# ATOMIC ALCHEMY

by Gordon Edwards

## Transmutation

For centuries, the transmutation of elements was an obsession for alchemists searching avidly for the "philosopher's stone" – a legendary substance that could transmute lead into gold. Such a discovery would confer unlimited wealth.

That dream faded with the emergence of modern science. Experiments demonstrated that elements are unique and distinct, their atoms the immutable building blocks of matter. Elements have permanence. Transmutation is superstition.

The periodic table was published in 1869, listing all known elements – from the lightest, hydrogen, to the heaviest, uranium. Elements combine to form chemical compounds, but there are exceptions. Noble gases like helium, neon and argon form no compounds, so they cannot be released by any chemical reaction.

By 1900, transmutation was thoroughly discredited – until one day in 1901, at McGill University in Montreal. On that day, the soon-to-be famous chemists Ernest Rutherford and Frederick Soddy witnessed a seemingly miraculous event in the laboratory: the spontaneous emanation of a noble gas, thoron, from a metallic element, thorium.  It was like black magic.

Where was the thoron gas coming from? It wasn't there before – not as an element, certainly not as a compound. It seemed impossible. Are thorium atoms changing into thoron atoms?

"Rutherford, this is transmutation!" said Soddy. "For Mike's sake, Soddy, don't call it transmutation. They'll have our heads off as alchemists," Rutherford shot back. Yet the pair had stumbled across an astonishing aspect of the new science of radioactivity. When a radioactive atom like thorium disintegrates, it is transmuted into a completely different kind of atom, associated with an entirely different element.

Transmutation is a fact.

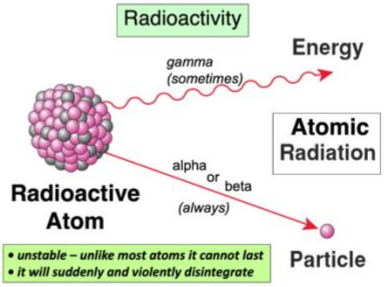
## Radioactivity

Radioactivity was discovered in 1896 by Henri Becquerel. He noticed that any rock containing uranium or thorium gives off penetrating energy – enough to expose a photographic plate, even one wrapped in thick black paper. He was astonished that a mere rock could be a source of energy. In fact, the energy release continues unabated for weeks, months, years. There is no way to turn it off or slow it down.

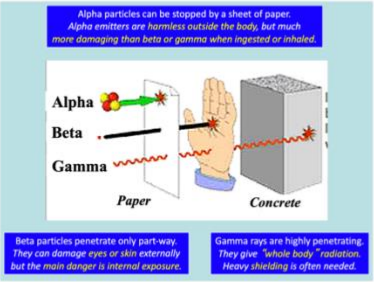
Marie Curie was excited by this discovery. She coined the word "radioactivity" to describe the phenomenon. Using her skill as a chemist, she crushed uranium ore by hand and carefully stripped out the uranium. She found that the crushed rock was far more radioactive than uranium. She guessed there must be other radioactive elements in the residues. By 1898 she had discovered two brand new elements, both very radioactive. She named them "polonium" and "radium". She had no idea where they came from.

Rutherford's work at McGill dispelled the mystery. It was radioactive transmutation. Just as thoron atoms started out as thorium atoms, the radium and polonium atoms found by Marie Curie must have started out as uranium atoms. Lesson learned: radioactive atoms routinely transmute themselves into new kinds of atoms.

Upon arrival in Canada in 1899, Rutherford discovered that radioactive atoms emit two kinds of electrically charged projectiles. He called them "alpha" and "beta" particles. Sometimes a penetrating burst of electromagnetic energy is also emitted – similar to an X-ray, but more powerful. It was later called a "gamma" ray as a tribute to Rutherford's work.



- *unstable – unlike most atoms it cannot last*
- *it will suddenly and violently disintegrate*



Alpha particles can be stopped by a sheet of paper.
*Alpha emitters are harmless outside the body, but much more damaging than beta or gamma when ingested or inhaled.*

Beta particles penetrate only part-way.
*They can damage eyes or skin externally but the main danger is internal exposure.*

Gamma rays are highly penetrating.
*They give "whole body" radiation. Heavy shielding is often needed.*

Because subatomic projectiles – alpha or beta particles – are emitted when radioactive atoms disintegrate, it follows that any disintegrating atom is fundamentally altered by losing a part of itself. That's how it becomes a new kind of atom.

