CANADA
AND THE ATOM

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CHAPTER ONE

SHARING IN THE TRIUMPH

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The Glory Days at McGill

Atomic research in Canada began in 1899, before the existence of the atom was fully accepted as a scientific fact. In that year, a 27-year-old New Zealand physicist arrived in Montreal from England. A Canadian tobacco merchant, W.C. Macdonald, had given McGill University a generous donation sufficient to build a brand new Physics lab and hire several new professors. This newcomer was selected to be one of them. Though no one could have guessed it at the time, he was destined to become “the Newton of atomic physics”. His name was Ernest Rutherford.

Rutherford was eager to explore the mysterious new world of radioactivity. Three years earlier, in Paris, Henri Becquerel had left a lump of uranium ore in a closed drawer containing some photographic plates that were securely wrapped. Later, he found a pattern of intense light on the prints, radiating outward from the exact spot where the rock had been sitting. Becquerel was astonished. How can a rock, unstimulated by sunlight or any other external agency, spontaneously emit energy – an invisible kind of light that can’t even be blocked by thick black paper?

While still in England, Rutherford had just begun to investigate these peculiar rays, given off by any and all ores containing uranium or thorium. “There are present at least two distinct types of radiation,” he wrote, “one that is very readily absorbed, which will be termed for convenience the alpha radiation, and the other of a more penetrative character, which will be termed the beta radiation.” A third type of atomic radiation, having far greater penetrating power than either the alpha or beta variety, was discovered by Paul Villard in France one year later, in 1900. It was called gamma radiation in keeping with Rutherford’s scheme of nomenclature.

By the time Rutherford’s observation had appeared in print, he was already busy in his new Montreal lab, which he declared to be “the best of its kind in the world.” In 1900, he detected a radioactive gas emanating from solid thorium. He enlisted the aid of a 23-year-old Oxford chemist, Frederick Soddy, then working at McGill. Soddy found that it was a “noble gas” similar to argon. By its nature, such a gas cannot be produced by any kind of chemical reaction. That fact implied “the tremendous and inevitable conclusion,” wrote Soddy, “that the element thorium was slowly and spontaneously transmuting itself” into an entirely different element. It was one of the most earth-shattering discoveries of the century: the spontaneous transmutation of radioactive substances into new substances, later to be called “decay products”.

The phenomenon of radioactive transmutation explained a lot. Two years earlier, in Paris, when Marie Curie extracted pure uranium from the rocky ore that Bequerel had put in his desk drawer, she was amazed to discover that the residues were much more radioactive than the uranium she had removed. She earned a Nobel Prize by discovering two previously unknown radioactive elements in the residues – radium and polonium – each far more radioactive than the uranium itself. The discovery of transmutation at McGill suddenly made it clear: radium and polonium were simply two decay products of uranium, created when uranium atoms disintegrate.

For several years, Soddy and Rutherford worked as a team at McGill. They found that each radioactive substance has its own characteristic "half-life" – the time required for half of its radioactivity to disappear. Simple multiplication shows that when two half-lives have elapsed, one quarter of the original radioactivity will still remain; and after ten half-lives, about one part in a thousand is left. They calculated the half-life of uranium at 4.5 billion years, and the half-life of radium at 1,620 years. They identified one decay product of thorium with a half-life of 22 minutes, another with a half-life of 27 days. Some decay products, they observed, can appear and disappear in the blink of an eye.

Rutherford persisted in his investigations. He managed to prove that beta rays are really beams of negatively charged particles called electrons. Unlike ordinary electrons, however, they are ejected with incredible energy – like sub-atomic shrapnel from some miniature explosion. Where on earth does all this hidden energy come from? And how much is there in all?

In 1903, Rutherford and Soddy calculated the total energy released by radioactive decay. The answer was staggering. It must be, they wrote, "twenty thousand times, and may be a million times as great" as the energy released by the most powerful chemical reactions. In the same year, Rutherford playfully 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 in 1937, however, Rutherford never believed that such an "atomic explosion" was possible. He knew that the rate at which a substance releases energy through radioactive decay is constant. Nothing can be done to speed it up or slow it down. Changes in temperature, pressure, or chemistry, have absolutely no effect. Thus, there is no potential detonator in sight. Radioactive atoms will continue to disintegrate at a predetermined rate.

In the summer of 1903 the Rutherfords visited the Curies in Paris, arriving on the historic day when Marie Curie received her doctorate in science – the first ever granted to a woman. "We retired about 11 o'clock in the garden," Rutherford recalled, "when Professor Curie brought out a tube coated in part with zinc sulphide and containing a large quantity of radium in solution. The luminosity was brilliant in the darkness and it was a splendid finale to an unforgettable day." The light was bright enough to allow Rutherford to see Pierre Curie's hands, "in a very inflamed and painful state due to exposure to radium rays." These radiation burns offered yet another, more insidious testimonial to the great power of atomic radiation.

