy stored in forces holding particles together, and both are the result of specific details about atomic structure. The difference that gives rise to the magnitudes between the energy outputs is in the location of these reactions. While chemical reactions alter electronic arrangements and molecular structures, nuclear reactions, as the name suggests, involve changes in the contents of the atomic nucleus. The force holding the nucleus



The Bohr atomic model

together is far stronger than that of chemical bonds, so strong that for much of history, nuclear reactions existed only in stars, where immense heat and pressure were the only places where this force could be overcome. However, physicists in the beginning of the 20th century, despite only just beginning to understand the atomic nucleus and the nature of subatomic particles, had reason to believe that the immense energy contained in the atomic nucleus was capable of being harnessed by mankind[6}. The great potential Einstein's theories promised was on its way to conception.

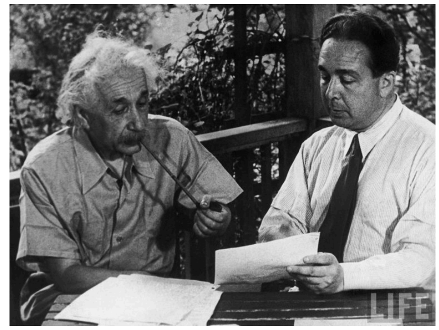
Nuclear fission, as coined by physicist Lise Meitner, was discovered in 1938[6]. Recreating Enrico Fermi's experiment of bombarding uranium with neutrons, Meitner and her colleagues observed the division of the nucleus into rough halves, a shock to the German team as well as the worldwide scientific community that quickly caught wind. In cases where the resulting energy is great enough, fission occurs when a free neutron reacts with an atomic nucleus, causing the nucleus to break apart, usually into two separate nuclei. In such a reaction, the mass going into the reaction is greater than that afterwards. This results in an immense increase in energy, a direct confirmation of $E=mc^2$. Along with the daughter nuclei produced by nuclear fission, some number of neutrons are released as well. It is this property that allows for nuclear chain reactions, the basis of nuclear fission weapons as well as nuclear energy. By releasing neutrons, one fission reaction can trigger another in a nearby atom. In order for a chain reaction to occur, fissile material must have a certain mass and density, in order to allow released neutrons to come into contact with other nuclei instead of escaping the system. This required mass at a certain density is known as critical mass.[8]



Lise Meitner, atomic pioneer and namesake of the element meitnerium

With the discovery of fission, scientists worldwide came to the same conclusion: the possibility of a chain reaction, akin to the self-sustaining nature of fuel combustion[8], meant that this scientific feat could yield practical utility. In particular, as World War II advanced in Europe (after all, nuclear fission was discovered in Germany), the specific application that many had in mind was shaded with a particular lens. Thus, the nuclear bomb was conceived, a former science fiction concept now rendered technically possible[6].

One of those who had realized the feasibility and the implications of a nuclear bomb was Leo Szilard, a Hungarian physicist interested in quantum physics who had fled Europe with the rise of Nazism and ended up in the United States. Mere months after nuclear fission was proven, Szilard recruited a friend, another Hungarian expat, to drive him to the Long Island home of Albert Einstein. Einstein signed off on Szilard's letter to Franklin Delano Roosevelt, urging that this scientific development and its likely consequences be taken seriously and responded to with support for research by American scientists. Years later, after the U.S. officially entered WWII, this plea was answered, and the Manhattan Project was established[6].

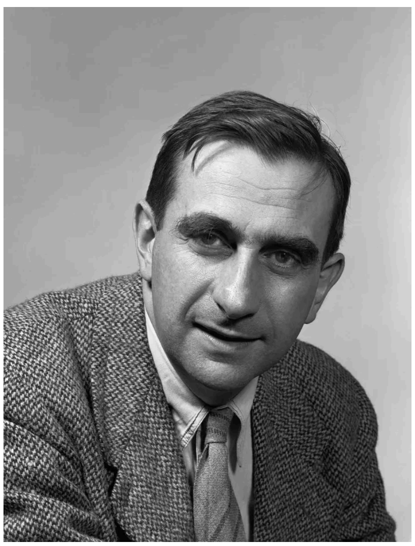


Leo Szilard and Albert Einstein

Nearly fifteen years earlier, a 23-year-old graduate student proposed a mathematical approximation for the energy of molecules resulting from separating the wave functions and relative movements of electrons and nuclei. This approximation is vital to the **application of IR spectroscopy (core concept #3 vibrational spectroscopy)**, which relies on the vibration of molecular bonds in relation to the atomic nuclei that make up a compound[9]. It is also an early accomplishment of the man who would later be chosen as director of the Manhattan Project. The Born-Oppenheimer approximation was the proposal of the same J. Robert Oppenheimer who lives on in history as "the father of the atomic bomb".