Rutherford and Soddy discovered that every radioactive element has its own characteristic "half-life" – the time it takes for half of its atoms to disintegrate. Half-lives differ widely. Thorium has a half-life of 14 billion years, whereas thoron's half-life is only 55.6 seconds. Uranium's half-life is 4.5 billion years, whereas radium and polonium have half-lives of 1620 years and 138 days respectively.

In 1903 Rutherford and Soddy, still at McGill, calculated the amount of energy given off by the disintegration of a radium atom. It is "twenty thousand times, and may be a million times as great" as the energy released by the most powerful chemical reactions.

By the time all the atoms in a single gram of radium have disintegrated, the sum total of the energy released is staggering. Soddy quipped "that, could a proper detonator be found, it was just conceivable that a wave of atomic disintegration might be started through matter, which would indeed make this old world vanish in smoke."

To his dying day, Rutherford did not believe such earth-shattering destruction was achievable. He knew it would take over a thousand years for half of the radium atoms to disintegrate. Radioactivity cannot be speeded up.

Little did he know that a subatomic particle called a “neutron”, which he predicted but never observed, would prove to be the “detonator” needed to unleash atomic Armageddon. Nor could he know that a human-made element called plutonium – a derivative of uranium, created by transmutation – would be the ideal explosive for such a nightmarish scenario.

His five years at McGill earned Rutherford a Nobel Prize in Chemistry. His brilliant scientific work laid bare the secrets of radioactivity. Becquerel and Soddy also won Nobel prizes – one in Physics, the other in Chemistry. Marie Curie won two Nobel prizes, one in Physics, that was shared with husband Pierre, and one in Chemistry.

The international unit of radioactivity is the Becquerel: one Becquerel equals one atomic disintegration per second. An older unit is the Curie. One Curie equals 37 billion Becquerels – it represents the radioactivity of one gram of pure radium.

## The Atomic Nucleus

Back in England, Rutherford discovered that every atom has a tiny but very dense nucleus.

He aimed alpha particles at an extremely thin sheet of gold foil. Most of them passed right through, as if there was nothing there. Only a few – one in twenty thousand – were deflected through very sharp angles. Evidently, they collided with something immovable and ricocheted off. Some of them even rebounded back toward the source.

“It was quite the most incredible event that has ever happened to me in my life,” he wrote. “It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”

This experiment showed that atoms are mostly empty space. The entire mass of the atom is compressed into an unimaginably tiny volume. Only a few alpha particles chanced to hit that elusive target – the atomic nucleus – and were deflected.

We now know that the atoms of different elements have differing nuclei. It follows that the transmutation of elements cannot occur unless the atomic nucleus of one is somehow altered.

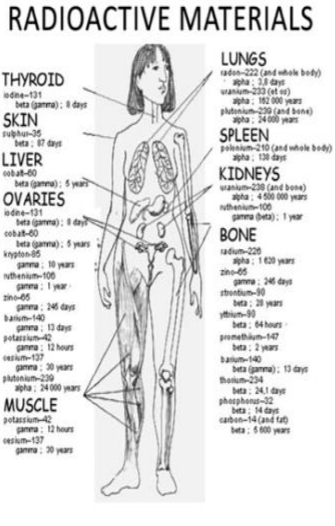
Most elements are stable and eternal precisely because the atomic nucleus never changes. But a radioactive element is transitory. Its atoms have unstable nuclei. Such a nucleus will eventually disintegrate, throwing off subatomic "shrapnel" in the form of an alpha or beta particle. At that instant the nucleus is changed. It now corresponds to a different element. Those high-energy projectiles coming from the nucleus indicate that the nucleus is a reservoir of boundless energy. It is called "nuclear energy"

