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ÚSTAV JAZYKŮ

THE MANHATTAN PROJECT AND THE TECHNOLOGY OF THE FIRST ATOMIC BOMBS

PROJEKT MANHATTAN A TECHNOLOGIE PRVNÍCH ATOMOVÝCH BOMB

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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Bachelor's Thesis

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The Manhattan Project and the Technology of the First Atomic Bombs

INSTRUCTION:

The aim of the semester project is to examine the technology of the first atomic bombs created as a result of the Manhattan Project and testing at Los Alamos. The student should first give an outline of the goals of the Manhattan Project, then look at the different theories behind using a uranium or plutonium bomb, and how this led to the making of 'Little Boy' (Hiroshima bomb) and 'Fat Man" (Nagasaki bomb), which also had different triggering mechanisms. Finally, the student will summarize everything in a conclusion. The thesis will go further in examining competing theories behind the creating and testing the first atomic bomb at Los Alamos.

RECOMMENDED LITERATURE:

Bird, Kai. American Prometheus: The Triumph and Tragedy of J. Robert Oppenheimer. London: Atlantic Books, 2008. at https://archive.org/details/americanpromethe0000bird

Rhodes, Richard. The Making of the Atomic Bomb. 2nd ed. London: Simon & Schuster, 2012.

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Subject Council chairman

ABSTRACT

This bachelor thesis describes the key events in the Manhattan Project. The focus is on the technologies and concepts that led to the development and subsequent dropping of the first atomic bombs. The thesis begins with the discovery of nuclear fission of the uranium isotope and the potential chain reaction. The next chapter focuses on a detailed description of the three methods used to obtain enriched uranium, followed by an introduction to the first nuclear reactors that were subsequently used to produce plutonium. The final chapters describe the first nuclear test at Los Alamos, along with the various types of triggering mechanisms of the Little Boy and Fat Man, and their ultimate effects in Hiroshima and Nagasaki. Finally, various views on the advisability of using atomic bombs during World War II are portrayed.

KEYWORDS

Manhattan Project, fission, uranium, plutonium, reactor, Trinity, Little Boy, Fat Man

ABSTRAKT

Tato bakalářská práce popisuje stěžejní události v Projektu Manhattan. Důraz je kladen na technologie a koncepty, které vedli k vývoji a následnému svržení prvních atomových bomb. Práce začíná s objevem jaderného štěpení izotopu urania a jeho potencionální řetězové reakce. Další kapitola se zaměřuje na detailní popis tří metod, které byly použity pro získání obohaceného urania a následuje představení prvních jaderných reaktorů, které byli následně využity pro výrobu plutonia. V posledních kapitolách je popsán první jaderný test v Los Alamos spolu s různými typy spouštěcích mechanismů atomových bomb Little Boy a Fat Man, a jejich konečné následky v Hirošimě a Nagasaki. V závěru je diskuze a různé názory na smysluplnost použití atomových bomb za Druhé světové války.

KLÍČOVÁ SLOVA

Projekt Manhattan, štěpení, uranium, plutonium, reaktor, Trinity, Little boy, Fat Man

ROZŠÍŘENÝ ABSTRAKT

Cílem této bakalářské práce je provést rešerši dostupné literatury a podrobně prozkoumat technologie, které stály za vytvořením prvních atomových bomb. Projekt Manhattan byl bezprecedentní čtyřletá vzájemná spolupráce mezi vládou, vědci a vojenskými inženýry, na jejímž konci definitivně označil Spojené státy americké za novou supervelmoc.

V úvodu se tato práce zabývá dobou před Druhou světovou válkou, kdy bylo objeveno jaderné štěpení Urania, konkrétně isotopu U-235, a jeho potencionální řetězové reakce. Objevem těchto fundamentálních základů jaderné bomby začal celosvětový závod, kdo jako první sestrojí funkční atomovou bombu. Při jaderném štěpení se totiž uvolňuje obrovské množství energie, které je de facto možné využít dvěma způsoby – pro svět prosperující (jaderné reaktory) nebo devastující (jaderné zbraně). Ke konci první kapitoly jsou také vysvětleny termíny jako jsou pomalé (termální) a rychlé neutrony kde každý z nich má určité vlastnosti a používají se v jiných oblastech.

Druhá a daleko obsáhlejší kapitola pojednává o třech metodách, které byly použity za účelem obohacení přírodního urania. Všechny tyto metody se nacházeli ve státě Tennessee v tajném vojensko-vědeckém areálu v Oak Ridge.

Jako první je zmíněna elektromagnetická metoda. Ta je založena na principu hmotnostní spektrometrie, kde se pomocí elektromagnetu oddělovali hmotnostně lehčí ionty U-235 od těžších iontů U-238. Byla umístěna a zprovozněna v areálu s krycím názvem Y-12 a jsou zde zobrazeny dílčí prvky celé operace spolu s rozdělením na dvě takzvané dráhy – Alfa a Beta – které urychlily celý proces obohacování. Také se vyskytli určité problém, jako nedostatek mědi a časté zkraty elektřiny, které museli být adekvátně vyřešeny. I přesto že areál Y-12 spotřebovával spoustu energie, produkoval velké množství obohaceného materiálu, který byl nakonec využit v první uranové bombě. Uranium bylo zde obohacováno na požadovaných osmdesát procent.

Druhá popisovaná metoda fungovala na principu difúze plynu, a byla umístěna v obrovském areálu s názvem K-25. Tato metoda funguje na principu Grahamova zákona, kde lehčí plyn (v tomto případě U-235) má tendenci unikat rychleji než těžší plyn (U-238), pokud jsou oba plyny různé hustoty smíchány a umístěny v izolované nádobě

s propustnými bariéry. Jak lehčí plyn proudí póry v bariéře, jeho množství, velikost, rozložení a tlak samotného plynu určují, nakolik je možná jednostupňová separace. Během projektu Manhattan tato metoda obohacovala uranium do padesáti procent a zbytek byl obohacen v areálu Y-12. Ke konci Druhé světové války byla nejvíce efektivní, co se týče spotřebované energie/výkon, a jako jediná ze všech tří byla používána během Studené války.

Třetí a poslední metoda používána ve velkém měřítku v projektu Manhattan, byla metoda tepelné difúze kapalin. Ta nejprve nebyla brána v potaz, ale s nastávajícími problémy v Y-12 a K-25 byla nakonec uvedena do provozu v areálu S-50. Základní princip operace byl následující: kapalná sloučenina urania (UF6) byla umístěna v izolované nádobě kde jedna strana nádoby byla teplá a druhá studená. Lehčí U-235 bylo přitahováno k teplé straně a těžší U-238 bylo přitahováno ke straně studené. A následovně vlivem konvenčního proudu byly tyto izotopy nahromaděny buď na spodní nebo na horní straně nádoby. I přesto že tepelná difúze kapalin v S-50 zvyšovala pouze obohacení uranu z 0,72 na 0,85 procent, hrála klíčovou roli jako dodavatel pro další separační metody. Díky zkombinování všech separačních metod, kdy se navzájem doplňovali, Spojené státy dosáhli tížených výsledků dříve než kdokoliv jiný.

V kapitole 2.2 je zmíněno objevení transuranu – uměle vytvořeného prvku – plutonia (Pu-239), které bylo o něco více náchylné k jadernému štěpení než U-235. Plutonium bylo získáváno zejména v jaderných reaktorech, více známé jako množivé reaktory. A právě detaily největší komplexu pro získávání Pu-239 během Druhé světové války jsou popsány v kapitole 2.3.5. V kapitole 2.3 je zmíněny první jaderné reaktory, včetně Chicago Pile-1 kde bylo poprvé dosaženo jaderné štěpení s výstupním výkonem 200 Wattů. Tento úspěch, kdy člověk poprvé zkrotil sílu atomu, znamenal první krok k atomovému věku a vývoji daleko lepších jaderných reaktorů do podoby, jak je známe nyní. Jeho nástupci, Chicago Pile-2 a Chicago Pile-3, byli postupně vylepšováni a modifikováni pro dosažení většího výkonu.

Ke konci druhé kapitoly následuje popis spouštěcích mechanismů prvních atomových bomb, které byly zkoumány v tajném areálu v Los Alamos v Novém Mexiku. Jsou zde vylíčeny zejména dva typy mechanismů: dělová puma a imploze. Dělová puma byla použita v uranové bombě Little Boy a princip imploze byl použit u plutoniové bomby Fat

Man. Jsou zde zmíněny důvody jejich využití a proč se nemohlo využít plutonium v dělové pumě. Také se vyskytlo několik nehod během výzkumu a zjišťování kritického množství plutonia pro atomovou bombu, a proto jsou zde objasněny dvě smrtelné nehody kdy obě souvisely s prací s plutoniovou koulí, později známou jako Démonické jádro (Demon Core).

Následuje popis prvního atomového testu v Novém Mexiku s názvem Trinity. Bylo zde použito plutoniové jádro, které bylo obaleno výbušninami se speciálně vytvořenými rozbuškami. Jsou zde uvedeny následky tohoto výbuchu společně s celkovým významem tohoto technologického úspěchu.

Ve třetí a poslední kapitole jsou prvně vylíčeny technické specifikace atomových bomb Little Boy a Fat Man. Následuje popis jejich devastujících účinků v japonských městech Hirošima a Nagasaki a proč byly vybrány právě tyto města. Konečná čísla mrtvých nelze přesně určit, ale data uvádí že v Hirošimě zemřelo na 70 tisíc osob při výbuchu a dalších 100 tisíc v následujících dnech. Po skončení války je odhadováno že až 200 tisíc bylo obětí první uranové bomby, s přihlédnutém na následovné radiačními účinky,

Na závěr je krátké shrnutí jaderného výzkumu nacistického Německa a Sovětského svazu během období 1939-1945 a je zodpovězena otázka, proč byly Spojené státy americké ve všech ohledech napřed. Německý atomový program zvaný Uranverein nikdy nedosáhl toužených výsledků, jelikož se nedostal plné podpory Adolfa Hitlera. Navíc, Němci spoléhali na využití těžké vody jako moderátoru, ale po sabotáži v Norské těžko-vodní elektrárně Vemork byl jejich program v koncích. Také jaderný program v Sovětském svazu byl pozadu oproti tomu Americkému. Ale díky špehům, kteří nasbírali a přeposílali informace z tajných vojenských areálu, Sovětský svaz nakonec dohnal Spojené státy v oblasti jaderných technologii. V úplném závěru je diskuze ohledně nutnosti použití atomových bomby během Druhé světové války, jakou celosvětovou změnu přinesli a co znamenali pro budoucnost.

