History and Science of the Manhattan Project

Spring 2023, Deep Springs College, Prof. **Brian Hill**

Overview

The Manhattan project is a chance to look simultaneously at the almost unbelievable scientific and technological developments which came in rapid succession just before, during, and after WWII, and at their historic consequences. The fundamental science begins in the late 1800s with the discovery of natural radioactivity (by Becquerel and the Curies), the development of controlled fission (Fermi's atomic pile), and the possibility of violent fission chain reactions. The history includes the race to make weapons based on fission, the destruction of two cities, and the setting of the stage for the superpower stalemate that has continued with slowly shifting characteristics decade-after-decade ever since.

A study of the Manhattan Project is not just an opportunity to study momentous scientific developments and past events. Its ongoing significance makes it nearly a duty to understand what we have collectively created. By the end of the course, each person will have their own response to the events and the resulting situation.

Unit Outline

Term 4 — Fundamental Physics and Atomic Technology

I. The Atom, and Basic Physics for Nuclear Fission

II. Discovery of Radioactivity

III. Physics Background needed for Chapter 2 of Reed on Controlled Fission (Enrico Fermi's Atomic Pile)

IV. Possibility of a Fission Bomb (A-Bomb)

V. The Race to Develop the Atomic Bomb

VI. Assembly of the Manhattan Project Scientists

VII. Creation and Refinement of Fissile Isotopes

Term 5 — Weapons Design and the Arms Race

VIII. Gun and Implosion Designs for Criticality

IX. Technology to Deliver a Bomb

X. The First Three Atomic Bombs: Trinity, Little Boy, and Fat Man

XI. The Destruction of Hiroshima and Nagasaki

XII. The Fusion Bomb (H-Bomb)

XIII. The Arms Race and The Beginning of the Cold War, Mutually Assured Destruction, Arms Control

XIV. Contemporary Problems and Analyses, Nuclear Proliferation, Nuclear Terrorism, Stability-Instability Paradox, Superpower Behavior

Primary Text (2nd Edition, 2019, Required)

- *The History and Science of the Manhattan Project, 2nd Edition,* 2019 by Bruce Cameron Reed on **Amazon** or **AbeBooks** (the 1st Edition is much different and not suitable for this class)

Other Resources

- *To Win A Nuclear War: The Pentagon's Secret War Plans*, Michio Kaku and Daniel Axelrod, Black Rose Books, 1987
- *Going Nuclear: Nuclear Proliferation and International Security in the 21st Century*, Ed. Michael E. Brown, Owen R. Coté Jr., Sean M. Lynn-Jones and Steven E. Miller, MIT Press, 2010

Grading

- A one-hour exam covering the science toward the end of Term 4, worth 25% of the grade. Homework problems on the science, 45%. A paper 1500-1800 words on a topic of your choice at the end of the second term, 10%. Consistent preparation for and participation in class discussion, 20%.

Miscellaneous Policies

There will be a lot of handouts. Get a three-ring binder to keep all the handouts and problem sets organized. Assignments should be on 8 1/2 x 11 paper (and not torn out from a bound notebook). Multi-page assignments should be stapled. Corrections should be erased (if done in pencil) or recopied (if done in pen). To make nice diagrams and graphs, you will often need a ruler.

The College's general policies on absences and late work are applicable. There was an email from the Dean on this September 8, 2022. The policies below are consistent with that email:

Whereas missed coursework affects both your classmates and professors by lowering the thinking and understanding you bring to a given class, and interrupts the course schedule that has been set up and is adjusted on an ongoing basis with substantial care. The same is true for absences — whereas a handful of absences might be "normal" at colleges with large lectures or less serious academics, at Deep Springs we expect students to miss *no classes* save for legitimate health issues or emergencies requiring also missing labor and governance obligations.

For a student wishing to submit a course assignment past its required deadline, the student may request an extension on the assignment directly from the professor 48 hours in advance. Within 48 hours of the due date, the student must request an extension directly from the Dean. Exceptions will be granted by the Dean only if the student faces unforeseen and unforeseeable circumstances. A student who misses the deadline will be penalized an amount that is roughly equivalent to a letter grade for each day the assignment is late. Assignments cannot be turned in after solutions and graded assignments have been passed back, which generally happens one to two classes after they were turned in.