## Orbital Electrons

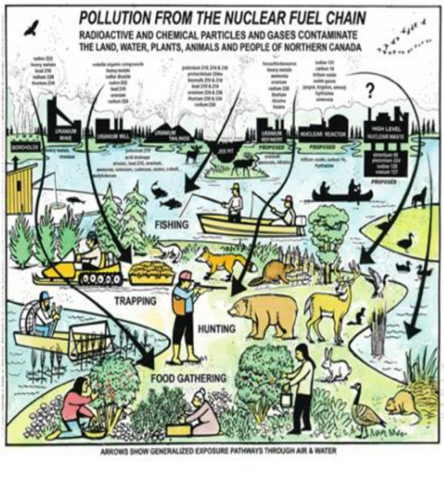
Niels Bohr, the Danish physicist, complemented Rutherford's picture of the atom. He showed that the nucleus is surrounded by orbiting electrons, each having far less mass than the nucleus. The atom was seen as analogous to a miniature solar system with a diameter hundreds of times greater than the nucleus at the centre. Orbital electrons from one atom can be exchanged or shared with those of other atoms to form molecules – chemical compounds. The nuclei are unaffected. Conversely, nuclear energy comes directly from the nucleus; it does not involve the orbital electrons.

During Rutherford's lifetime, radioactivity was the only manifestation of nuclear energy accessible to humans. It was already clear, however, that one of the smallest objects in the universe– the atomic nucleus – embodies the most powerful forces ever encountered.

Painful episodes soon revealed that radioactive emissions are harmful to living cells. Large exposures over short time periods cause radiation burns, radiation sickness or even death. Prolonged exposures at lower levels can cause cancer or damage the gene pool. To protect humans and other creatures, radioactive materials must be carefully handled at all times and kept out of the environment of living things.



RADIOACTIVE MATERIALS



POLLUTION FROM THE NUCLEAR FUEL CHAIN

RADIOACTIVE AND CHEMICAL PARTICLES AND GASES CONTAMINATE THE LAND, WATER, PLANTS, ANIMALS AND PEOPLE OF NORTHERN CANADA

ARROWS SHOW GENERALIZED EXPOSURE PATHWAYS THROUGH AIR & WATER

### Artificial Transmutation

Uranium, thorium, and their radioactive by-products are naturally occurring radioactive materials (NORM). They undergo spontaneous transmutation when their atoms disintegrate. An obvious question arises – can elements be transmuted by human effort?

Radioactivity alters the nucleus by removing something. Perhaps the nucleus can also be changed by adding something. Rutherford rose to the challenge.

In 1919, he transformed nitrogen atoms into a rare variety of oxygen atoms, thus becoming "the first successful alchemist in history." He did this by bombarding nitrogen atoms with alpha particles from a radium source. As a bonus, he discovered the proton – a positively charged particle that was thrown off. A proton is identical to the nucleus of a hydrogen atom.

Here's what happened. The nitrogen nucleus bonded with the incoming alpha particle, instantly transforming itself into an oxygen nucleus, and simultaneously spitting out a proton.

Two lessons emerged: (1) transmutation is do-able even without radioactivity; (2) protons are basic constituents of heavier nuclei.

The number of protons in any atomic nucleus –the "atomic number" –determines what element the atom represents. The positive charge of the nucleus gets steadily greater as the atomic number increases, from the first element, hydrogen, to the ninety-second element, uranium. Because positive charges repel each other, a positively charged alpha particle cannot reach a nucleus that has a great many protons. The repulsive force is too strong. It doesn't matter how fast the incoming alpha particle is travelling.

Soddy had previously observed that one element can have atoms with different atomic masses. For example, ordinary oxygen atoms have an atomic mass of 16, whereas the rare oxygen atoms created by Rutherford have an atomic mass of 17. Soddy called these distinct varieties of the same element "isotopes". For example, oxygen-17 and oxygen-16 are two different isotopes of oxygen. Almost identical chemically, they both behave the same way.

Since all oxygen atoms have the same number of protons, Rutherford speculated that there must be an uncharged particle, about the same size as a proton, to account for the difference in mass.

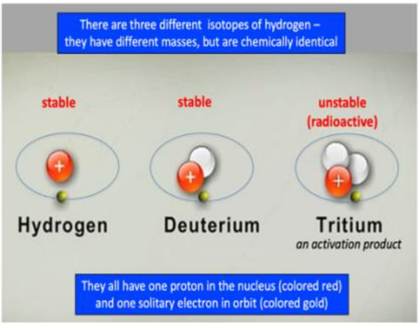
### The Neutron

In 1932, Rutherford's student James Chadwick discovered that neutral particle. He called it a "neutron". As predicted, it had almost exactly the same mass as a proton. Chadwick learned that when a beryllium nucleus bonds with an alpha particle, it changes into a carbon nucleus and spits out a neutron. The neutron, like the proton, must be a basic constituent of the atomic nucleus.