Bibliographic citation

ZÁBOJNÍK, Vojtěch. *Projekt Manhattan a technologie prvních atomových bomb* [online]. Brno, 2024 [cit. 2024-05-23]. Dostupné z: https://www.vut.cz/studenti/zav-prace/detail/160183. Bakalářská práce. Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií, Ústav jazyků. Vedoucí práce Kenneth Froehling.

Author's Declaration

Author:	*Vojtěch Zábojník*
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Paper type:	*Bachelor's Thesis*
Academic year:	*2023/24*
Topic	*The Manhattan Project and the Technology of the First Atomic Bombs*

I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the project and listed in the comprehensive bibliography at the end of the project.

I declare that I do not violate the law on the non-proliferation of nuclear weapons according to Act No. 263/2016 Coll., Atomic Act. This bachelor's thesis is research of publicly available literature and does not contain new designs of nuclear weapons or their testing.

As the author, I furthermore declare that, with respect to the creation of this paper, I have not infringed any copyright or violated anyone's personal and/or ownership rights. In this context, I am fully aware of the consequences of breaking Regulation S 11 of the Copyright Act No. 121/2000 Coll. of the Czech Republic, as amended, and of any breach of rights related to intellectual property or introduced within amendments to relevant Acts such as the Intellectual Property Act or the Criminal Code, Act No. 40/2009 Coll., Section 2, Head VI, Part 4.

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Brno, May 24, 2024 ---------------------------------------

author's signature

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Poděkování

Tímto bych chtěl bych poděkovat vedoucímu mé práce M.A Kennethu Froehlingovi a svému konzultantovi doc. Ing. Karlu Katovskému Ph.D. za jejich užitečné rady a podporu. Chtěla bych také poděkovat své partnerce Nikole Bursíkové za to, že ve mě vždy věřila. V neposlední řadě celé mé rodině, bez jejíž podpory by nebylo možné tuto práci napsat.

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INTRODUCTION

Project Manhattan brought together the greatest scientists of the time to create the first atomic bomb. A weapon of unprecedented power marked the end of World War II and the beginning of a new atomic era. The project started because of the threat, that Nazi Germany could create and use the atomic bomb against their enemies. This bachelor thesis aims to search the available literature to examine in detail the technologies behind the creation of the first atomic bombs and convey a comprehensive sequence of events that eventually resulted in thousands of deaths in Hiroshima and Nagasaki.

The first part of my bachelor thesis describes the discovery of atomic fission from uranium isotope U-235 and its possible chain reaction. The discovery of these fundamental aspects of the atomic bombs completely changed the perception of this scientific field and it started a worldwide race to be the first to build a working atomic bomb. Therefore, the project had to change from a scientific to a military perspective and the US took the opportunity to become the first and maybe the only nation implementing atomic bombs in their military arsenal.

Different separation methods had to be researched and developed to obtain the rare isotope U-235, which is only 0.71 percent part of the uranium element. The first described is the electromagnetic method which was based on mass spectroscopy. Second was the gaseous diffusion method where a toxic uranium hexafluoride (UF_6) was used in never-ending separating stages forming a cascade. The third method, liquid thermal diffusion, attracted the lighter liquid form of U-235 to the hotter side of a container and separated it from the U-238. All these methods were implemented in large facilities in Oak Ridge, Tennessee. In these chapters, the focus is on the operation principle of each separation method as well as their performance and utilization.

The thesis continues with the first nuclear reactor in the Chicago-Pile-1, where Enrico Fermi and Leo Szilard tried to control nuclear reactions. Subsequently, a miss-product of this operation was a new type of element – plutonium. This eventually set the foundations for large-scale production of this transuranic element in the Hanford facility, Washington.

The next chapters include broader information about the secret Los Alamos area, where the theoretical part met with practice. There, the first atomic bombs – Little Boy and Fat Man – were developed and produced. Various triggering mechanisms, such as a gun-type or an implosion, are described in detail. Furthermore, these chapters convey information about the amount of destruction and the total number of deaths of Little Boy and Fat Man dropped on Hiroshima and Nagasaki

In the end, there is a summary of the nuclear research of Germany and the Soviet Union during the period 1939-1945 and why the United States was ahead in every way. To conclude the thesis, there is a discussion about the necessity of using the atomic bomb during the Second World War, what global change they brought, and what they meant for the future.

1. MANHATTAN PROJECT

The ancient Greeks, around 5th B.C., already thought about the concept of the atom but scientists had not been able to extend this concept for nearly two thousand years. In 1801, the English chemist John Dalton made a theory that each known physical element is made of atoms with the same amount of mass. Later, in 1895, German physicist Wilhelm Rontgen discovered short-wavelength electromagnetic radiation, called X-ray (Jones, 1985). The discovery of this invisible ray opened new discussions about atoms in the world of science. Rhodes states that Sir Joseph J. Thompson, an English experimental physicist, started working on this new phenomenon immediately. His work climaxed in 1897 with the discovery of a negative particle in the atom – the electron. The first of three element particles in the atom (2012).

The 1930s and 40s were uncertain times. Nazi Germany spread its nationalist and ideological ideas throughout Europe and their hatred was mostly directed at the Jewish population in Germany and Austria. However, they also targeted scientists, scholars, and overall educated people. Some of them stayed and adjusted to the new system. But others had gone to the USA, Great Britain, and Canada and helped the fight against injustice. In these turbulent times, the atom's nuclei were to become the subject of further investigation.

1.1 Atomic Fission

In 1934, Italian physicist Enrico Fermi attempted to bombard the nucleus of known elements with neutrons. Fermi in his Nobel Lecture (1938) clarified that 'neutrons, having no electric charge, can reach the nuclei of all atoms, without having to overcome the potential barrier, due to the Coulomb field that surrounds the nucleus. Furthermore, since neutrons practically do not interact with electrons, their range is very long, and the probability of a nuclear collision is correspondingly larger than in the case of α-particle or the proton bombardment.'

The neutrons were slowed down by the presence of carbon and hydrogen which were basically the first moderators. The more kinetic energy the electron has, the faster it is. By measuring the energy of the electron, it can be divided into two categories: fast and slow.[1] Fermi discovered that neutrons penetrated some of the nuclei of elements and transmuted them into nuclei of other elements. One of them was radioactive uranium and Fermi thought that he created a new type of element – transuranic – which was not present in nature. Natural uranium consists of 92 protons and 143 neutrons; however, this new uranium appeared to be with 93 or even 94 protons. Despite Fermi's conclusions, many scientists at that time were doubtful if it was even possible (Jones, 1985).

German radiochemists Otto Hahn and Fritz Strassman continued Fermi's work In 1938. They concluded that Fermi did not discover a transuranic element but rather Barium. With the bombardment of neutrons, they had essentially created two different elements roughly half the weight of the uranium (Jones, 1985). In other words, some of the mass disappeared; therefore, must have been transformed into energy, according to Einstein's equation $E=mc^2$ (energy is equal to mass times the square of the speed of light). According to Allardice & Trapnel (1946), 'this energy release would be of the order of 200 000 000 electron volts for each atom fissioned.' (p.42).

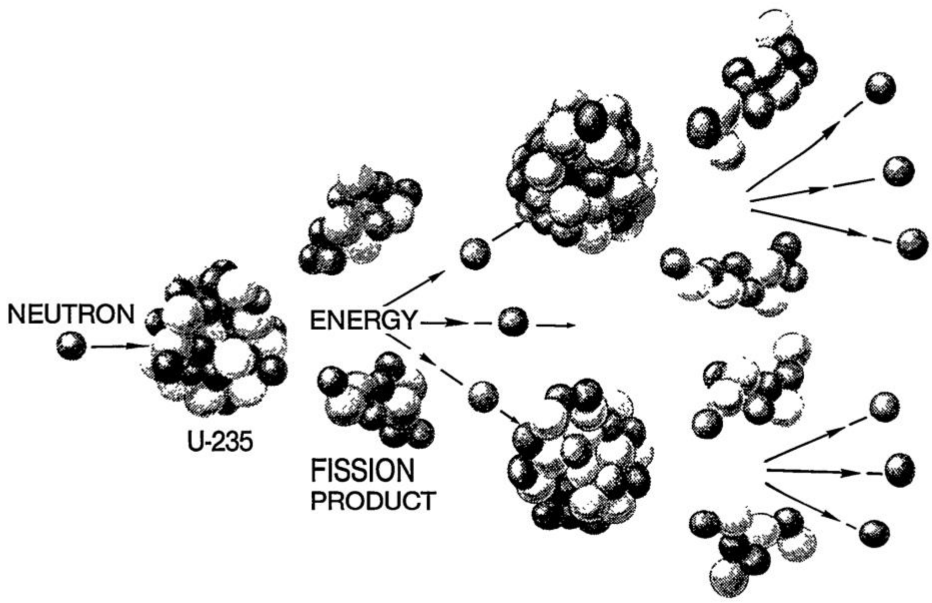

Fig. 1. U-235 fission chain reaction (Gosling, 2011)

[1] More information about the fast and slow neutrons is in chapter 1.2.1. Fast and Slow Neutrons.

1.2 Chain Reaction

For many scientists across the globe, it became evident that aside from the immediate release of vast energy, this process possessed another crucial characteristic – the emission of neutrons. As uranium underwent fission, it generated neutrons that escaped via kinetic energy from the two main fragments as they separated. Under specific conditions, these secondary neutrons had the potential to collide with other atoms, releasing more neutrons in a cascading effect, and releasing energy nonstop. The process which started with a single uranium nucleus, could not only release a significant amount of energy at once but other reactions may be added which would release a growing quantity of energy. Dwarkesh (2023) states that 'if a neutron with very little energy bumped into the nucleus of the Uranium-235 atom, it would lead to a massive response. Isador Rabi said it would have been like the moon struck the Earth'.

The concept of a chain reaction fundamentally changed the possibilities for unlocking nuclear energy. A self-sustaining, regulated reaction has the potential to generate a significant quantity of energy which could be transformed into heat and then into electricity. On the other hand, an uncontrolled reaction could result in an explosion with a power unknown to human civilization. Since uranium fissioned by emitting only two neutrons on average, the question was which of the three isotopes of uranium was most likely to do so.