Manhattan Project — Daily Schedule — Term 4

Week 1 — Discovery of Mysterious Radioactivity

- Preparation for Tuesday, Jan. 10 — Preface and Chapter 1 (Overview) from *The History and Science of the Manhattan Project, 2nd Edition*, 2019, by Bruce Cameron Reed
- Tuesday, Jan. 10 — Discussion of Preface and Chapter 1, particularly the reasons for studying the Manhattan Project at a semi-technical level, key dates in WWII (1939, 1941, and 1945) — First assignment, due Tuesday, Jan. 17 (see below) — Remainder of class, lecture on **Elements and Energy**
- Preparation for Friday, Jan. 13 — pp. 19-36 of Chapter 2 of *The History and Science of the Manhattan Project, 2nd Edition*, 2019, by Bruce Cameron Reed — Ignore Equations 2.1-2.8 on pp. 26-27. They are college sophomore math. I will be able to explain them to you. Maybe on Friday.
- Friday, Jan. 13 — We analyzed the overlapping discoveries and terminology of early nuclear chemists and early particle physicists: α particles, β rays, γ rays, electrons, and X-rays (two pairs in these five are arguably redundant) — We discussed the cathode ray tube (also known as the Crooke's tube) — We did an accurate, but without-calculus derivation of the fundamental exponential decay equations (equations (2.1)-(2.3)) — We did a naive definition of the mol, and then we discussed how isotopic abundance and the mass defect both force upon us a more precise definition of mol and N_A — We started using three hand-outs: **Isotope Table**, **Isotope Plot** Color-Coded by Decay Type, and the Binding Energy or **Mass Defect Plot** (and we will continue learning to use these handouts next time)

Week 2 — Investigation of the Atom and the Nucleus

- Preparation for Tuesday, Jan. 17 — Email me **Assignment 1 - Essay Draft** before class — Continue reading in Chapter 2 to p. 45 — The author's discussion of major discoveries has often been insufficiently detailed in terms of what the actual experiments were (as opposed to the experiment's results) — Therefore, individually research and prepare as follows: Trey, Crooke's Tube and Cathode rays (the electron); Brandon, Roentgen discovers X-rays; Anna, The Curies isolate polonium and radium; Mac, Aston discovers many isotopes with mass spectrometry — Say as much as you can and think is important in each of these discoveries, especially how the experiments were actually done (feel free to share handouts of materials that you consulted)
- Tuesday, Jan. 17 — Start **Assignment 2**
- Many questions queued up from presentations and Tuesday's reading.
- From presentations (these I have looked up the answers to):
  - Why do electrons come out of the cathode of a cathode ray tube when chemists say that the cathode is the electrode where electrons go into the battery? A: A single piece of wire has two ends. The end in the Crooke’s tube we call the cathode, because it emanates electrons. The other end of this same wire is the anode to the electrochemist because it is taking in electrons from the battery solution.
  - Does the cathode ray tube have to have phosphor on the glass to glow? A: No, the glass glows green even without phosphor.
  - Where did the Curies get the pitchblende (uraninite) form which they concentrated Polonium? A: From the Joachimasthal mine in Austria. (For more detail, **A Short History of Polonium and Radium** by Jean-Pierre Adloff is wonderful.)
  - Pierre Curie was killed in Paris in 1906 after falling under a carriage. Marie Curie and André Debierne isolated 0.1mg of polonium from uranium ores in 1910. How much ore did they Marie Curie and André Debierne start with before they isolated Polonium? A: Tons!
- From Tuesday's reading:
  - What is the positron? A: We did an extensive discussion of anti-particles and the observed fact that the universe is electrically neutral and has a preponderance of protons, neutrons, and electrons.
  - Why do atoms decay? Do all atoms decay? Why do some atoms decay faster than others? A: We went all the way down to the 1967 Glashow-Weinberg-Salam theory of the weak interactions
  - How can I make a radioisotope? What is alpha bombardment? A: We discussed the Joliot-Curie experiment where alpha particles from Polonium bombarded Beryllium?
  - What makes something choose to alpha decay vs. a beta decay? A: We discussed the Binding Energy or **Mass Defect Plot** and the **Isotope Plot**, and that Iron-56, Iron-58, and Nickel-62 are all very close to the sweet spot with the least mass per nucleon. Decays tend to move an isotope

toward the sweet spot. We looked carefully at Fig. 2.12.
    - The answer to the question above leaves the answer to the following question vague: Which of Iron or Nickel is actually the most tightly bound? A: This is advanced, but if you want, read this **StackExchange discussion** or read Section 2.5 of Reed carefully (most people should skip it)
- Preparation for Friday, Jan. 20 — At the beginning of class, turn in **Assignment 2** — **Assignment 2 Solution** — For reading, go to end of Section 2.2 (p. 60) but skip over the equations on p. 50 about the Coulomb barrier, which I will cover next week
- Friday, Jan. 20 — Finish first set of short presentations: we have done four, so that leaves Norah left to present Rutherford and collaborators discoveries that (a) the positive charges of an atom are concentrated in a tiny nucleus, and (b) that alpha particles are Helium nuclei — Worked through all the old and new questions queued up above — Finally, from today's reading we started into why the neutron is so effective as a particle for bombardment (Reed pp. 59-60), and next time we will go into detail on the Coulomb barrier