The secret was out. Beryllium metal, paired with an alpha-emitter, is a "neutron initiator". Later, that combo would be useful as a triggering device in the world's first atomic bombs. The picture was now complete: an atomic nucleus is made of protons and neutrons. The atomic number – the number of protons – tells you what chemical element you have. The number of neutrons is variable, giving rise to various "isotopes" of that same element.

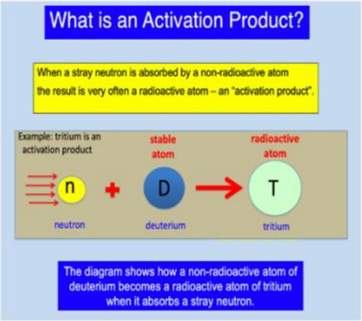
The number of protons plus the number of neutrons is the "mass number". It is often attached to the name of the element to make it clear which isotope is being discussed. Different isotopes have different nuclear characteristics. In the case of a radioactive element, each isotope has a different half-life. For example, polonium-210 has a half-life of 138 days, and polonium-218 has a half-life of only 3 minutes.

Some elements have both radioactive and non-radioactive isotopes. For instance, hydrogen-1 (protium) and hydrogen-2 (deuterium) are both non-radioactive, but hydrogen-3 (tritium) is radioactive with a half-life of 12.3 years. (They all have only one proton.)



There are three different isotopes of hydrogen – they have different masses, but are chemically identical

They all have one proton in the nucleus (colored red) and one solitary electron in orbit (colored gold)



What is an Activation Product?

When a stray neutron is absorbed by a non-radioactive atom the result is very often a radioactive atom – an "activation product".

The diagram shows how a non-radioactive atom of deuterium becomes a radioactive atom of tritium when it absorbs a stray neutron.

In 1934, Marie Curie's daughter Irène and her husband Frédéric Joliot created the first artificial radioactive element – phosphorus-30, a beta-emitter. They used alpha particles to bombard non-radioactive aluminium atoms. When the stable aluminium nucleus bonds with an alpha particle it is transmuted into a radioactive phosphorus isotope.

The neutron became the tool of choice for provoking artificial transmutations. Since it has no charge, the neutron is not repulsed from the positively charged nucleus the way an alpha particle is. And when a nucleus bonds with an incoming neutron, it is often destabilized and undergoes transmutation. In this way, non-radioactive deuterium atoms become weakly radioactive tritium atoms, and non-radioactive cobalt-59 becomes intensely radioactive cobalt-60 – a powerful gamma-emitter.

From 1934, Enrico Fermi in Rome used neutrons as the ideal tool to transmute elements. No matter how fast a neutron travelling, it can bond with any nucleus of any size. Fermi found slow neutrons to be more effective than fast neutrons – more likely to bond – so he passed his neutrons through a block of paraffin to slow them down. Thus he created many previously unknown isotopes not observed in nature, by bombarding various atoms with neutrons and transmuting their nuclei. In the end, he irradiated virtually every element in the periodic table with neutrons.

The heaviest atom in the table was uranium, so Fermi tried to create new, man-made, heavier-than-uranium atoms by bombarding uranium with neutrons. He announced that he had created two new "transuranic" elements, which he called ausonium and hesperium, but made little fuss about it. Some disputed his claim. When he received the Nobel Prize in 1938 there was no mention of the controversy. Those two transuranic elements are now known as "neptunium" and "plutonium".

## Nuclear Fission

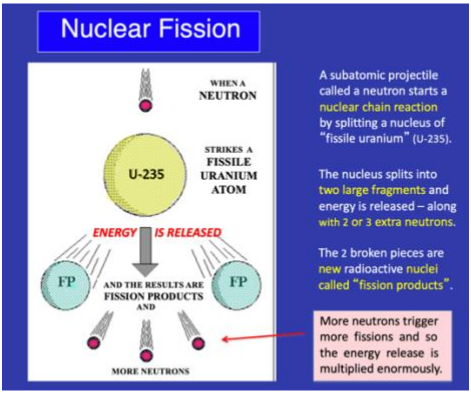
Shortly after Fermi's Nobel award, two chemists in Berlin, Otto Hahn and Fritz Strassman, aimed neutrons at a uranium target during a Christmas holiday. They expected to produce large, heavy atoms like uranium itself – perhaps those transuranic elements that Fermi mentioned. But no. They were perplexed to find elements with much smaller and lighter atoms. They could not fathom how such elements could have been created. Hahn wrote to his long-standing physicist colleague, Lise Meitner, asking for help. She had fled from Berlin to Stockholm in July to avoid Nazi persecution because of her Jewish heritage. When Hahn's letter arrived, her nephew Otto Frisch was visiting her from Copenhagen. He was a young physicist then working with Niels Bohr in Denmark.