In nature, uranium is composed of three isotopes: U-238, 99.28 percent; U-235, 0.71 percent; and U-234, just a trace (Jones, 1985). All three isotopes are chemically identical but differ in physical property – mass. At Columbia University, E. Fermi, Leo Szilard, and other co-workers were investigating which of the three isotopes is the most suitable for nuclear chain reaction. It was found out, that U-235 is the most auspicious. This discovery suggested that a chain reaction utilizing the U-235 might be achieved but only under difficult conditions: U-235 had to be separated from U-238 and then concentrated into a critical mass (Gosling, 2011).

Natural uranium occurs in concentrated form. Before II. World War, vital sites of this element were in Belgium Congo, northern Canada, and the US. Other not so frequently used were in former Czechoslovakia, Portugal, and England (Jones, 1985). Barlow (2019) notes, that it was projected that 150 tons of uranium would be required by 1944. Subsequently, it was found that 1,250 tons of 65 percent uranium oxide, mined by the Belgians in Congo, had been kept on Staten Island. Later, more supplies were obtained from Canada and the Colorado Plateau.

1.2.1 Slow and Fast Neutrons

It is important to distinguish and describe these two categories. The slow neutrons (also called thermal) are mainly used in thermal nuclear reactors where a moderator slows fission neutrons down. Power nuclear reactors are mostly based on thermal neutrons. The moderator depends on the nuclear reactor design; thus, it varies from heavy water, graphite, ordinary (light) water, etc. and the kinetic energy of slow neutrons is in order of a few electronvolts (for moderator temperature of 20 degrees Celsius, their most probable energy is 0.0253 eV). Slow neutrons have higher fission probability than fast ones, and with a good moderator (graphite or heavy water), it is possible to establish a chain reaction even with natural uranium fuel. If light water is used, uranium fuel must be enriched by fissile isotope 235 (for power reactors usually in the range of three to five percent).

On the other hand, the fast neutrons have kinetic energy between 0.1 to more than two MeV. They have a lower probability of causing fission, so reactors without moderators (as called fast reactors) must have much higher enrichment to increase the fission rate of must contain Pu-239 or U-233 fuel. However, fission caused via fast neutrons emits more neutrons per one reaction than in the thermal neutron case (about four in comparison with 2,4), also the neutron lifetime is shorter. In the Manhattan Project, it was concluded that a bomb would require fission by fast neutrons. If the slow neutrons were used, then the bomb would be very large and could pre-detonate and cause little damage. U-238 was considered as it fissioned with fast neutrons; however, it could not sustain a chain reaction. Only the U-235 seemed to be the ideal isotope for the project at the moment. Although enough natural uranium was obtained, now was the time to design and manufacture a separation method (Atomic Archive n.d.-a, Radioactivity – EU.COM. 2024).

2. Uranium vs Plutonium Bomb

On December 7, 1941, the Japanese Empire launched a long-prepared attack on the United States naval base at Pearl Harbor in the Hawaiian Islands. This unexpected attack drew the US into World War II, as Germany and Italy formally declared war four days after Pearl Harbor. Cimino states the American scientists feared that their attempts to produce a bomb might lag behind Nazi Germany and were feeling a newfound sense of urgency (Cimino 2001). According to Reed 'by early 1942, only milligram-scale quantities of uranium-235 had been isolated' (2011). The government now with more commitment funded further research in order to create the first atomic bomb, which would help to win the war. The nature of the American atomic bomb effort changed from one dominated by research scientists to an enterprise run by the military.

On September 17, 1942, Colonel (and later Brigadier General) Leslie R. Groves was appointed by the army as a chief director of the Manhattan Project. Groves was an educated engineer with solid management and executive skills who was mainly known as the chief director for the construction of the Pentagon. His first step was to acquire an area in Tennessee, where all uranium isotope separation units would be placed (Gosling, 2011). The area had almost 260 square kilometers and about 3,000 residents had to be moved away. A brand-new city, named Oak Ridge, was built and from the initial 13,000 residents, it quickly grew up to 75,000. Most of them were working on the distribution of enriched uranium, but Reed explains that until the announcement that an atomic bomb had been dropped on Hiroshima by President Truman, the majority of them had no idea what they were working on (2011). In Oak Ridge, three uranium separation facilities were built during 1942-1945: The Y-12 electromagnetic plant, the K-25 gaseous diffusion plant, and the S-50 liquid thermal diffusion plant (US Department of Energy, n.d.-2023).

2.1 Uranium and Isotope Separation Methods

2.1.1 Y-12: The Electromagnetic Method

The utilization of electromagnetic mass spectroscopy emerged as one of the most promising methods. Furthermore, an electromagnetic plant could be constructed in self-sufficient sections that could all start producing material as soon as they were finished, and mass production could be reached more quickly. The objective was to build a series of Calutrons – a combination of the words California University and Cyclotron – which would consist of the mass spectrometer and the Cyclotron magnet (designed and built by physicist Ernest Lawrence). Calutrons were supposed to function every day and every month without failure to produce a sufficient amount of material (Jones, 1985).

Calutrons required a considerable amount of copper for the windings of coils. But copper became a crucial resource with high priority during the war, as it was employed in shell casings. Therefore, an alternative had to be implemented – silver. Silver is an important metallic element and a cornerstone in electromagnetic mass spectroscopy. As Reed states: *'in an optical context, spectroscopy refers to using a prism to separate light into its constituent wavelengths. Similarly, mass spectroscopy separates atoms or molecules by their masses, with a magnetic field playing the role of the prism'* (2011). Silver solenoids appeared to be a sufficient alternative as they produced a high-intensity magnetic field. Furthermore, it helped to keep the project in secrecy, as the government did not need to turn aside larger amounts of copper to secret locations (Reed, 2011).

The operation principle was based on the following procedures: First, the heat caused uranium hexafluoride (UF_6) to evaporate, producing positively charged ions. Second, an electric field accelerated the ions where U-235 with its lighter atoms would create a straighter trajectory, and the U-238 with a little greater mass generated a broader one. That divided the stream in half and in the end, a magnetic field twisted the ensuing stream of ions inside the vacuum tank where the collecting area was located. Ions in this area, as Rhodes (2012) states: '…they give up their charge and are deposited as flakes of metal' (p. 423) (Reed, 2011).

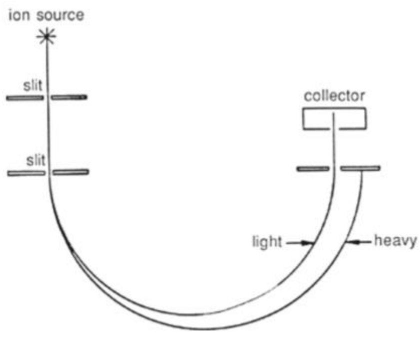

Fig. 2. Divided stream of ions (Rhodes, 2012)

To minimize the amount of material needed for the construction of severe individual calutrons, two similar arrangements – racetracks Alpha and Beta– were built in the Y-12 facility. The magnets were wound with silver windings and embedded in the welded steel boxes and the oil had flown as it dispersed the heat. Alpha consisted of nine racetracks with ninety-six Calutrons in total. On the other hand, Beta consisted of eight racetracks in a rectangular shape, with smaller sizes than in Alpha, and each racetrack consisted of thirty-six Calutrons. The main objective of Beta was further enrichment from Alpha's ten percent to desperately needed eighty percent (US Department of Energy, n.d.-a).

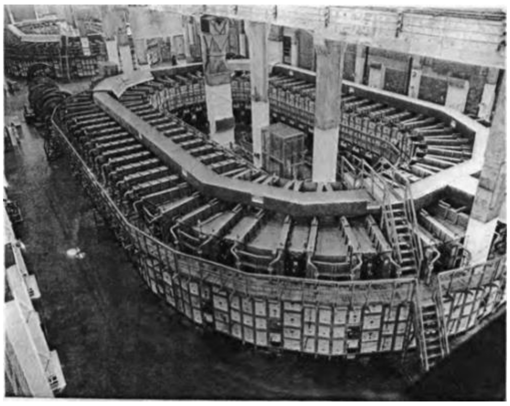

Fig. 3. Alfa racetrack
(Hewlett & Anderson, 1962)

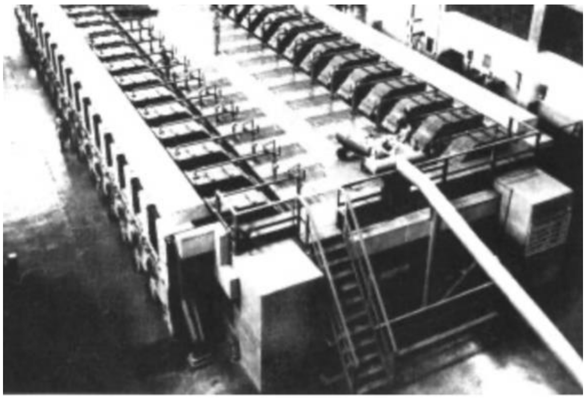

Fig. 4. Beta racetrack
(Hewlett & Anderson, 1962)

Over 4,800 people were operating and maintaining the Y-12 facility. But as it was a new technology, many things were unknown. Therefore, many problematic situations occurred as the production gained momentum.

The first problem was with leaked electricity, where upholding the right level of ion beam fluctuated as the heavy magnets shook in steel boxes. This was solved by welding the boxes right on the concrete floor. The second problem had beginnings in the design of the boxes. The silver windings, where the electric current flowed, were too close to each other. As the excessive particles such as rust and dust flew in the oil, the winding gaps had connected and short-circuited. Because of the complicated structure of the racetracks, the magnets needed to be dismantled and sent to another facility, located in Milwaukee, to redesign and rebuild (Rhodes, 2012). Reed concludes that by using the

Biot-Savart law for magnetic induction, it is possible to calculate the approximate current flowing through the windings. The current flowing in the nine Alpha racetracks was about 30,000 amperes. More than 13,300 silver was used for 74,000 coils for the electromagnetic method, and in 1945, about one percent of the total electrical power produced in the US was used for the current flowing in the coils Alpha and Beta (2011).