A young German physicist, Otto Hahn, visited Rutherford at McGill in 1905-1906. Together they showed that alpha radiation, like beta radiation, is composed of a stream of charged particles – unlike x-rays and gamma rays, which are immaterial forms of energy.

In the spring of 1907, Rutherford left Montreal and returned with his family to England, where he had accepted a position at the University of Manchester. When next he returned to Canada, to attend the British Association meeting in Winnipeg in 1909, he had become a celebrity. His McGill work had earned him the 1908 Nobel Prize in Physics. In that same year, 1908, he finally proved what he and Hahn had long suspected: that alpha particles are positively charged helium atoms, seven thousand times more massive than the beta particles he had earlier identified. That explained a mystery – why traces of helium gas were always found trapped in the inter-crystalline spaces of uranium and thorium ores. Alpha particles at rest are helium atoms.

Now the glory days of atomic research in Canada were apparently past, as the hub of innovative activity shifted back to Europe. But some of the most potent seeds of thought first planted at McGill had not yet borne fruit.

The Anatomy of the Atom

In 1906, while still at McGill, Rutherford began a series of experiments that would reveal the innermost secrets of the atom. He fired alpha particles through extremely thin sheets of various materials – mica, gold, aluminum, silver and platinum. Most of the particles passed through as if there were nothing there – nothing at all! – suggesting, paradoxically, that solid matter is mainly empty space. But a few of the alpha particles were slightly deflected, as if they had ricocheted – as if some curious kind of collision had occurred. Rutherford was intrigued.

Back in England, he continued to study these odd ricochets. One day, on a whim, he looked for evidence of a far more dramatic deflection of alpha particles, bouncing backwards at a sharp angle from the surface of the flimsy foil. To his surprise, he found exactly that. "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."

He realized that such behavior could only be explained if "the greatest part of the mass of the atom was concentrated in a minute nucleus," many thousands of times smaller than the atom itself. Only a very few alpha particles, those impinging directly on the nucleus, would rebound or carom off. The great majority would miss the tiny target and pass straight through, completely unaffected. He announced his discovery of the atomic nucleus on March 7, 1911.

In 1912, Rutherford discussed these matters with a young Danish physicist, Niels Bohr. It was an extraordinarily fruitful encounter. Within a year, Bohr had worked out all the rudimentary features of modern atomic theory. Each atom, he argued, must have a small, massive, positively charged nucleus, with negatively charged electrons orbiting around this central core somewhat like planets revolving around a massive sun in a miniature solar system. The number of positive charges in the nucleus exactly balances the number of electrons in orbit; this is the so-called "atomic number". Each consecutive atomic number corresponds to a distinct chemical element, ranging from "1" for hydrogen, the lightest element, to "92" for uranium, the heaviest element.

The pieces of the puzzle started falling into place. An alpha particle is in fact just a naked helium atom, stripped of its orbiting electrons – that's why it is positively charged. In other words, it's a very fast-moving helium nucleus – that's why it is so massive. So, when an alpha particle is ejected from a sample of uranium, it must come straight from the nucleus of an individual uranium atom, because that's where all the mass resides. Since a helium nucleus carries two positive charges, the loss of an alpha particle reduces the atomic number by "2". Consequently, the atom that remains behind is no longer element 92, it is element 90. When this atom in turn emits another alpha particle, it is transmuted into element 88. That is one way that new radioactive decay products are spawned – by the process of "alpha decay".

By the year 1914, when Rutherford visited his old friends in Montreal once more, he had been dubbed "Sir Ernest". His reputation was as solid as the Rock of Gibraltar. But despite all the accolades, he knew that his picture of the atom was not yet complete.

Some years earlier at McGill, Soddy had remarked that some radioactive substances are not really new elements, but simply new versions of existing elements. He called them "isotopes". Following Soddy's line of thought, Bohr correctly guessed that each new radioactive isotope has the same atomic number as its non-radioactive twin. Since the number of orbiting electrons would be the same in both cases, Bohr realized that any differences between two given isotopes must lie in their nuclei. But what possible differences could there be between two otherwise identical nuclei? This baffling question went unanswered for two decades.

Rutherford kept on working. In 1919 he reported the first case of artificial transmutation. He found that alpha particles are sometimes captured by the nuclei of light atoms such as nitrogen. This increases the atomic number, creating new isotopes by transmutation. Similar results did not occur with much heavier atoms. Apparently, the much greater positive charge on a heavier nucleus was strong enough to repel the incoming positively charged alpha particle, preventing contact. In such cases, the alpha particle's electrical charge acted as a hindrance.