Lise and her nephew Otto "went for a walk in the snow to talk it over, he on skis and she on foot. They stopped at a tree stump to do some calculations." Meitner suggested they think of the uranium nucleus as a heavy liquid, a model previously proposed by Bohr. The uranium nucleus might, "like a water drop, become elongated, then start to pinch in the middle, and finally split into two drops." These fragments would be two new nuclei, both much smaller than the original. That would explain the odd results that Hahn and Strassman had observed.

Frisch named the newly conceived process "nuclear fission" after learning that the term "binary fission" was used by biologists to describe cell division. Meitner and Frisch sent their results for publication in *Nature* in January 1939.  They calculated that each fission event would release about 200 million electron-volts of energy. That's 40 to 100,000 times greater than the energy released by any radioactive disintegration event.

Hahn and Strassman published their findings separately but failed to acknowledge Meitner's key perceptions. In their second publication in February, they used the term *Uranspaltung* [uranium fission] for the first time. They also predicted the liberation of additional neutrons during fission. Extra neutrons indicated the possibility of a nuclear chain reaction. If one neutron can provoke one fission, and the number of neutrons doubles and redoubles at faster-than-lightning speed in an enclosed space – then you have an atomic bomb.

Soddy's "atomic detonator" had arrived. Rutherford predicted it. It was the neutron.



Nuclear Fission

A subatomic projectile called a neutron starts a nuclear chain reaction by splitting a nucleus of "fissile uranium" (U-235).

The nucleus splits into two large fragments and energy is released – along with 2 or 3 extra neutrons.

The 2 broken pieces are new radioactive nuclei called "fission products".

More neutrons trigger more fissions and so the energy release is multiplied enormously.

## Heavy Water

Four months later, in Paris, Frédéric Joliot-Curie was determined to achieve a nuclear chain reaction. He was well aware of both the civilian and military significance.

Natural uranium has different isotopes. Only one of them can sustain a chain reaction – uranium-235. But only seven atoms out of a thousand are that kind of uranium. Almost all the other atoms are heavier – uranium-238. The lighter, chain-reacting atoms are so scarce, and the neutrons travel so fast, that a chain reaction cannot be sustained in natural uranium. Too many neutrons get lost.

Remembering Fermi's paraffin trick, Joliot-Curie thought that slowing the neutrons down might increase the number of fissions so as to keep a chain reaction going. Fission of uranium-235 won't occur unless the neutron bonds with the nucleus. That's more likely with slow neutrons.

Anything that slows neutrons down efficiently is called a moderator. Joliot-Curie figured that the very best moderator is "heavy water" – that's $D_2O$ where D is deuterium, a heavier-than-usual isotope of hydrogen, and O is ordinary oxygen. The only sizable stock of heavy water was in Norway, which the German army was getting ready to invade.

Joliot-Curie warned the French government not to let Norwegian heavy water fall into Nazi hands, and allow Germany to develop its own atomic bomb. In February 1940 a French banker was sent on a secret mission to buy up the entire supply of heavy water and send it to Paris. Norway was happy to oblige, especially on account of German military motives.

The fears were well-founded. That country fell to Nazi forces in April. Joliot-Curie received the re-routed heavy water in May. He discovered there wasn't enough of it to get a self-sustaining chain reaction going, but careful measurements indicated that it would probably work if he just had a larger supply.

His research ended abruptly when the Germans invaded France in May 1940. The heavy water and members of the Paris team were secretly sent by boat to England in June. There they set up shop with their British colleagues at Cambridge. Eventually, the heavy water and the entire team moved to Montreal where they continued their research in collaboration with Canadian scientists at a secret laboratory on the slopes of Mount Royal.