The necessary isotope slowly accumulated as the war progressed and by April 1945, 25 kilograms of enriched material for the uranium bomb had been produced and by July 1945, the plant yielded a little over fifty kilograms. In the end, the endeavor proved to be so effective that each atom of the first uranium bomb core underwent at least one calutron separation step (Yergey & Yergey, 1997).

2.1.2 K-25: The Gaseous Diffusion Method

In 1941, leaders in the Manhattan Project thought of combining two or more procedures because the electromagnetic method was not able to produce a sufficient amount of U-235. Therefore, another approach was chosen for full-scale development alongside the electromagnetic – the gaseous diffusion method. The process had been studied since 1940, in a hub at Columbia University, New York, and at the beginning of 1942, the plant's construction got underway with a code-name K-25.

The design and operation principle of gaseous diffusion plants was complicated as it relied on a stable uranium compound that could remain fluid at room temperature. In addition, the new method brought uncertainty about what would happen if the process was moved from a laboratory environment to a large-scale production facility. Karl P. C. Cohen, a mathematician employed by Columbia University, developed the basic theory based on Graham's Law with the usage of UF_6.

According to Graham's Law, the lighter gas will tend to escape faster than the heavier gas if two gases of unequal densities are mixed and pumped into a porous barrier located in an isolated container. As the lighter gas flows through the pores in the barrier, its quantity, size, distribution, and pressure of the gas itself determine how much of a single-stage separation is possible (Jones, 1985).

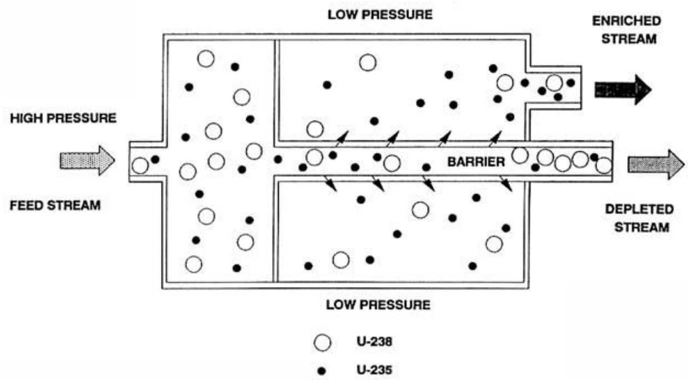

Fig. 5. The gaseous diffusion method (National Research Council, 1996)

The single separation contained four key stages, not to mention pipes, valves, control instruments, etc. A converter where the barrier was located, a compressor that pushed UF_6 with a precise amount of pressure from one stage to another, a motor that drove the compressor, and in the end a coolant that conducted the heat from the motor (National Research Council, 1967). These stages are shown in Fig. 6.

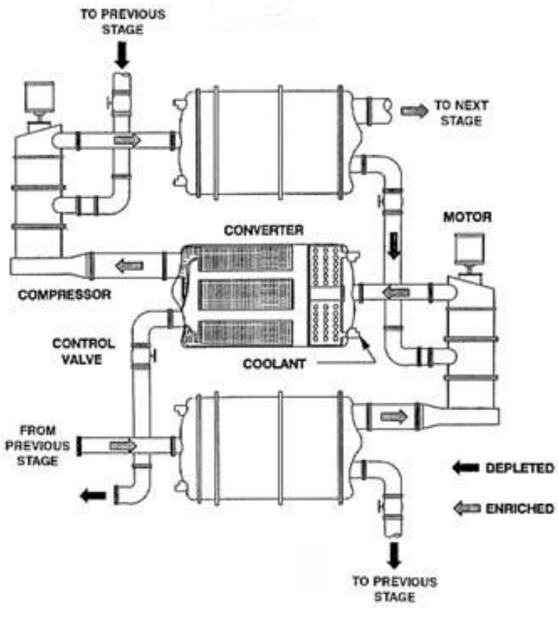

Fig. 6. Stages of diffusion separation method (National Research Council, 1996)

The main component in the whole process was the porous barrier which consisted of a metallic sheet with millions of submicronic holes just around 2.5 square centimeters.

However, as the density of the gases determines their molecular weights. UF_6 consisted of only 0.85 percent of lighter U-235 so it needed not just one separation stage, but about thousands to achieve the highest purity. These separation stages became known as cascades. With preparations begun in 1942, the K-25 facility was finished in June 1945 with nearly 3,000 cascade stages. About 500 million dollars was spent on research and construction with over 12,000 workers. The building stood in a total area of thirty-one football fields, twice the total ground area of Y-12 (Rhodes, 2012; US Department of Energy, n.d.-b).

The K-25 separation plant was ready to operate by 1945 but there were several problems. The first and the most crucial was that there was no sight of sufficient barrier quality. Therefore, Groves ordered a common meeting with experts from the British atomic program to solve this problem. A promising new material for the barrier, consisting of a nickel-powder compound, was created a year later. The cooperation and interchange of crucial information between the allies helped speed up the development and this was not the first time, that Great Britain participated in the Manhattan Project.

Health safety was another feature of the K-25 that needed to be solved. There cannot be any leak of the toxic gas that could contaminate the environment and jeopardize the health of the maintenance workers. Rhodes emphasizes that 'a single pinhole leak anywhere in the miles of pipes would confound the entire system' (p. 429). A new type of plastic seal, a substance still at the beginning of its mass usage at that time, had to be developed. This new material used in Oak Ridge was later distributed to a mass population under the name of Teflon (Rhodes, 2012).

Due to its problematic nature and technical delays, it was decided that the K-25 would not enrich uranium up to ninety percent, but only to fifty percent. That half-enriched material would be sent to Y-12 where it would go up to its needed percentage (Gosling, 2011). An additional 4 enrichment facilities were built as a part of the whole K-25 area during 1945-1964. It was K-27 whose enrichment went up to twenty percent, K-29 with its ten percent enrichment capability, and K-31 with K-33 capable of only two percent of uranium enrichment. The last two were primarily used as a supplier of enriched material for the first nuclear reactors (Oak Ridge Gaseous Diffusion Plant, 1967).

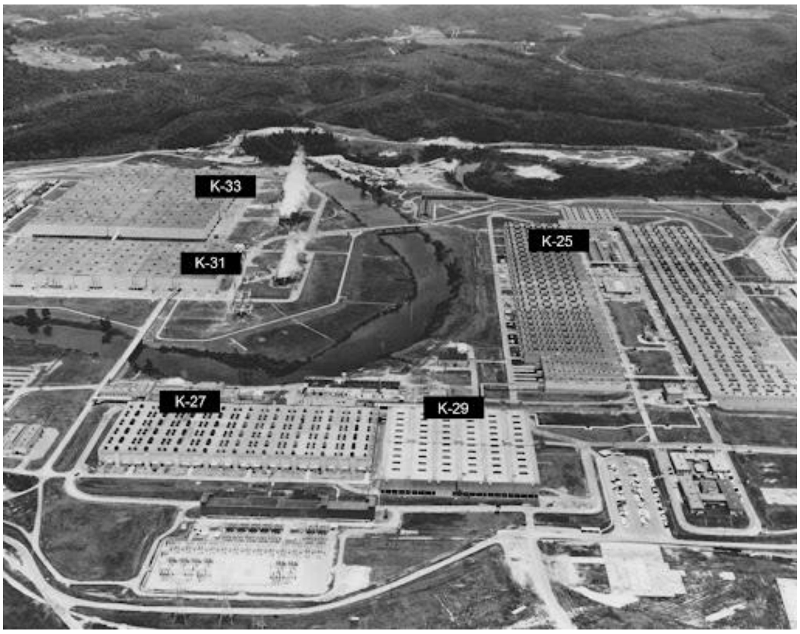

Fig. 7. Diffusion enrichment facilities in Oak Ridge (K-25 Virtual Museum, n.d.)

2.1.3 S-50: The Liquid Thermal Diffusion Method

In contrast to the Y-12 and K-25 facilities, the S-50 thermal diffusion plant was not included in the initial uranium enrichment plan. However, as the problems in Y-12 and K-25 accumulated and the production of enriched material slowed down, it led to the decision to construct S-50. The objective was to gain some of the enriched uranium, which would be further enriched in the Y-12 facility. American physicist and chemist Philip Abelson has worked on the liquid thermal diffusion method (LTDM) since 1940 (Hewlett & Anderson, 1962).

The basic principle of LTDM is as follows: If a fluid element with two different molecules (in our case, UF_6) is placed in an annular container in a vertical position (columns) with two sides of different temperatures, the outer wall cold and the inner wall hot, the lighter U-235 will be pushed to the hot side whereas the heavier U-238 will be moved to the cold one; these two isotopes are changing their molecules by thermal diffusion. Due to a conventional current in the container, the U-235 will rise up whereas the U-238 will flow down. By the accumulation of these isotopes in different places, extraction is possible (Abelson et al. 1958).

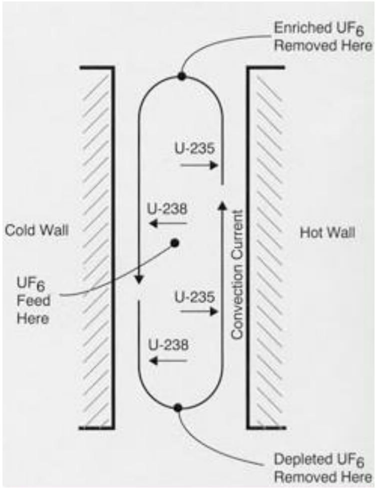

Fig. 8. LTDM operation principle (Hewlett & Anderson, 1962)

The major advantage of LTDM was its simplicity. The components were firmly attached without the possibility of movement and the whole process operated by the basic physic element – convection. To stop the enrichment process, the pressure and temperature of the UF_6 had to be simply modified and the dry ice would be used on the supply line (Hewlett & Anderson, 1962).

