Project Suggestions:

Using Einstein's equation $E=mc^2$, calculate the loss of mass in a fission reaction which would release 200 million electron volts. How does this mass defect compare with the mass of a single neutron? (You will need to use a physics reference book to obtain the necessary values. Be careful that your units are consistent.) If a critical mass of thirty kilograms of U^{235} were to undergo complete fission, how much mass would be converted into energy and how much energy would be produced?

Issue #3: Nuclear Cross Sections, Capture, and Fission

Since nuclei are very small in comparison with the spaces between them, free neutrons usually pass through these spaces without being affected. A free neutron that passes near a nucleus may be affected in one of three ways. First, it may transfer some of its kinetic energy to the nucleus and thus "slow down." No change in the composition of the nucleus occurs in this case. Second, it may be "captured" by the nucleus, resulting in the formation of an isotope of higher atomic mass. Third, it may react with the nucleus, causing the nucleus to become unstable and to split into two smaller nuclei. Simultaneously, energy and additional neutrons are emitted. This is called fission.

The probability that a nucleus will undergo a nuclear reaction when a small particle, typically a neutron, passes near it depends on two factors: the energy of the approaching neutron and its distance of approach. A measure of the probability that a nuclear reaction will occur with a neutron having a given energy is called the cross section. There is a significant difference between the cross section values for fission and capture. Calculating these values was the most important early experimental work done by the physicists working on the bomb.

Project Suggestions:

Using a physics reference book, look up the cross sections for U^{235} and U^{238} for neutron capture and for fission. What is a "barn"?

Issue #4: Piles and Bombs, Moderators and Tampers

While both nuclear "piles" (reactors) and atomic bombs derive their energy from self-sustaining nuclear chain reactions, there is a fundamental difference between the two processes. In a nuclear pile, the rate of the chain reaction is controlled to produce a steady release of energy primarily in the form of heat. This heat energy is absorbed by circulating water under pressure. The heat transforms the water into steam, which, in turn, drives generators that produce electricity. While Fermi used natural uranium containing less than 1 percent of fissionable U^{235} in his first pile, most reactors now use enriched fuel in which the concentration of fissionable material has been increased for efficiency. Since the neutrons produced by fission in a pile often have too much kinetic energy to react with other fissionable nuclei before they are captured by non-fissionable nuclei, they must be slowed down considerably. A moderator such as heavy water or graphite is often used. Deuterium and carbon nuclei have low cross sections for neutron capture but are both very effective in slowing down the fast neutrons and consequently absorbing much of their energy. Once the neutrons are moving at a slower pace, they are more likely to continue the chain reaction. (Ordinary water is not as effective a moderator since the hydrogen nuclei are likely to capture the neutrons and be transformed into deuterium nuclei.) If the density of slow neutrons becomes too high, a control rod is lowered which captures many of the free neutrons and slows down the reaction rate, thus ensuring a steady generation of energy.

In contrast, the chain reaction in a nuclear bomb must occur as rapidly as possible to ensure a maximum release of energy before the heat generated melts the apparatus, thus causing expansion and a loss of critical mass. To achieve this, the fuel must be highly concentrated fissionable material (80 percent or more usually) and the fast neutrons released must be reflected back into the critical mass until they cause other nuclei to undergo fission. Since the neutrons may be traveling at more than 10 percent the speed of light, the chain reaction occurs in less than a microsecond. The material encasing the critical mass, called the tamper, must be able to reflect the neutrons effectively. Natural uranium is an effective tamper and a thick shell of it was used to surround the critical masses of U^{235} (about 25 kilograms at 80 percent purity) and Pu^{239} (about 5 kilograms) in the "Trinity," "Little Boy," and "Fat Man" bombs. This thick shell also retarded the thermal expansion which could have brought the chain reaction to an end before most of the fissionable material had reacted. Even with the use of a tamper, the early bombs released considerably less than 50 percent of their theoretical yield.

Project Suggestions:

Explain why a nuclear pile gone out of control cannot produce a nuclear explosion and why the energy released by atomic bombs is far below their theoretical yield.