In April 1944, it was decided in Washington DC to allow a large heavy water moderated research reactor to be built in Canada. The site selected was Chalk River, on the Ottawa River. The Canadian CANDU reactor, which uses natural uranium as a fuel and heavy water as a moderator, was the ultimate culmination of this remarkable sequence of events.

## Uranium Enrichment

Back in March 1940, physicists Otto Frisch and Richard Peierls – both living in England – spelled out on three sheets of paper how to build an atomic bomb by first separating uranium-235 from uranium-238. Using concentrated uranium-235 (preferably over 90 percent) a very simple atomic bomb can be made – guaranteed to work, with no need for testing.

This paper was a thunderbolt. It was immediately classified. A top-secret government committee – the MAUD committee – was established to validate its claims.

The main question was this: how can you separate uranium-235 from uranium-238? They are the same element. Chemically, they're identical. Whatever happens to one happens to the other. Only the slight difference in mass can be used to distinguish them or separate them.

Uranium "enrichment" refers to any method that increases the concentration of uranium-235. There are several ways. They are all slow, laborious, expensive, and energy intensive. To be enriched, uranium has to be in the form of a gas. That gas is uranium hexafluoride ("hex") – a nasty, highly toxic fluorine compound.

When hex is introduced into an ultracentrifuge, spinning very fast, the heavier uranium-238 atoms are thrown to the outside, and the gas in the center becomes slightly enriched. By repeating this process, a great many times, a high degree of enrichment can be obtained.

If the concentration of uranium-235 is below 20 percent, it is Low Enriched Uranium (LEU). It is not considered weapons-usable – but that is debatable. At any rate, uranium with a degree of enrichment 20 percent or higher is designated as High Enriched Uranium (HEU). HEU is regarded as a serious weapons proliferations risk.

The Hiroshima bomb used uranium enriched to about 80 percent uranium-235. A criminal organization or terrorist group with access to HEU can easily make a similar device.

Commercial power reactors now in operation worldwide use either natural uranium (as in the CANDU reactor) or LEU below 5 percent uranium-235 (in the case of "light water reactors" – LWRs). These nuclear fuels cannot be used as a nuclear explosive without further enrichment. Luckily, enrichment technology is beyond the capability of subnational groups.

Many 'Small Modular Nuclear Reactors' (SMNRs) now being proposed are designed to use uranium fuel enriched to a much higher level – considerably more than 5 percent and in some cases very close to 20 percent. Some of these fuels – called High Assay Low Enriched Uranium or HALEU – may be weapons usable already. If the fuel needs further enrichment for weapons use, 80 to 90 percent of the work of isotope separation is already done.

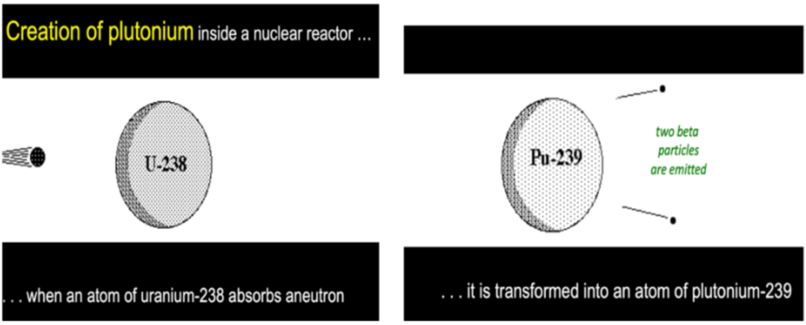
## Plutonium

Uranium is the 92nd element in the periodic table. That element was discovered in 1789. It was named after the planet Uranus, discovered just eight years earlier. When a uranium-235 atom is struck by a neutron, it fissions readily, releasing more neutrons in the process. Uranium-238 is very different, as it doesn't easily fission. When a uranium-238 atom is struck by a neutron, it transmutes into two transuranic elements in rapid succession – neptunium (the 93rd element) and plutonium (the 94th element). (After Uranus, the next planets out from the sun were Neptune and Pluto.)

Minute amounts of neptunium and plutonium were produced in December 1940 at University of California (Berkeley) using a cyclotron – a particle accelerator. Within months it was proven that plutonium, like uranium-235, can support a nuclear chain reaction. It is a nuclear explosive! In fact it is a more efficient explosive than uranium-235.