Hewlett & Anderson (1962) mention that the first large-scale facility of LTDM was supposed to be built at the Philadelphia Navy Yard. This location was selected because it offered a sufficient amount of steam. This high-pressure steam was needed to increase column temperature to reduce the equilibrium time for enrichment. The plant in Philadelphia was supposed to be built by July 1944. In original plans, it was supposed to consist of 300 columns with 14,6 meters of height and operated in a seven-stage cascade. As Reed (2011, May 26) states ‘the cascade was expected to deliver about 100 grams of product per day at a concentration of 6% U-235‘ (p. 173). However further investigations showed that the Philadelphia plant would be insufficient as it would not produce enough enriched uranium. Therefore, it was decided that a much larger full-scale facility needed to be built in Oak Ridge, Tennessee. The plant was named S-50 and as mentioned earlier, enough steam supply was crucial for S-50 operation. The steam was provided by the K-25 powerhouse and after required modification, the steam was delivered to S-50 at 1,000 psi and 285 degrees Celsius. The K-25 powerhouse with the three smokestacks may be seen in Fig. 9. together with the S-50 facility (the long dark building on the left side of the powerhouse).

Fig. 9. S-50 plant in Oak Ridge, Tennessee (U.S. Department of Energy, n.d.-b)

The S-50 plant was built in ninety days, whereas the first production unit operated in under seventy-five days. The design and operation principles were the same as it was supposed to be in Philadelphia. All production units were operable by July 1944 with a total of 2,142 columns with a height of fifteen meters. These columns were also formed in racks, each consisting of two parallel rows of fifty-one columns, and they were connected like a circuit. The enriched material was obtained at the top, and the depleted material was removed at the bottom by the projecting nickel tubes (Reeds, 2011). The S-50 played a crucial role as a supplier for other separation methods even though it only increased uranium enrichment from 0.72 percent to 0.85 percent. By July 1945, the S-50 produced about twenty tuns of slightly enriched U-235. (Reed, 2011, May 26).

2.2 Plutonium

At the University of California, Berkeley, Glenn T. Seaborg was exploring the U-238 together with Joseph W. Kennedy, Edwin M. McMillan, Arthur C. Wahl, and Philip H. Abelson. They used Lawrence's Cyclotron in which deuterons were utilized to bombard uranium. They knew that the U-238 was unsuitable for a chain reaction because it was far more likely to absorb it when hit by a neutron. But when the nucleus absorbed the neutron, the neutron became uncharged, increasing the atomic mass of the nucleus: U-238 became U-239 which was far less stable. Due to its instability, the U-239 then decayed through the Betta decay process in which it emitted an electron and one of the neutrons became a proton. From this process, the new transuranic element – neptunium – was discovered. But the neptunium was also unstable and transformed into a new element – Plutonium.

Pu-239 was suitable for fission, just like the U-235, and therefore it had the potential to become a fuel for atomic bombs. Moreover, Pu-239 had a 1.7 times greater chance for fission than U-235 (Nuclear Museum, 2014-a).

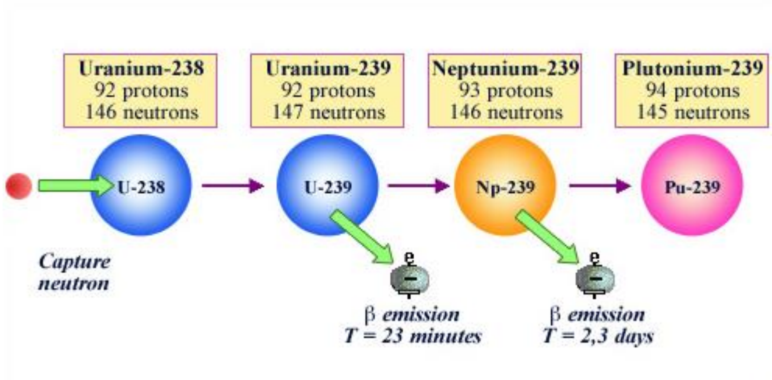

Fig. 10. Breeding of plutonium (Radioactivity – EU.COM, 2024)

The whole process of obtaining Pu-239 from U-239 by the bombardment of deuterons is called *breeding*. Notice, that these elements are named after the last planets in our solar system: Uranus – Neptune – Pluto. This was a huge success in the history of science because, for the first time in human history and 6 years after Fermi's experiments with barium, the first transuranic (man-made) elements were discovered. However, the important question was whether Pu-239 could be manufactured in large-scale quantities in order to be efficient as a fuel for a bomb.

2.3 The Piles

While various methods of U-235 separation were being investigated, a program for a controlled slow-neutron chain reaction was in the process of discovery. This was not an easy task. The job was to design equipment for a technology poorly understood at that time. It is important to understand that the “reactor bomb” was also considered. In the upcoming chapters, several smaller experimental piles are described (pile was an early name for a reactor). In these experimental piles, several studies were conducted: studies of reactor physics, radionuclide metabolism in laboratory animals, and most importantly plutonium separation studies. Because scientists noticed that Pu-239 was present when they chemically examined the burned rods from reactors. This meant that large-scale facilities, focusing directly on Pu-239 production were possible.

All the piles had to work on the fundamental operation: the neutrons released during the fission must hit other neutrons and so forth to create a sustainable chain reaction. Cimino (2001) states that to quantify the efficiency of chain reaction, the scientists suggested a multiplication factor *k*. 'If k was less than one, any chain reaction would fizzle out. But if k=1, a chain reaction would be maintained and if k was greater than one, the reactor risked going supercritical with the chain reaction running out of control' (p. 55). In July 1941, Fermi and Szilard had already begun designing an experimental pile at Columbia University, New York which provided a k of 0.87. This was only 0.13 from the desired outcome but still insufficient.

The time was running out, and Groves made a reorganization in December 1941. This area of the Manhattan Project was assigned to Arthur H. Compton and with his decision, several scientific groups from Princeton and Columbia merged into the Metallurgical Laboratory (MetLab) now at the University of Chicago. In MetLab, *k* reached up to 0.914 a then to 0.94. Now it was time to create a full-size pile (Allardice & Trapnel, 1946).

2.3.1 Chicago Pile-1

Gosling states, that heavy water was recognized as the most suitable moderator for the controlled nuclear chain reaction. However, the reserves of this chemical compound were scarce due to the German invasion of France in 1940. Therefore, it was decided that the carbon-element graphite would be used. A graphite moderator would slow down the neutrons produced by the fission process, which would increase the possibility of another neutron fission. By providing enough amount of natural uranium, the reaction would continue (2011). Another obstacle to overcome was to define the placement of uranium in the pile. Fermi and Szilard suggested placing the uranium in a cubic lattice of the moderating material, thus, ensuring that a neutron would cross paths with the uranium (Allardice & Trapnel, 1946).

Construction of the first full-sized pile, named Chicago Pile-1 (CP-1), started in November 1941 and finished a year later. An abandoned racket court at Stagg Field was chosen as a final location for this final experiment, more precisely its underground area. About 45,000 graphite blocks were used in the form of two layers which were stacked on each other. The first layer contained graphite blocks with no natural uranium and the second layer was made of graphite blocks containing uranium coats. In the end, the pile was made of fifty-seven layers. Another crucial component was the control rods, made of cadmium, which had been used to control the fission reaction (Thomas, 2017) In total, four control rods were present and they were operated from a distance by electric motors. In addition, a safety rod called Zip would be triggered by the solenoid. As Cimino (2001) clarifies: ‘if the neutron intensity exceeded a predetermined setting, the solenoid would trip and the weighted rod would drop into place under the force of gravity’ (p. 59).

On December 2, 1942, the CP-1 went critical with $k = 1.0006$ and operated for twenty-eight minutes. It generated an output power of 0.5 watts and ten days later it would rise up to 200 watts, sufficient to run a lightbulb. This first artificial nuclear reaction changed the view on atomic science and proved that the energy released during controlled fission can be used as a source of power. Despite the success, the CP-1 was terminated three months after the first operation. Because of the danger of contamination of the city’s environment, the pile was dismantled and relocated to a more isolated location. The Argonne National Laboratory in Illinois was chosen as a place for the upgraded version: Chicago Pile-2 (Nuclear Museum, 2016).

2.3.2 Chicago Pile-2

This experimental uranium-graphite reactor operated on the same principle as the CP-1 but with slight modifications. It used more natural uranium, was larger than its predecessor, had improved control rods, and most importantly, was covered in a concrete shield that would prevent scientists from dangerous radiation levels. CP-2 did not have a cooling system just like the CP-1, so the output power was limited and operated only from 1 kW to 10 kW. The power levels were calculated from neutron flux measured by the two galvanometers. CP-2 was operated from 1943 to 1954 (Argonne National Laboratory, n.d.).

2.3.3 Chicago Pile-3

Chicago Pile-3 (CP-3) became the first nuclear reactor where heavy water was used both as a moderator and a coolant. The location of CP-3 was also in the Argonne National Laboratory area with the construction finishing in 1943. After seven years of proper functioning, the CP-3 was dismantled due to corrosion on the fuel rods. This was due to the natural uranium, which was used as a fuel, and needed to be changed to enriched uranium. The new version, called CP-3 Prime operated until 1954 (Argonne National Laboratory, n.d.).

2.3.4 X-10 Graphite Reactor

The first reactor that would focus primarily on continuous production of the Pu-239 was built and ready to operate on November 4, 1943. Located in Oak Ridge, Tennessee, the X-10 facility provided a training ground for the personnel which would eventually be used in the final, large-scale plutonium separation facility in Hanford, Washington. Like its predecessors, X-10 contained graphite blocks sealed in a concrete shield where the air served as a coolant that dissipated the heat from the fission. 1,248 fuel-loading channels in a horizontal position were placed in this radiation-protective shield. When the personnel inserted a new fuel rod (slugs), the burnout slugs were pushed away into the water vessel for cooling. That is why the horizontal position for slugs was chosen.

To conclude this, the process of extracting Pu-239 from the burned slugs is called *reprocessing*. The X-10 pile operated until 1963 and during the war, it eventually supplied the Los Alamos site with an experimental amount of material. Furthermore, the same design of X-10 but on a larger scale was used in the final pile in Hanford, Washington. (US Department of Energy n.d.-d, Atomic Archive n.d.-b).

2.3.5 Hanford, Washington

Located on the desert wasteland near the Columbia River in Washington, the Hanford site offered an isolated area suitable for mass production of the toxic Pu-239. The isolation was an advantage due to the radiological hazards connected with the Pu-239 extraction and production. Overall, the Hanford site can be divided into three groups, each of which played a different but equally important role: 1) reactors, 2) separation plants, and 3) metal fabrication.