Issue #5: Diffusion in Detail

The most expensive and technologically difficult aspect of the Manhattan Project was the separation of the isotopes of uranium. Natural uranium contains only 0.7 percent of the fissionable U^{235} isotope. For an atomic bomb, the Los Alamos team needed a fuel that was at least 80 percent U^{235}. Of the two methods employed—ion beam separation using calutrons and gaseous diffusion—the latter was the most successful, though it was still difficult. While simple in theory, gaseous diffusion presented many frustrating obstacles in practice. First, the natural uranium mixture had to be converted into a gas. Fluorine gas is one of the few substances that reacts with uranium to form a gas—uranium hexafluoride. Unfortunately, UF_6, or "hex" as it was called, is extremely corrosive, attacking all common organic oils and greases, and most metals. Consequently, a huge gaseous diffusion mechanism had to be made from nickel with pump seals that could be kept tight without using conventional greases. The plastic developed specifically for these pumps, polytetrafluoroethylene, became widely used after the war and marketed under the brand name "Teflon." Second, U^{235} enrichment through diffusion requires many repeated steps.

Project Suggestions:

Applying a few basic chemical principles will help you understand the process of gaseous diffusion. In a gas mixture, the average kinetic energy per gas molecule depends only on the temperature of the mixture. Show that the ratio of the velocities of the lighter and faster $U^{235}F_6$ molecules to the heavier and slower $U^{238}F_6$ molecules is 1.0043.

Since in a single stage of diffusion the maximum separation factor is equal to this ratio, after one diffusion process the concentration of U^{235} can be increased by no more than 0.43 percent. Calculate how many successive diffusion stages will be required to enrich the mixture to 80 percent U^{235}. (Hint: the U^{238} content must be reduced from 99.3 percent [0.993] to 20 percent [0.20]. After the first stage, the concentration is reduced to 0.993/1.0043. The method for solving this problem is similar to that used in solving compound interest problems.)

In practice, because of reverse diffusion and less than ideal conditions, several thousand stages of diffusion were required. The technical name for an apparatus containing many successive diffusion stages is a cascade. Now you can appreciate the technological problems associated with producing kilograms of 80 percent U^{235}. Why is the production of 100 percent pure U^{235} not possible with the diffusion method?

Issue #6: The Implosion Process

The most difficult mathematical problems associated with building "Fat Man" were encountered in designing the precisely shaped explosives and timing sequences necessary to produce implosion in the plutonium bomb. A simple model will help you understand the complexities of this problem.

Imagine that you want to squash a grapefruit inward so that the density of the grapefruit is increased without any of the grapefruit oozing out. To generate the inward force, you design explosive charges. Think of them as little people with large hammers. At your command, these people will simultaneously smash the grapefruit with equal force, thus generating shock waves directed toward the center of the grapefruit. As you have by now imagined, the initial shock waves will cause some of the grapefruit to ooze out at the boundaries of adjacent shock waves. To prevent this, you will need another group of little people with large hammers positioned at these boundaries with instructions to smash the grapefruit a microsecond after the first group. Of course, there will now be other boundary areas where the grapefruit may ooze out. Therefore, you will need a third team of little people, and a fourth team, and so on to achieve symmetrical inward compression.

The configuration of shaped explosives in "Fat Man" was called a "lens" because the shock waves were successively focused into the center, instead of being allowed to diverge as shock waves normally do. This design and the electronic circuitry necessary for the timing were and remain today the most closely guarded secrets related to the construction of the atomic bomb. The government's case against Julius and Ethel Rosenberg for atomic espionage involved allegations that they had passed the lens design to Soviet agents. In fact, the Soviets received far more useful information from Klaus Fuchs, a top scientist on the Los Alamos team, than they did from David Greenglass, an Army machinist who was Ethel Rosenberg's younger brother.

While most scholars today believe that the Rosenbergs were involved in espionage, many argue that their trial was unfair. In contrast, Fuchs admitted his guilt when confronted with the evidence. As a British citizen, he was tried in Britain and served a prison term there before being released.

Project Suggestions:

The Rosenberg case still generates controversy today. Research the scientific evidence used in the trial and the manner in which the trial was conducted.

Issue #7: Radioactive Decay and the Tunnel Effect

The fission process is quite easy to visualize in an elementary sense. A high-energy particle smashes into a cluster of tightly bound particles and breaks the bonds holding them together. Fragments result, and some of these fragments continue the fission process with other nuclei.