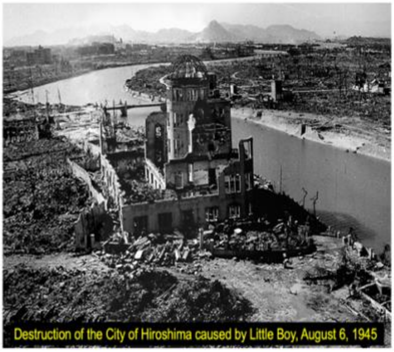
What's more, ***all*** plutonium isotopes are chain-reacting. No "isotope separation" technology is necessary to build a nuclear arsenal based on plutonium. It's easier to acquire than uranium, because no form of enrichment is required. Virtually all plutonium is weapons-usable.

These findings affected the focus of the work carried out in Montreal by the French/British/Canadian heavy water team. They quickly realized that a chain reaction using natural uranium and moderated by heavy water would be particularly efficient at producing plutonium. Neutrons from fissioning uranium-235 atoms, which are scarce, will strike uranium-238 atoms, which are abundant, and transform them into plutonium atoms.



The purpose of the Montreal laboratory shifted from pure nuclear research to plutonium production – and the subsequent extraction of plutonium from used nuclear fuel. In effect, any uranium-fueled nuclear reactor is a transmutation factory. It transmutes abundant uranium-238 atoms, which are not chain-reacting, into plutonium atoms, which are.

The alchemists of centuries past tried to turn lead into gold – a symbol of opulence. Our modern nuclear alchemists wanted to turn uranium-238 into plutonium – a symbol of unparalleled death and destruction, as demonstrated by the plutonium bomb dropped on Nagasaki. (The Hiroshima bomb used uranium-235, the Nagasaki bomb used plutonium.)



Destruction of the City of Hiroshima caused by Little Boy, August 6, 1945

This glass ball is exactly the same size as the ball of plutonium in the bomb that destroyed the City of Nagasaki

Photo by Robert Del Tredici

British and French scientists were part of the Montreal team, so Canadian wartime research on plutonium gave France and Britain a head-start on their own nuclear weapons programs. Their first bombs used plutonium, foregoing the need for uranium enrichment. The Canadian experience also positioned France to help Israel develop its own nuclear weapons capability.

When the uranium bomb was dropped on Hiroshima, Canada's "Minister of Everything" C. D. Howe, released a prepared statement: "It is a distinct pleasure for me to announce that Canadian scientists have played an intimate part, and have been associated in an effective way with this great scientific achievement."

Canada's first nuclear reactor started operating at Chalk River one month after Hiroshima. It was explicitly justified as plutonium production for the WWII atomic bomb project. From 1947 to 1976, plutonium produced at Chalk River was sold to the US for weapons use. In 1974, India used plutonium from a Canadian-donated reactor for its first atomic bomb.

Canada chose not to develop a nuclear weapons capability, but it helped other countries to do so.

**Reprocessing**

In the USA, the UK, France, the USSR, China, India, and even in Canada, the first nuclear reactors were built for the purpose of producing plutonium for bombs.

To be used in bombs, plutonium must first be separated out from used nuclear fuel. In principle, this is much easier than separating uranium isotopes because plutonium is a completely different element. It can be separated using ordinary chemical methods. However, irradiated nuclear fuel is so intensely radioactive that it will kill any unshielded human being in a very short time. Plutonium extraction requires heavy shielding and normally uses robotic equipment, or at least remote handling techniques.

Any technology designed to extract plutonium from used nuclear fuel is called "reprocessing". It is a dirty and dangerous procedure. Some of the most radioactively contaminated sites in the world are places where large-scale reprocessing has taken place. Such sites include Hanford, Washington; Sellafield, England; Mayak, Russia; La Hague, France; Rokkasho, Japan; and West Valley, New York.

Two chemical extraction plants of military interest were operated at Chalk River in the 1940s and early 1950s. One plant separated plutonium from irradiated uranium fuel. The other plant separated an artificial isotope of uranium – uranium-233 – from rods made of thorium and inserted into a nuclear reactor. Uranium-233 is a powerful nuclear explosive that is very highly enriched the instant it is created; it is a transmutation of naturally-occurring thorium.