A similar story played out ten years later. In 1937, two young scientists collaborated to describe strange distortions in the symmetry of molecules with certain electronic configurations. These men were the British scientist Hermann Arthur Jahn, and the Hungarian physicist Edward Teller, who would serve as Leo Szilard's chauffeur two years later[10]. Both men were immortalized by **the Jahn-Teller effect (core concept #4, symmetry)**, which is fundamental to molecular geometry in inorganic chemistry, still used nearly a hundred years later. However, while Jahn remained in the field of applied mathematics and group theory, spending the majority of his career as a professor in England, Teller went on to drastically impact not just the field of theoretical chemistry, but also nuclear physics, U.S. policy, and global affairs for a large part of the 20th century. The 29 year old physicist who helped formulate the Jahn-Teller theorem would later be known as "the father of the hydrogen bomb".

Edward Teller was an early recruit for the Oppenheimer-headed Manhattan Project, with his prior work in atomic theory and quantum mechanics. He was stationed in Los Alamos, New Mexico, essentially the headquarters of the project. Teller's contributions, and his reputation among other scientists he worked with, are not remembered positively. He was called a primadonna, a nuisance, playing piano in the shared housing late at night and refusing to work on calculations he was assigned. Much of this reputation was born of his apathy towards the focus of the Manhattan Project, a weapon powered by nuclear fission. It wasn't that Teller had no interest in the potential of such a scientific achievement. He was simply *more* excited about the separate project he had set his sights on: the possibility of a fusion weapon, one which had the potential to yield a hundred times as much power as the fission bomb was projected to. This was a project that consumed his attention throughout WWII and beyond, into the early years of the Cold War and the nuclear arms race[10].



Edward Teller, theoretical physicist and father of the hydrogen bomb

Teller doesn't necessarily deserve credit for the conception or the invention of the fusion weapon, more commonly known as the hydrogen bomb. The idea of such a weapon can be attributed to Enrico Fermi, nuclear physics forefather and Teller's close friend and mentor. The design that led to a testable version is at least partially credited to Stanislaw Ulam, who adjusted Teller's dead end plans into a working weapon (the division of credit for the Teller-Ulam design, which is thought to be used in almost all of the current U.S. nuclear arsenal, is highly debated, particularly because the patent itself is classified). "Father of the hydrogen bomb" is an accurate moniker for Teller, however, because of his passionate, persistent push for development of the weapon in spite of resistance from a large portion of morally objecting scientists[10]. Even with the likes of J. Robert Oppenheimer and Albert Einstein objecting to such a weapon being researched and built, Teller's wish was granted with the first successful hydrogen bomb test, *Ivy Mike* in 1952[5].

The hydrogen bomb, as mentioned before, is a “fusion weapon”, in contrast to the fission-reliant nuclear bomb. Fission and fusion are both nuclear reactions, and similarly require great energy input to initiate the even greater energy output. Fission requires the bombardment of nuclei with neutrons, achieved in nuclear weapons by compressing fissile material to the critical mass with precisely timed conventional explosives. Fusion requires a much greater compressive force, achievable in most cases only by the energy of a fission reaction. While fission relies on the interaction between a neutron and the nucleus of an atom, fusion consists of the interaction between two nuclei, which must overcome Coulombic repulsion in order to form a heavier combined nucleus. The energy required to overcome the Coulomb force is immense, more so than that to overcome the same force in a fission reaction. Prior to 1952, nuclear fusion was restricted to the core of stars, responsible for the very energy allowing the Sun to generate spectacular light and heat. However, the energetic price of fusion reactions is proportional to the energetic reward. *Trinity* had a yield of trillions of Joules, more often reported as the equivalent of 25 thousand tons of TNT. *Ivy Mike*, in contrast, yielded quadrillions of Joules, or 10 million tons of TNT[5]. It is inherently difficult to emphasize the power of nuclear weapons, just as it’s difficult to wrap one’s head around the fortune of billionaires or the size of the solar system. The difference between fission and fusion weapons is easy to grasp, though. A nuclear bomb, known to be capable of city wide destruction, of tens of thousands of instantaneous deaths, is dwarfed by factors of thousands by a hydrogen bomb.