1) Hanford consisted of three water-cooling reactors from the initial four. As mentioned earlier, they were larger but similar to the X-10 facility in terms of operation principle. The concrete shield was penetrated by 2,004 aluminum tubes and the designated operation power level was 250,000 kW. These reactors were

so massive, that their water consumption would approach a city of one million people. The first reactor was called 100 B and became operational in August 1943. The other ones, 100 D and 100 F were completely identical to 100 B and ready to use in the following years. Ultimately, these water-cooled reactors produced sufficient Pu-239 by August 1945 for the Trinity device and the Fat Man.

2) As the uranium slugs were turned into the Pu-239, they had to be chemically separated from other unwanted materials and radioactive decay products. The process of cleaning the Pu-239 was called the oxidation-reduction cycle. The Pu-239 was fed into the cooling pools with lanthanum fluoride. This chemical compound had helped purify the Pu-239 which was then transformed into plutonium nitrate. The nitrate was then converted to metal and shipped to Los Alamos, New Mexico. The separation buildings had contained forty cooling pools and operators manipulated these toxic chemical compounds remotely behind a concrete shielding with periscopes.

3) The Hanford site contained other auxiliary buildings such as a technical laboratory, instrument shops, and slug-fabrication buildings with a small fifty-watt reactor. In this area, the main objective was to manufacture and test not only the uranium slugs but also the graphite blocks. According to MetLab director Arthur Compton, the development and production of uranium slugs was the most critical project (The Atomic Archive, n.d.-c; Hewlett & Anderson, 1962).

To conclude this, three main locations of the Manhattan Project have been discussed in previous chapters. The first was in Oak Ridge in Tennessee, where most uranium enrichment occurred. The second was MetLab in Chicago where the first uranium reactors were researched and tested. And the last, the Hanford site in Washington with its large-scale plutonium production facilities. All locations served as testing and production sites for U-235 and Pu-239. Now was needed to bring all the work together in one place. The final piece of the puzzle was the Los Alamos site, where scientists led by R. J. Oppenheimer were tasked with finding a solution for a usable atomic bomb.

2.4 Los Alamos

The site in the desert of New Mexico, codenamed Project Y, gained momentum in March 1943. Several facilities and auxiliary buildings had to be constructed as the physicists, chemists, engineers, and military-technical experts moved to Los Alamos. The groups of these intellectually gifted people were separated into divisions. There was a theoretical and experimental physics division and a chemistry and metallurgy division, and each was devoted to a particular aspect of bomb research and development. The scientific management was under Robert J. Oppenheimer who was known for his theoretical research in quantum physics. His effort was now based on two fundamental tasks: solving the theoretical and experimental problems of a fission bomb (Jones, 1985).

2.5 Uranium Bomb

In order to detonate an atomic bomb, both uranium and plutonium, a critical mass must be built up until it becomes supercritical and explodes on its own. Since delayed pre-detonation may cause a small explosion that would destroy the bomb before it achieves its optimal mass, the critical mass must be put together rapidly. Therefore, scientists in Los Alamos came up with two major methods: a gun-type method and an implosion method. The gun-type method became popular since it was easy to design. Thus, in July 1944, the gun-type method was determined to be the detonation mechanism in the uranium bomb (Cimino, 2001).

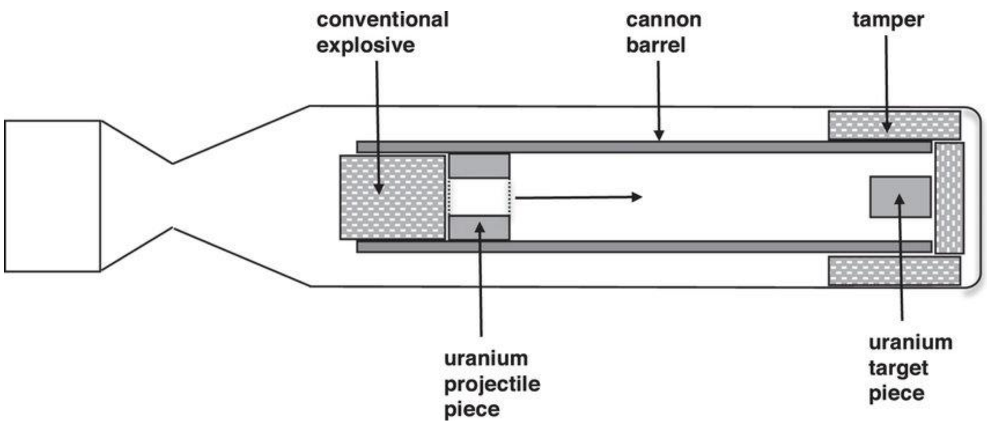

Fig. 11. Principle of the gun-type method (Reed, 2016)

The system used a tube in which the two halves of U-235 were fired toward each other. First, an explosive propellant fired a filled cylinder in the target which was in the shape of a hollow cylinder. Subsequently, these two objects fitted precisely and as they collided; it produced an explosive fission reaction and the heavy metal tamper increased the explosive power. Scientists had confidence in the method's performance due to successful lab experiments they did on a smaller scale, even though the notion of the gun firing concept was not completely proven until the bomb detonated in Hiroshima (Kratz, 2020). To conclude this, it is often wrongly assumed that the tube-shaped mass is fired against its counterpart which was hollow cylindric. It was exactly the other way around.

2.6 Plutonium Bomb

One subcritical mass might be fired into another using U-235, but this technique would only be effective for Pu-239 if complete purification of the material could be accomplished. Unable to fully purify the plutonium, the team devised a plan to compress a plutonium sphere into a supercritical mass using high explosives, which would release neutrons and set off a chain reaction. But achieving symmetrical implosions turned out to be an issue. It was challenging to achieve explosion uniformity without some leaking out the side since the high-explosive shell would melt the metal core. Nevertheless, the studies and tests on the implosion continued and later was clear, that there was a chance to produce a bomb that was more dependable and faster (Cimino, 2001).

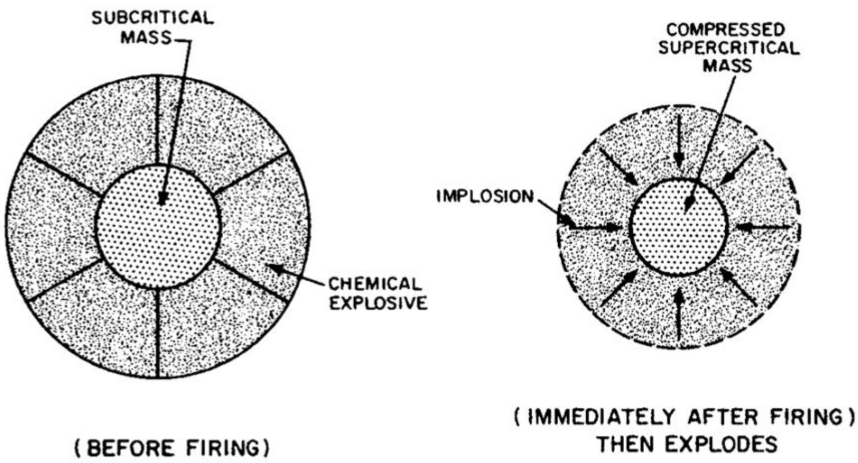

Fig. 12. Implosion principle (Glasstone & Dolan, 1977)

2.6.1 Thin Man

Despite the efforts on the implosion method for a plutonium bomb, the scientists were still considering the gun-type plutonium bomb. A prototype of this bomb was created and named Thin Man. However, Seaborg's research in MetLab discovered that the Pu-239, produced in the Hanford facility, would gain an extra neutron when exposed to a longer radiation period. It would become Pu-240 with its spontaneous fission characteristics and the pre-detonation was more likely to happen. Subsequent calculations confirmed that the projectile and the target would melt before they collide. After some time, Thin Man's detonation issue led to its elimination, and the focus was directed only on the implosion device (Cimino, 2001).

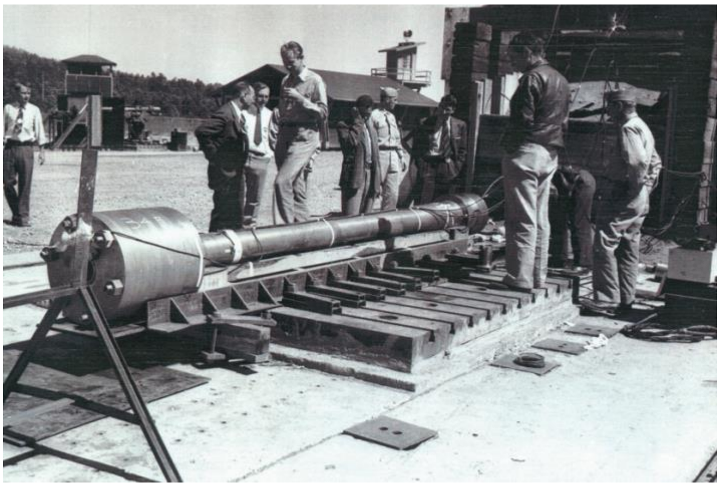

Fig. 13. Plutonium gun-type bomb Thin Man (US Army Corps of Engineers, n.d.)

2.6.2 Demon Core

Working with a toxic plutonium was difficult and two fatal accidents happened at Los Alamos. The first accident was on August 21st, 1945. A physicist Harry Daghlian was working with a plutonium core, which had been created for determining the critical mass of the plutonium bomb. The core was nine centimeters in diameter and placed between tungsten carbide blocks. The blocks acted as a reflector and neutrons emitted from the core reflected back. That day, Daghlian accidentally dropped one of the blocks too close to the core and the reflected neutrons turned the core into critical mode. A blue flash appeared and Daglian threw the brick away but it was too late. Daghlian received a fatal level of radiation and died twenty-five days after the accident at the age of twenty-four.

Precisely nine months later, On May 21st, 1946, another accident happened with the same plutonium core. This time, physicist Luis Slotin was conducting a slightly different criticality experiment but rather with a dangerous technique. The core was placed between two beryllium spheres that acted as reflectors and Slotin was using a screwdriver as a lever to keep the spheres apart. Slotin conducted this dangerous experiment dozens of times but this time, the screwdriver slipped, and the spheres had closed. The core went critical and the blue light with heat consumed Slotin. The fatal dose of radioactivity lasted only a fraction of a second as the core melted due to the heat. But the damage was done and Slotin died nine days later at the age of thirty-five (Thomas 2017, Fraga 2022).