Thorium is not a chain-reacting material. When exposed to neutrons, however, it transmutes into uranium-233, a human-made isotope that is chain-reacting and can be used in nuclear weapons. So, just as uranium-238 "breeds" plutonium in a nuclear reactor, thorium "breeds" uranium-233. In both cases, the subsequent chemical extraction is called "reprocessing".

## Conclusion

From the dawn of the nuclear age, enthusiasts have dreamed of using plutonium as the nuclear fuel of the future. Society will run on a "plutonium economy", they imagine. Advanced reactors called "breeders" will run on plutonium fuel and – by irradiating a "blanket" of uranium-238 with stray neutrons – will create even more plutonium fuel.

If commercial reprocessing is allowed, nuclear explosive materials will be routinely separated and traded for commercial use. Preventing the spread of nuclear weapons becomes nightmarishly difficult. A 1976 UK Royal Commission Report declared: "We should not rely for energy supply on a process that produces such a hazardous substance as plutonium unless there is no reasonable alternative." The author was Sir Brian Flowers, a nuclear physicist with impeccable credentials in both the military and civilian nuclear fields.

In 1977, US President Jimmy Carter, himself trained as a naval nuclear engineer, banned commercial reprocessing in the USA and tried to get it banned worldwide. He also ended the sole US breeder reactor project at Clinch River. In 1978 Prime Minister Pierre Elliot Trudeau urged the UN General Assembly to implement a "strategy of suffocation" to help end the nuclear arms race by banning the production of nuclear explosive materials – HEU and plutonium. The two critical technologies needed for bombs are uranium enrichment and/or reprocessing.

Breeders have not succeeded commercially. They were abandoned by the USA, France, Britain, Germany, and Japan. However, efforts are still underway to bring about a "plutonium economy".

In Russia, two breeder reactors are in operation. They are not competitive with older reactors. Only one is fuelled with plutonium. A third Russian breeder has been indefinitely postponed.

Plutonium-fuelled breeders are currently under construction in China and India. The Indian one was to be operational in 2010. It was still not functioning at the end of 2022.

Many experts believe the Chinese breeders will be "dual purpose" facilities, producing plutonium for bombs as well as electricity for civil society. The same could be true for India. The Indian Department of Atomic Energy has insisted – successfully – that the Indian breeder should not be subjected to international safeguards.

In New Brunswick, two "small modular nuclear reactors" are proposed, both based on using plutonium as a nuclear fuel. Reprocessing is part of the package. The intention is, eventually, to mass produce these SMNRs in Canada and export them around the world to any customers that wants to buy them. (So far there are none.)

Nine US non-proliferation experts sent three letters to Prime Minister Justin Trudeau in 2021 urging Canada to examine the weapons proliferation risks associated with these projects. There has been no meaningful response. The nine experts worked under six different U.S. Presidents.

What's wrong with reprocessing? Here's how Dr. Bernard Feld put it back in 1978. He was involved in the first plutonium bomb test conducted at Alamogordo, New Mexico. He later became editor of the prestigious Bulletin of Atomic Scientists.

> *Plutonium is the stuff out of which atomic bombs are made. And the amount of plutonium in the world is increasing year by year as nuclear power spreads. Within the next ten years nuclear power plants will be producing around 100 tons of plutonium a year – enough for 10,000 atomic bombs, each with the same power as the one that destroyed Nagasaki. It is hard to believe that a figure as big and as threatening as this is realistic – but I assure you that this is what is being planned.*
>
> *So within the next ten years, there will be hundreds of tons of plutonium wandering around the world. It will be as easy as pie for a determined group to get hold of the 20 or so pounds needed for a Nagasaki-type bomb….*
>
> *Today the world stands at a crossroads. Will the needed steps be taken to avert the world-wide proliferation of nuclear bomb materials, or will it be another example of too little, too late?*

If plutonium becomes an article of global commerce, it will inevitably fall into many hands. No amount of policing can prevent disastrous consequences in such a world. We could wake up one morning and find Washington DC gone – or London, or Paris, or Moscow, or Beijing – and not even know who did it. Moreover, any conflict, anywhere in the world, could suddenly turn into an all-out nuclear war.

A sustainable future on planet Earth depends on ending plutonium production and putting an end to reprocessing. Otherwise, humanity is planting the seeds of its own destruction.

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