The use of a nuclear bomb, to nearly anyone other than the U.S. military and international lawmakers, is considered unforgivable. Even Curtis LeMay, the WWII general responsible for commanding the bombings of Hiroshima and Nagasaki, remarked "I suppose if I had lost the war, I would have been tried as a war criminal."[11] In the coldest logic of armament and strategy, use of the hydrogen bomb is considered impractical, too powerful to be of any possible use. Despite arguments like this, despite broader, wider moral objections,

| Type/Designation | No. | Year deployed | Warheads x yield (kilotons) | Warheads (total available)[a] |
|---|---|---|---|---|
| **ICBMs** | | | | |
| LGM-30G Minuteman III | | | | |
| Mk12A | 200 | 1979 | 1–3 W78 x 335 (MIRV) | 600[b] |
| Mk21/SERV | 200 | 2006[c] | 1 W87 x 300 | 200[d] |
| **Total** | **400[e]** | | | **800[f]** |
| **SLBMs** | | | | |
| UGM-133A Trident II D5/LE | 14/280[g] | | | |
| Mk4A | | 2008[h] | 1–8 W76-1 x 90 (MIRV) | 1,511[i] |
| Mk4A | | 2019 | 1–2 W76-2 x 8 (MIRV)[j] | 25[k] |
| Mk5 | | 1990 | 1–8 W88 x 455 (MIRV) | 384 |
| **Total** | **14/280** | | | **1, 920[l]** |
| **Bombers** | | | | |
| B-52H Stratofortress | 87/46[m] | 1961 | ALCM/W80-1 x 5–150 | 500 |
| B-2A Spirit | 20/20 | 1994 | B61-7 x 10–360/-11 x 400<br>B83-1 x low-1,200 | 288 |
| **Total** | **107/66[n]** | | | 788[o] |
| **Total strategic forces** | | | | **3, 508** |
| **Nonstrategic forces** | | | | |
| F-15E, F-16C/D, DCA | n/a | 1979 | 1–5 B61-3/-4 bombs x 0.3–170[p] | 200 |
| **Total** | | | | **200[q]** |
| **Total stockpile** | | | | **3,708** |
| Deployed | | | | 1,770[r] |
| Reserve (hedge and spares) | | | | 1,938 |
| **Retired, awaiting dismantlement** | | | | **1,536** |
| **Total Inventory** | | | | **5,244** |

United States nuclear forces, 2023[20]

the United States has thousands of actively deployed missiles carrying fusion-powered warheads today. The cost of these weapons lies not only in the constant threat to safety worldwide, but also in the very real, devastating price of tests like *Ivy Mike* that were necessary to designing and proving the hydrogen bomb. No test had a greater individual cost than *Castle Bravo*.

The Castle series of nuclear tests was conducted in 1954 in Bikini Atoll, the neighbor of Enewetak Atoll where *Ivy Mike* was tested 2 years prior[12]. The aim of this test series, primarily, was to determine the efficacy of deliverable thermonuclear weapons. Previous tests proved the

mechanism of fusion weapons, but *Ivy Mike* and subsequent designs utilized refrigerated deuterium and tritium. This required a large and heavy cooling apparatus, rendering the weapon as a whole impossible to carry in an airplane. To circumvent this problem, the new design used fuel that was solid at ambient temperature. Specifically, these weapons used lithium deuteride.


Castle Bravo

Lithium deuteride was advantageous for multiple reasons. First of all, as mentioned before, it allowed deuterium, the fusion fuel, to be stored in a solid state, eliminating the need for cooling systems in the weapon itself and massively reducing size and weight. Lithium hydride is light in proportion to its hydrogen content, and it therefore has the highest hydrogen content of any hydride. Lithium-7 is the most abundant natural form of lithium, with lithium-6 making up only about 1.9-7.8% of terrestrial lithium. The lithium deuteride fuel used was enriched to a ratio of about 40% lithium-6 to 60% lithium-7. Lithium-6, as opposed to lithium-7, reacts when bombarded with neutrons to produce tritium. More precisely, lithium-6 reacts exothermically to produce tritium, a distinction that's important in the outcome of the test.

The most notable characteristic of *Castle Bravo* wasn't the novel design, as it was intended to be. As stated before, *Bravo* was in fact the largest yield weapon ever detonated by the United States. It wasn't supposed to be.

The predicted yield of *Castle Bravo* was six megatons (millions of tons) of TNT, four short of *Ivy Mike*'s yield. It was, in actuality, nearly ten million tons more powerful than predicted. This error, which wasn't accounted for in safety measures and radiation containment, was fatal. It was fatal to the *Lucky Dragon*'s radio operator, fatal to the majority of the crew that developed and succumbed to a broad variety of cancers, fatal to the people of the Marshall Islands who were warned late, evacuated late, and impacted to this day by cancer mortality rates many factors greater than U.S. mainland statistics[13].