Fig. 14. Demon core (Los Alamos National Laboratory, 1962)

2.7 Trinity

By 1945, the war in Europe progressed and it seemed that Nazi Germany was on the edge of surrender in which case Japan would probably be the first country to be hit by an atomic bomb. Nevertheless, the work on the atomic bombs continued and plans for the first atomic blast were set in motion. The chosen site was on the Alamogordo Bombing Range known as the "Jornada del Muerto" which can be translated as "Journey of Death". This isolation offered a flat area suitable for accurate measurements of the explosion. Additionally, the site was close to Los Alamos and the wind was not frequent. Thus, the radioactive fallout would not be dispersed into the wider area.

According to Thomas (2017), the tower on which the bomb was placed was thirty meters high. It was made of steel with a hole inside it, where the bomb, called the Gadget, was raised via an electric winch. The Gadget consisted of a Pu-239 ball-shaped core and a shell with thirty-two highly explosive spheres. To avoid the pre-detonation risk, the components were delivered separately. Subsequently, they were assembled at the top of the tower alongside the detonators. The detonators were specifically developed for this event to achieve the precise accuracy of detonation. It consisted of a thin wire through which a pulse of 100 kA was passed. When this extreme amount of current had passed through the wire, it exploded and started detonation. These Exploding Bridge Wire Detonators were connected via thick power cables and spaced around the shell. The detonation was planned early in the morning of Monday, July 16, 1946. At 2 a.m. the storm and heavy rain came to the testing site and the detonation had to be postponed. At 5 a.m. the weather cleared, and everything was ready. Oppenheimer controlled the detonation sequence inside a concrete control bunker 9.5 km from the tower.

At 05:29:21, the Gadget exploded with the force of 20,000 tons of TNT which was four times than predicted. The explosion left a crater about 1.4 meters deep and eighty meters wide and scattered radioactive glass (trinitite) in a radius of about 300 meters around the crater. Thomas (2017) emphasizes that 'the resultant pressure was more than a hundred billion times the pressure at the surface of the Earth and was the greatest pressure ever to exist on the Earth.' (p. 109).

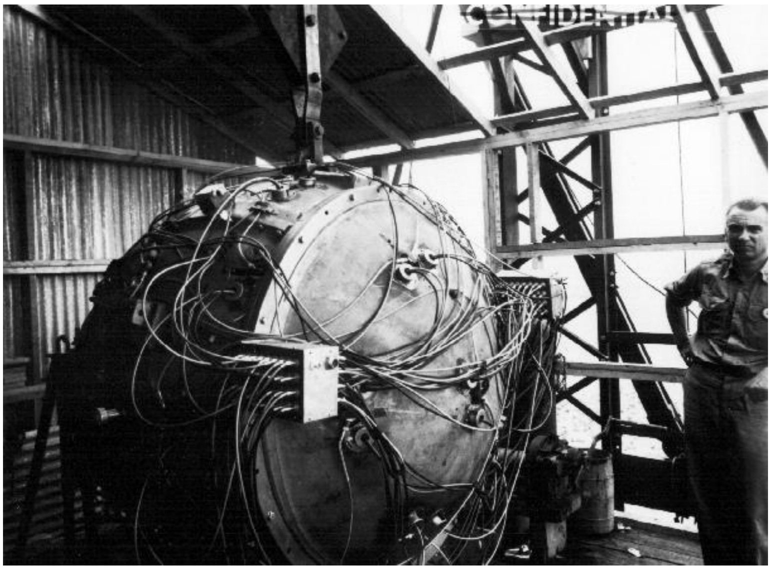

Fig. 15. The Gadget at the Trinity site (Federal government of the United States, 1945)

The successful explosion of the first atomic bomb on 16 July 1945 was the greatest physical experiment of all time. An immeasurable amount of effort has paid off, and the US has since become a nuclear power. A few months before Trinity, Nazi Germany surrendered and the war in Europe had ended. However, it seemed that the Japanese Empire would not surrender that quickly, and fighting for every island in the Pacific Ocean became gradually exhausting in terms of money, material, and manpower. Therefore, after several consultations and discussions, the Manhattan Project executives decided that atomic weapons would be used in order to end this war for good.

3. TECHNOLOGY AND THE OUTCOME OF LITTLE BOY AND FAT MAN

3.1 Little Boy

The Little Boy was a name for a gun-type uranium bomb. The U-235 used in this bomb was produced by the three isotope separation methods – liquid thermal diffusion, electromagnetic separation, and gaseous diffusion. The bomb was not assembled in the US but on Tinian Island, which is in the Pacific Ocean south of Japan. Various parts were first transported to San Francisco, California, and then shipped by the USS Indianapolis cruiser to its destination. Furthermore, the sixty-four-kilogram target plume of U-235 was transported independently by three C-54 Skymaster transport aircraft to prevent accidental denotation. By July 26, 1945, all parts of the bomb were ready to be assembled. In the end, the deadliest weapon at that time was 4,400 kilograms heavy three meters in length and seventy-one centimeters in diameter (Kratz, 2020).

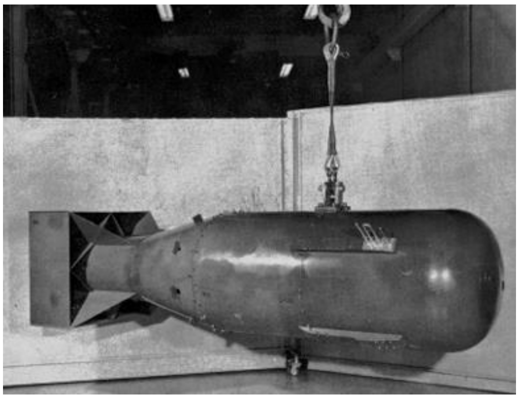

Fig. 16. Little Boy before use in combat (US government DOD, n.d.)

3.1.1 Hiroshima

A B-29 bomber known as Enola Gay took off from Tinian Island on August 6, 1945. With the Little Boy on board, the bomber was eight tuns over its weight. In addition, due to security precautions, the bomb had to be armed once airborne. Hiroshima, located on the Honshu Islands, was to become the target of the first atomic bomb. The city was chosen due to its strategic and military position with a population of around 300,000 residents in addition to 43,000 soldiers. Cimino emphasizes that up until that point, Hiroshima had mostly avoided the bombardment. Therefore, when two additional B-29s appeared in the sky at 8:06 a.m., flying at 9.600 meters above the surface, not many people noticed. They appeared to just overfly the city; thus, no air-raid warning was set out.

Enola Gay launched Little Boy above the city at about 8:15 a.m. An explosion lit the morning when the bomb detonated 580 meters above the city. The explosion's force was calculated to be 15,000 tons of TNT. The total amount of deaths is still unknown to this day. The blast with heat and radiation impacts killed about 70,000 people. The total amount was probably above 100,000 by the end of 1945 due to the aftereffects of radiation sickness and the ongoing effects of radioactive fallout. By considering cancer and other long-term consequences, the total death number may have even surpassed 200,000 (Cimino 2001; Kratz, 2020).

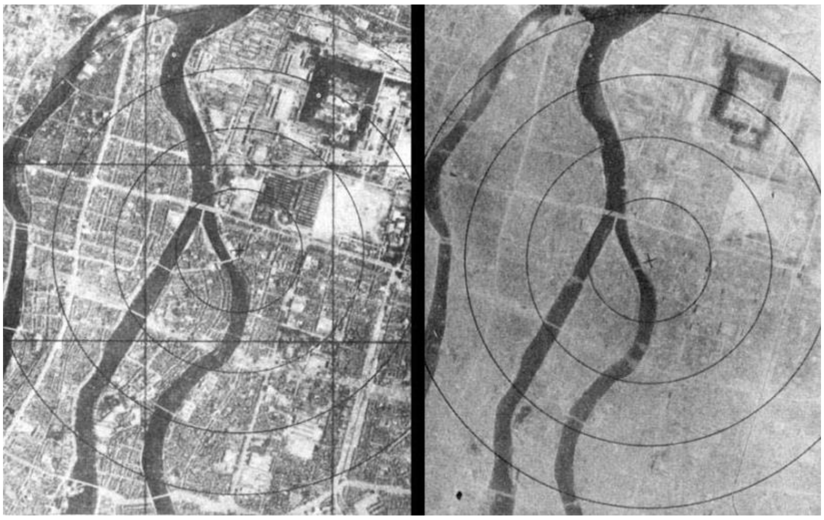

Fig. 17. Hiroshima before and after (United States Army, n.d.)

3.2 Fat Man

After still unknown consequences of Little Boy in Hiroshima, Japan was unable to agree to the parameters set out by the Allies due to internal conflicts and communication issues. Therefore, conventional bombing of Japanese cities continued, and the Manhattan Project executives were planning to use the second atomic bomb. This time, the bomb with a six-kilogram core of Pu-239 called Fat Man would be used.

Fig. 18. Fat Man before combat (U.S. Department of Defense, n.d.)

3.2.1 Nagasaki

Three days after the bombing of Hiroshima, another B-29 nicknamed Bockscar took off from Tinian Island carrying a Fat Man. Contrary to Little Boy, the operation was dangerous as the plutonium bomb had to be armed before the take off. The main objective was Kokura with plenty of army facilities. If anything went wrong, the secondary target was Nagasaki's harbor, where torpedoes used in Pearl Harbor were manufactured. Due to the bad weather that occurred around Kokura and by receiving considerable resistance during its three flights over the objective, Bockscar headed to Nagasaki. Cloud also covered the city and Bockscar was running out of fuel. But at last, a hole in the clouds appeared to allow optical aiming at six kilometers.

Fat Man was dropped at 11:02 a.m. precisely above the industrial core of the city. With a force equivalent to 21,000 tons of TNT, Fat Man burst 495 meters above the city's hills. The entire damaged area was about 3.5 kilometers and sixty-eight percent of the city's industrial capacity was destroyed. Once more, the results of the death toll were staggering. In the first hour, over 35,000 human beings were killed and another 70,000 individuals had perished in Nagasaki by January 1946. With a fatality rate comparable to that of Hiroshima, the total finally approached 140,000 (Cimino, 2001; The National WWII Museum, 2020).