Week 3 — The Neutron is Discovered

Which completes the rough outline of nuclear physics and eliminates the Coulomb barrier

- Preparation for Tuesday, Jan. 24 — Reading: Finish Chapter 2 - Except skip the final section (Section 2.5)
- Tuesday, Jan. 24 — Norah did a detailed job of describing both: (a) The apparatus used by Rutherford to discover that the positive charge in a nucleus is concentrated at the center, and (2) The apparatus that Rutherford's associates used to discover that the alpha particle was the same as a Helium nucleus — We delved into spectroscopy enough to understand how spectroscopy was used to identify Helium (it is very hard to identify using chemical reactions, because noble gases, He, Ne, Kr, Ar, Xe, and Rn don't react — that's why they are called noble gases) — We went deep into understanding **The Coulomb Barrier** — We finished with Rutherford's declaration that making a chain reaction with protons is "talking moonshine" and Szilard's response that "pronouncements of experts that something cannot be done have always irritated me." — In 1934 Szilard even patents the idea that power and explosives can be created using chain reactions of neutrons (but because of the military potential, the patent is not published until 1949)
- Preparation for Friday, Jan. 27 — At the beginning of class, turn in **Assignment 3** — **Assignment 3 Solution** — Read through Section 3.1 of Reed — Bring questions from the Problem Set 2 solution that I distributed, and about Problem Set 3 that you are turning in, in addition to the new reading
- Friday, Jan. 27 — We applied energy and momentum conservation (and used both the relativistic formula for energy and momentum and the non-relativistic formula for energy and momentum in order to analyze the **Photon-Proton Collision** which was fundamental to hypothesizing the existence of the neutron — We also discussed cross-sections, the barn, and the meaning of the log-log graph in Fig. 2.27 before turning to the evidence for fission being found by the now-fragmented team of Meitner, Hahn, and Strassman, on December 17, 1938 (Hitler has already taken Austria and Meitner has fled to Holland)

Week 4 — Fission is Discovered

Which raises the possibility of fission chain reactions to make bombs and generate power

- Preparation for Tuesday, Jan. 31 — Continue Chapter 3, Reed Sections 3.2-3.6
- Tuesday, Jan. 31 — We had three presentations: (1) Trey: the timeline for the discovery of transuranic elements, especially plutonium, (2) Mac: possible explanations for rift between Hahn and Meitner, and (3) Norah: what are the primary ways that Uranium-235 fissions — Topics discussed following presentations: mass spectrometry (and explaining why it is analogous to spectroscopy), neutron-richness and instability of fission products, chemical similarities of elements and isotopes produced in fission to the more common elements that the body uses, the empirical Z/N stability pattern that strongly favors even Z and even N
- Preparation for Friday, Feb. 3 — Finish Chapter 3 (Reed Sections 3.7 and 3.8) — At the beginning of class, turn in **Assignment 4** — **Assignment 4 Solution** — For Friday, Mac will prepare a discussion of the most recently-discovered transuranic element, element number 118, the specific name and isotope being Oganesson-294, focusing on the technique and cost of production, the method of detection, and the half-life
- Friday, Feb. 3 — Hand out copies of each other's **mock journal entries** to read for Tuesday — Mac:

Element 118 presentation — Discussed droplet model of fission, including surface tension, typical units are MeV per square Fermi (1 Fermi = 1 femtometer = 10^{-15} — Pushed billiard ball dropping into a pocket analogy — Finished Chapter 3 — Frisch and Peierls have interesting biographies, as do Meitner, Hahn, and Strassmann (actually, most of these 1930s physicists have fascinating biographies) — Hand out supplementary articles on **Meitner and Frisch Conceive of Nuclear Fission**, **Portrait of Lise Meitner** and **Meitner's Escape from Germany** to Sweden