Radioactive decay, however, runs counter to common sense and is very difficult to comprehend. Why should a nucleus suddenly, for no apparent reason and with no external prodding, break apart? This phenomenon cannot be understood using classical, Newtonian mechanics and can be explained only with the help of quantum mechanics. A simple model will help you understand the process better.

Imagine a teacup glued to the top of a flagpole. Inside the teacup is a marble rolling around. The marble does not have enough kinetic energy to roll up over the rim of the cup. According to classical mechanics, the marble will stay forever confined within the teacup. The marble in our model represents an alpha or beta particle bound tightly within the nucleus. It does not have the energy to break these bonds, represented by the height of the sides of the cup. It is trapped within an energy well.

Quantum mechanics, however, offers a different way of looking at the model. According to quantum mechanics, subatomic particles cannot be located precisely at a point. Instead, they are described as occupying a wave-like probability distribution curve, looking somewhat like a common sine curve. The tail end of the wave actually extends ever so slightly beyond the finite walls of the teacup, or energy well. At any given moment, there is a tiny probability that the marble will appear outside the walls of the cup and fall to the ground with a large amount of energy. The marble, or alpha particle, does not roll over the rim. That would be impossible. Rather, it tunnels through the walls. This is called the tunnel effect. While there is no way to predict when a particular alpha particle will tunnel through, with a large number of nuclei you can approximate statistically how many nuclei will undergo radioactive decay within a given time period.

Project Suggestions:

The tunnel effect is observable only with subatomic particles. Thus, watching a marble roll around in a teacup is not the best use of your time to deepen your understanding of the phenomenon. Instead, research how archeologists use the radioactive decay of the carbon-14 (C^{14}) isotope to determine the age of organic artifacts, or research how physicians use radioactive isotopes of iodine and barium to study biological processes within a patient.

Issue #8: Designing the Super Bomb

The so-called "super bomb" conceived by Edward Teller and Stanislaw Ulam is based on fusion—a type of nuclear reaction that is completely different from the fission reactions of "Little Boy" and "Fat Man." At extremely high temperatures, some nuclei with low atomic weights have the kinetic energy to overcome their mutual electrostatic repulsion and collide with enough energy to break the bonds which hold their nuclei together and thus form new nuclei. Typically, these reactions involve isotopes of hydrogen or lithium. The mass defect, or conversion of some of the initial nuclear masses into energy, generates tremendous amounts of energy. Most of the energy released by the sun is generated by nuclear fusion reactions. Below are descriptions of some common fusion reactions, with the energy released expressed in terms of millions of electron volts (MeV):

$$D + D \rightarrow He^3 + n^o + 3.25\ \text{MeV}$$

$$D + D \rightarrow T^3 + p^+ + 4.0\ \text{MeV}$$

$$T + D \rightarrow He^4 + n^o + 17.6\ \text{MeV}$$

$$He^3 + D \rightarrow He^4 + p^+ + 18.3\ \text{MeV}$$

$$Li^6 + D \rightarrow 2He^4 + 22.4\ \text{MeV}$$

$$Li^7 + p^+ \rightarrow 2He^4 + 17.3\ \text{MeV}$$

The two isotopes of hydrogen, deuterium (D) and tritium (T), which can fuel such reactions are actually easier to obtain than fission fuel. Since fusion reactions only take place at very high temperatures, a large mass of fusionable material can be assembled without any danger that a critical mass may set off a spontaneous chain reaction. Theoretically, scientists could build a fusion bomb of almost infinite power. The largest fusion bomb tested so far yielded the equivalent of 60 megatons of TNT (4,800 times more powerful than "Little Boy").

To generate the high temperatures required to initiate a fusion reaction, a fission device is exploded. Scientists working on the fusion, or hydrogen, bomb in the late 1940s and early 1950s, however, faced a design problem similar to the one encountered in the design of the implosion fission bomb. Enough energy from the explosion of a fission bomb needed to be transferred to the fusionable material before the shock wave produced by the fission explosion blew everything apart. The problem, which involved high temperature plasma physics, was the principal obstacle to building the "super bomb." Many scientists, including Robert Oppenheimer, initially believed that the problem could not be solved.

Project Suggestions:

Research the development of the fusion bomb, especially the theoretical breakthroughs that allowed scientists first in the United States and then in the Soviet Union to trigger a fusion reaction with a fission explosion. *The Making of the Atomic Bomb*, written by Richard Rhodes, offers a readable history of the fusion bomb project.