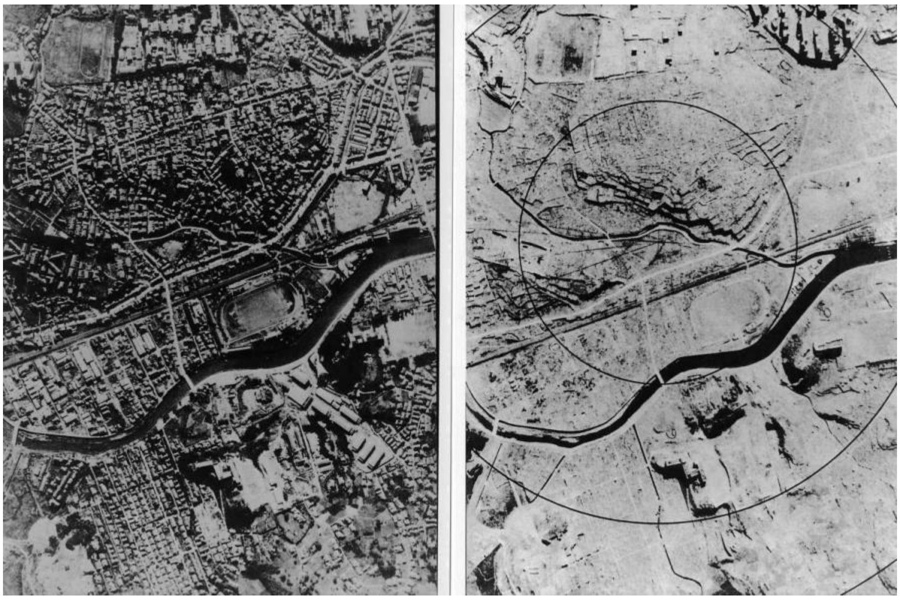

Fig. 19. Nagasaki before and after (United States Army, n.d.)

3.3 The Outcome

After these events, the Japanese Empire decided to surrender on August 14, 1945; Four years after the surprising attack on Pearl Harbor. Gosling states that when President Truman revealed the Hiroshima raid to the American public on August 6, the curtain of secrecy that had concealed the atomic bomb effort was removed. The Manhattan Project was announced to the public on August 12, 1954, with generic technical details and without nuclear secret revelation. When the American public discovered that there was a vast, top-secret government enterprise with a workforce, payroll, and physical facility similar in scale to the U.S. car industry, they were astonished. More than 2.2 billion dollars was spent on the Manhattan Project. The project also employed some 130,000 individuals, many of whom were among the top scientists and engineers in the country (Gosling, 2011).

To properly end the chapters about the enrichment and the plutonium production facilities, it is important to mention that after WWII, the effort was shifted to efficiency. In Oak Ridge, all processes used energy to separate the U-235 and U-238. Some of them used a lot of power, such as Y-12, but also produced a large increase in enrichment material. Other processes took less power but produced a low increase in enrichment. To calculate the efficiency of these facilities, scientists suggested a number called Separative

Work Unit which could be applied equally to all methods. It was calculated that the K-25 facility was more efficient than the Y-12 and S-50 and it became the main uranium enrichment facility during the Cold War. On the other hand, the Y-12 transitioned into isolating other isotopes whereas S-50 was deactivated and demolished. Nevertheless, by combining all of these methods, the US achieved a significant lead in the production of the first atomic bomb.

The three water-cooled reactors in Hanford continued during the upcoming Cold War. The 100 F reactor was deactivated in 1965, the 100 D reactor in 1967, and the first 100 B reactor ended plutonium production in 1968. All facilities: reactors, separation plants, metal fabrication, and auxiliary buildings were demolished due to environmental and safety reasons (Atomic Archive, n.d.-c).

The outcome of Little Boy and Fat Man divides people. The first group is against the usage of atomic bombs with the following arguments: 1) By 1945 the war was almost over, and Japan would have surrendered anyway. If the United States had agreed to allow the emperor to remain on the throne, and the Soviet Union had openly admitted its impending invasion of Manchuria, the whole bloodbath could have been avoided. 2) The United States could not continue to advance on the main Japanese islands due to logistical problems; thus, they could have been more patient. 3) The use of atomic bombs was useless and pointless, and only brought more harm than good. That it nothing changed and eventually started the Cold War.

On the other hand, the other group argues that Little Boy and Fat Man were necessary to end the war as quickly as possible. While Japan no longer had a realistic prospect of winning the war, Japan's leaders believed they could make the cost of invading and occupying the Home Islands too high for the Allies to accept, which would lead to some sort of armistice rather than total defeat. To that, Cox emphasizes the Japanese propaganda slogan: ‘The sooner the Americans come, the better… One hundred million die proudly’ (2021). Cox continues that Operation Downfall (invasion on the main Japanese islands) would cause between 1.7 to four million US casualties and five to ten million Japanese dead (2021).

The truth is that the atomic bombs accelerated the war after all, and by comparing the estimated number of victims together with the Japanese mentality of not giving up at any cost, the price in Hiroshima and Nagasaki may have paid off. But as the nuclear weapons – the ultimate weapons – spread around the world, no one could win anymore. Mutual destruction is possible but not war and that was a totally new ground for nations.

On the other hand, the successful Manhattan Project meant a new dawn of human civilization – the Atomic Era. This era brought a scientific breakthrough in fields such as medicine (Radiology with X-rays, CT scans, and improved diagnostic capabilities), science (development of particle accelerators and large-scale experiments like those at CERN), and space exploration (development of radioisotope thermoelectric generators for powering space missions). Perhaps these beneficial scientific discoveries that help us all on a daily basis are the most important things that the Manhattan Project has achieved.

3.3.1 German Atomic Program

It is good to mention the programs of other nations that were racing towards the first atomic bombs. The most important ones during World War II were the German and the Soviet atomic programs which are briefly described below.

The discovery of fission on December 1, 1938, in Berlin, meant that Germany was ahead of the US and the work on the nuclear technologies had started under the name Uranverein. However, the German project had major issues. One of the biggest was that many scientists flew from the nazi territory due to their Jewish origins, and many were sent to the front lines. This issue significantly decreased the number of experts available to work on a German bomb. Another problem was the lack of support from the government. Adolf Hitler was more obsessed with the long-range ballistic missiles called V-2; thus, the desperately needed resources were allocated to other priorities. Werner Heisenberg, a theoretical physicist, was working on the first German reactor but instead of using graphite as a moderator, he was focused on implementing heavy water. The heavy water powerplant called Vemork in Norway was the only plant for heavy water at that time, and due to the invasion in 1940, Heisenberg had full access to this chemical compound. However, the Germans had to rely on this Norwegian powerplant and later it became clear that heavy water was a less effective moderator than graphite. Furthermore, the Allies sabotaged the research with Operation Gunnerside on February 28, 1943, in which the Norwegian commando destroyed the facility (Powers, 1993).

By 1944, Niels Bohr escaped to the US together with secret documents about the Uranverein. Scientists at the Manhattan Project were relieved as it became clear that the Germans were nowhere close to controlled nuclear fission in a reactor let alone building a working atomic bomb. Furthermore, they had no method of enriching uranium, and never seriously considered plutonium as a viable substitute.

After the war, the US conducted Operation Paperclip where the objective was to smuggle scientists from the Nazi rocket industry, medicine, Uranverein, and chemical weapons divisions while preventing them from being captured by the Soviet Union. Many of them later worked in the Manhattan Project which became controversial as some of them were former members of the SS.

3.3.2 Soviet Atomic Program

Just like the Uranverein, the Soviet atomic program could not compare with the Manhattan Project during WWII. In 1940, only about twenty physicists and only a small number of staff were researching the controlled and uncontrolled chain reaction as well as separation methods of U-235. With the German invasion in 1941, the project almost stopped as the research facilities had to be moved from one location to another. After the Trinity and the outcome of Little Boy and Fat Man, Stalin fully supported the development of the atomic program and the project gained momentum. On August 29, 1949, the Soviets successfully tested their first nuclear device, called RDS-1. The power of the bomb was equivalent to the power of twenty-two kilotons of TNT, and it was overall very similar to the Fat Man dropped on Nagasaki (Nuclear Museum, 2014-b). With this information, it was clear that the secret information from the Manhattan Project was smuggled out. Security of the Manhattan Project was a very serious thing and it was successful in keeping secrets from Germany and Japan. However, the former ally – the Soviet Union – gained important information about the project via several spies that penetrated even the most secure places. Among the most famous spies was Klaus Fuchs, who provided crucial implosion bomb information from Los Alamos, and the husband-and-wife Julius and Ethel Rosenberg.

CONCLUSION

This bachelor’s thesis aimed to explore the technology of the first atomic bombs created as a result of the Manhattan Project. An incredible coordinated effort between science, government, and industry characterized this four-year operation and successfully achieved the desired results.

The first chapters cover the fundamental concepts of the first atomic bombs – fission and chain reaction. These discoveries started the race for the bomb and meant a first step towards the nuclear era. The project had changed from scientific to military and several technological fields gained momentum as several separation methods for uranium were explored. In the Y-12 facility, the uranium was enriched to the requested amount of percentage. However, the gaseous diffusion method was the most efficient in terms of power consumption and from all three became the only separation method during the Cold War Despite this, the effort to combine all methods has paid off and the US has gained a sufficient lead over other countries. Furthermore, the successful experiments with the first uranium reactors meant pivotal moments in nuclear energy that all of us benefited from. Plutonium, as a miss-product of the uranium chain reaction, became the first transuranic element which was subsequently used in the second atomic bomb.

The second chapter explores the secret laboratory in Los Alamos where the two detonation mechanisms were examined and tested. The gun-type mechanism that was essentially used in the first dropped atomic bomb – Little Boy – and the implosion method that was used in the plutonium bomb called Fat Man. These events marked pivotal moments in the course of human history. These destructive forces, born out of scientific innovation and strategic necessity, forever changed the geopolitical landscape and introduced a new era in warfare.

In the end, the German and Soviet atomic programs are mentioned. Despite its upper hand the German program couldn't keep the lead and ended up going in the wrong direction. The Soviet program was also no match for the Manhattan Project. However, after successful espionage, the Soviets obtained important information which they eventually used to the full and became the second nuclear power. At the very end is a discussion where the facts for and against the use of nuclear weapons in Japan are expressed. This ethical question divides humanity and yet shows that certain things are not wished upon even the worst enemies.

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