Week 5 — Manhattan Project Conceived

And the outlines of its administration emerge

- Preparation for Tuesday, Feb. 7 — Read each other's mock journal entries — Read the two handouts on Meitner from Friday — Read first half of Chapter 4 (4.1 to 4.6, pp. 125-153)
- Tuesday, Feb. 7 — Discussion of first half of Chapter 4 and readings
- Preparation for Friday, Feb. 10 — Read second half of Chapter 4 (4.7 to 4.11, pp. 153-179) — Short research topics (about 10 minutes, including questions): Norah, the thinking of Vannevar Bush and whatever skeptics you can find; Mac, what was China's role; Trey, why would Japan's leaders thought it was a strategically good idea to attack our naval base in Hawaii; Brian, Lise Meitner's living conditions at the time she was expelled from the KWG
- Friday, Feb. 10 — Discussion of remainder of Chapter 4 and readings continued — Discussion of conservation of energy and momentum problem on Assignment 4 — Presentations from Norah and Trey (Mac's presentation delayed to Tuesday)
- Sunday, Feb. 12 — of class, turn in **Assignment 5** — **Assignment 5 Solution**

Week 6 — Creation and Refinement of Fissile Isotopes — Part I, Uranium Enrichment

- Preparation for Tuesday, Feb. 14 — Study the pile program (the beginnings of nuclear reactors), pp. 183-198 of Chapter 5
- Tuesday, Feb. 14 — Mac's presentation on China's role in the war — Discussion of remainder of Chapter 4 — Discussion of pile program material in Chapter 5 — Drop by my place to see a piece of atomic pile
- Preparation for Friday, Feb. 17 — At the beginning of class, turn in **Assignment 6** — **Assignment 6 Solution** — Study the electromagnetic and gas diffusion programs pp. 199-222 of Chapter 5
- Friday, Feb. 17 — Mac's Presentation on CANDU reactors — The Y-12, K-25, and U-25 Enrichment Programs

Week 7 — Term 4 Exam — Shakespeare Festival

- Tuesday, Feb. 21 — **Term 4 Exam - FORTHCOMING** (open book and note)
- Friday, Feb. 24 — No class (due to Shakespeare festival)

Manhattan Project — Daily Schedule — Term 5

Week 8 (Mar. 12-18) — Creation and Refinement of Fissile Isotopes

- Preparation for Tuesday, Mar. 13 — Short Presentations: Trey, Experiments on animals and the beginnings of understanding radiation sickness; Brian, Thorium reactors; Mac, Diffusion membranes for clean water from seawater (as a way of learning more about gaseous diffusion) — Finish Chapter 5 (the thermal diffusion program), pp. 223-234
- Tuesday, Mar. 13 — **Midterm course evaluations** discussion and outcomes — Presentations from Trey and Brian — S-50 (thermal diffusion) discussion — Mean free path problem (Reed Problem 5.7)
- Preparation for Friday, Mar. 16 — Turn in **Assignment 7** — Short Presentations: Norah, Ruth Huddleston and what did the Calutron girls and other workers know; Trey, understanding medical ethics considerations for giving radioactive iron to pregnant mothers and radioactive iodine to babies (including dose and expected risk, informed consent, goals/benefits of these diagnostics and experiments, and the subsequent evolution of human subjects guidelines); Mac, Diffusion membranes for clean water from seawater (as a way of learning more about gaseous diffusion, assuming you are still interested in that subject); Mac 2, current status of Iran's U-235 and Pu-239 enrichment programs; Norah 2, economic sanctions and military threats and attacks on Iran to try to deter their nuclear program, including attacks on the gas centrifuges and the nuclear scientists — Go through Chapter 6 (the Hanford nuclear reactors), to p. 263 — For my (Brian's) contribution to the discussion of Sections 6.1 to 6.5, I will try to synthesize what we know about Hanford's reactor operation in terms of fundamental phenomenological facts including nuclear cross-sections for absorption, scattering, and fission, abundances, power generation, and energy per fission
- Friday, Mar. 16 — Turned in **Problem Set 7** — **Problem Set 7 Solution** and presentation from Trey (human subjects testing) — The layout of the Hanford complex near the convergence of the Columbia, the Yakima, and the Snake rivers — The problem of waste heat — The need for power — — The surprising 3,000,000 barn cross-section of Xenon