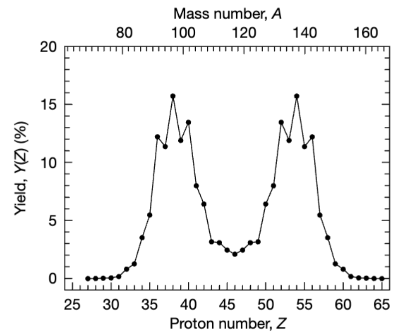
This fatal error was relatively simple. Lithium-7 was assumed to be inert and have no effect on the fusion reaction. To the contrary, in fact, lithium-7 undergoes an endothermic fission reaction, producing tritium. The tritium produced by fission of lithium-7, in addition to that produced by the less abundant lithium-6, resulted in significantly more fusion reactions, resulting in the drastically increased power of the weapon.

The underestimated yield of *Castle Bravo* demonstrates the inadequate level of concern and precision adopted by the personnel and scientists planning and designing the test when it came to the lives and health of those who would be unwillingly exposed. This isn't to say, however, that the harm caused by *Bravo* was attributable only to this error. In fact, by revealing the impact of such an error, the harmful nature inherently baked into nuclear tests is clear. *Bravo*'s increased yield resulted in a wider range of fallout, but every nuclear test results in a significant release of radioactive isotopes into the surrounding environment, isotopes which spread and linger and have the potential to inflict illness and injury for years to come.

To understand why the radioactive fallout of a nuclear test possesses such capacity for longevity and for harm, we must step back into theory for a moment. Radioactive isotopes have known patterns, or decay chains, of subsequent alpha or beta decays into other elements or isotopes, often also radioactive. In addition, the fission products of reactions in nuclear weaponry are predictable given the isotope used as fuel. When a nuclear reaction is initiated, it isn't difficult to predict what kind of fallout it will release.

The most prevalent nuclear fission products have been experimentally measured, but computational approaches considering symmetry and structure have provided greater detail and understanding. Fission products generally fall in mass number ranges of 90-110 and 130-150, or

Z-values of 35-40 and 50-55[14]. When considering fallout and its effects on organisms, these ranges are disastrous. In particular, nuclear fallout contains large proportions of radioactive strontium, cesium, and second-row transition metals. These products are structurally comparable to elements involved in extra- and intracellular processes. Radioactive cesium imitates potassium and concentrates in soft tissue[15]. Radioactive strontium behaves like calcium, depositing in bones and bone marrow where it remains for years[16]. Extended exposure to these isotopes, particularly in vulnerable biochemical processes, carries an acute risk of cancer and illness. The Marshallese communities of Bikini Atoll were exposed to immense concentrations of such isotopes in the fallout of *Castle Bravo*[17].




Yield distribution by mass of U-238 Fission[14]

The harmful effects of fallout are not limited to the isotopes absorbed by the human body in the initial blast. Isotopes imitating biological agents are absorbed by all organisms, not just humans. Greater concentrations of fallout were taken up by marine life and by plants. Vital elements of Marshallese diets, particularly coconut milk and seafood, accumulated hazardous levels of contamination. The contamination of natural resources persists to this day, as soil and water carry lasting contaminants with long half-lives. As a result, Marshall Islanders are given two choices: consume contaminated products, or survive on food imported from the United States; food that is highly processed and nutritionally poor. In addition to disproportionately high rates of cancer, Marshall Islanders also exhibit one of the highest rates of type 2 diabetes in the world[18]. Radioactive contamination of the natural resources in Bikini Atoll and the Marshall Islands as a whole remains present and harmful to this day[19].

At the time this essay is being written, the 70th anniversary of *Castle Bravo* has just passed. From the billowing mushroom cloud that overtook the Pacific skies in 1954, *Castle Bravo*'s impact has made ripples not only in pressure waves, but through space and time, in lives, in minds, in communities, and in history. Worldwide media coverage of *Bravo* and its mistakenly massive yield led to global outcry, to protest and organizing that led to strides in anti-nuclear action and eventually an international nuclear test ban. Marshallese activists and advocates have gained visibility and aid for the previously invisible communities in the Marshall Islands, working towards justice for the legacy of *Bravo* and the violence enacted by United States nuclear testing.

The fight for disarmament and elimination of nuclear weapons continues, and there is a long way to go towards achieving the goals that have been fought for since the genesis of the nuclear bomb. The United States continues to possess and deploy thousands of nuclear weapons, many of which are housed less than 50 miles from Seattle at the Kitsap Bangor Naval Base. The University of Washington maintains a close connection with Boeing, the primary manufacturer of US nuclear missiles among its vast portfolio of weapons and machines of warfare. Education and knowledge is an essential component of organizing resistance to militarism and imperialism. I strongly believe that *Castle Bravo* is an effective example of the history and legacy of US-led war and violence and the importance of anti-nuclear objectives as a component of anti-war activism and justice.

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