Week 9 (Mar. 19-25) — Finish Hanford Reactor Complex — Begin Los Alamos

- Preparation for Tuesday, Mar. 20 — Short Presentations: Trey, the current status of spent fuel rod and other nuclear waste disposal at Yucca Mountain; Mac, the current status of groundwater contamination at Hanford — Finish reading Chapter 6 (the Hanford reactors) Sections 6.6 and 6.7, and begin reading Chapter 7 (Los Alamos) through 7.3, p. 286
- Tuesday, Mar. 20 —
- Preparation for Friday, Mar. 23 — Continue reading Chapter 7 through Section 7.7.2, p. 312 — Prepare to discuss or present a solution of Problem 7.4 on p. 376 (which is directly related to the fizzle problem) — Look at my copy of Richard Rhodes, *The Making of the Atomic Bomb,* and decide if you want to read selections from it (I filed my copy on the library shelves at call number 539.71) — You have hard-copy ***Los Alamos from Below*** by Richard Feynman that you can get started on, but I am not imagining that we discuss it until Tuesday, Mar. 27 — Here is soft-copy of ***The Los Alamos Primer*** in case you are curious what scientists arriving at the project were given as a starting point
- Friday, Mar. 23 — Approximations for computing annuli volumes — How half-lives for different decay modes combine — Mean free paths — Causes of premature detonation in U-235 (mostly alpha decays and impurities) — Causes of premature detonation in Pu-239 (mostly spontaneous fissions of Pu-240)

Week 10 — Diffusion Theory Results — The Implosion Bomb

- Preparation for Tuesday, Mar. 27 — Continue reading Chapter 7 to the start of Section 7.11 (through p. 326) — Pick a chapter (or two!) from the Richard Rhodes classic (I filed my copy on the library shelves at call number 539.71) — Finish ***Los Alamos from Below*** by Richard Feynman
- Tuesday, Mar. 27 — Continue discussion of mean free paths and the formulae for critical mass
- Preparation for Friday, Mar. 30 — Finish Chapter 7 (but not the optional section on other fissile materials)
- Friday, Mar. 30 — Trey takes us further into **random walks (only go as far as the blue plot that looks like a downward-opening parabola)** — Random walks and transport theory, in a material that is expanding due to the pressure increase of the liberated energy is what the neutrons are doing as they scatter and cause additional fissions — Mac takes us further into nuclear proliferation in South Africa

and former Soviet Union states — I would like to watch a several minutes of **lecture version by Feynman of *Los Alamos from Below*** (we start with some levity about the stuck valves, and then where he recounts the beginnings of the entire field of computational physics)

Week 11 — Bombing and Aftermath of Hiroshima and Nagasaki

- Preparation for Tuesday, Apr. 4 — Continue in Reed through Section 8.3 — Instead of presentations on distinct topics, Trey and Mac will take opposing sides on the same issue: Trey will argue that using atomic bombs on two cities was inhumane and unjustified, because the war in the Pacific was already near an end; Mac will argue that the use of two atomic bombs was in fact decisive and that Truman's primary duty, both on moral grounds and as Commander in Chief was to swiftly end the war — My understanding of the status of the war in the Pacific tilts me toward the latter position, but the more time that goes by, the more people are lining up on the side that using an atomic bomb on a city under any circumstances is an atrocity, so it is certainly the case that both sides of this issue can be compellingly argued, at least with nearly eighty years of hindsight
- Preparation for Friday, Apr. 7 — Finish Reed Chapter 8 — As Problem Set 8, read and do the **three problems** at the end of Reed's **CP1 Pile Analysis** — Note that Reed did not give the formula for n = (1 + m)/(1/n_fuel+m/n_mod) because for large m it is awfully close to just n_mod — A **Problem Set 8 Solution Screenshots**

Week 12 — The German Nuclear Program — Postwar Developments (H-Bomb, Nuclear Stockpiles, Arms Limitation Treaties)

- Preparation for Tuesday, Apr. 11 — Read the entirety of Reed Chapter 9 — Presentations: Trey, destruction of German heavy-water facility (Operation Gunnerside); Mac, sinking of the Norwegian ship *Hydro*; Brian, Germany's contaminated moderator problem
- Preparation for Friday, Apr. 14 — **Problem Set 9** — Study the remainder of Reed (the entirety of Chapter 10)

Week 13 — Contemporary Analyses

- Preparation for Tuesday, Apr. 18 — The Rise and Fall of the South African Bomb by Peter Liberman — Nuclear Stability in South Asia by Sumit Ganguly — Ten Years of Instability in a Nuclear South Asia by S. Paul Kapur
- Preparation for Friday, Apr. 21 — Nuclear Terrorism — Israel and Iran

Week 14 — Contemporary Analyses (Continued)

- Preparation for Tuesday, Apr. 25 — Mutually Assured Desctruction vs. CNE (coercive nuclear escalation) aka escalation dominance
- Tuesday, Apr. 25 — Stability-Instability Paradox discussion — Expansionism and defense of spheres of influence discussion
- Preparation for Friday, Apr. 28 — Mutually Assured Destruction vs. CNE (continued) — Taiwan as a possible flashpoint — **Problem Set 10**
- Friday, Apr. 28 — Final paper discussion prior to submission — Discussion of Stability-Instability Paradox (continued) — Taiwan as a possible flashpoint