The following year, in a public lecture – and without a shred of supporting evidence – Rutherford speculated on the possible existence of a neutral particle or 'neutron", having about the same mass as a hydrogen nucleus or "proton", but having no electrical charge at all. He conceived of it as a proton with an electron buried inside – like a hydrogen atom whose solitary orbiting electron had somehow collapsed right into the nucleus. Although it aroused surprisingly little interest at the time, his was a prophetic insight, eventually having consequences for us all.

The concept of the neutron explains how different isotopes of the same element can exist. For, if a nucleus were to contain uncharged neutrons as well as positively charged protons, the number of neutrons would make no difference to the atomic number. The atomic number – and hence the chemical identity – is determined by the protons alone. So by tinkering with the number of neutrons without changing the number of protons, different isotopes of the very same element can result – each one having atoms with slightly different nuclei. For example, we find two common isotopes of uranium in nature: uranium-238 (with 92 protons plus 146 neutrons) and uranium-235 (with 92 protons plus 143 neutrons). The first isotope is a bit heavier than the second, but chemically they are the same, because the atomic number (i.e. the number of protons) is identical in both cases. They are just two different isotopes of element number 92.

The existence of the neutron might also help to explain how beta particles, which are negatively charged electrons, can originate from inside the nucleus, which is positively charged. If one imagines a neutron as, in some sense, equivalent to a proton that has engulfed an electron, it is conceivable that that “buried” electron can somehow be violently ejected from the neutron as a high-velocity beta particle. The neutron thereupon changes into a normal proton. When this happens inside an atomic nucleus, the atomic number of the atom increases by “one” because of the extra proton, and – voilà! – a new chemical element, with a slightly higher atomic number, has been created through the process of “beta decay”.

But the most important feature of the neutron, as Rutherford clearly foresaw in 1920, is its ability to penetrate to the very heart of matter, unhindered by electrical repulsion or any other kind of resistance. There it “may either unite with the nucleus,” said Rutherford, “or be disintegrated by its intense field.” The neutron is the perfect tool to probe the atomic nucleus.

Although Rutherford never knew it, the neutron would prove to be the essential sparkplug needed by every nuclear reactor and the indispensible trigger for every kind of nuclear explosion.

The Missing Link

Ten long years of searching by Rutherford failed to turn up the elusive neutron. Then, in 1930, W. Bothe, a German scientist, encountered a perplexing phenomenon. He bombarded a beryllium target with alpha particles, and was surprised to observe an extremely energetic, highly penetrating form of atomic radiation emitted from the target. Frédéric Joliot-Curie in France obtained similar results in 1931. Both scientists, misled by the extraordinary penetrating power of this remarkable radiation, thought they had stumbled upon an unusually intense form of gamma rays.

Only James Chadwick, who had worked with Rutherford for years, guessed the truth. He felt that the mysterious beryllium radiation must be made up of a stream of neutrons. He set about to prove this with the utmost care. It took him a year, but by February 1932, he had systematically disproved every alternative interpretation. The only remaining explanation must be the truth: highly energetic neutrons were being knocked out of beryllium nuclei as a result of collisions with alpha particles. In practice, this meant that one could obtain a source of neutrons just by mixing beryllium with an alpha-emitting substance such as radium.

The age of the neutron had arrived. Rutherford’s earlier predictions were amply borne out. In 1934, in Rome, Enrico Fermi bombarded sixty substances with neutrons, creating artificial radioactivity with ease in over forty cases by a process called “neutron activation”. Light elements got a bit lighter, as the incoming neutron knocks a proton out of the nucleus, and heavy elements got a bit heavier due to neutron capture, sometimes followed by beta decay. The pattern became quite clear, and the production of new radioactive isotopes proceeded apace.

In the case of uranium, however, a baffling result was observed. Several new radioactive substances were produced as a result of neutron bombardment, and none of them could be readily identified. This puzzling behavior went unexplained for years. By 1938, the German team of Lise Meitner and Otto Hahn had shown that there are at least a dozen different intensely radioactive isotopes created when uranium is bombarded by neutrons. Chemically, they resembled none of the elements that were known to have nuclei comparable in size to a uranium nucleus. So what were these strange new elements? And where had they come from?

Then, around Christmas of 1938 in Berlin, as the storm clouds of war gathered over Europe, Otto Hahn made an astounding discovery. Some of the uranium byproducts were finally identified, and were found to have nuclei only a fraction the size of the original uranium nucleus. Lise Meitner, as a Jewish refugee from the Nazi regime, was now living and working in Stockholm. Meitner deduced that some of the uranium atoms must have somehow split or "fissioned" into two or more unequal chunks, and Hahn concurred. All those radioactive byproducts that she had previously studied with Otto Hahn were in fact "fission products" – that is, broken pieces of uranium atoms that had been "split" by the incoming neutrons.

The uranium atom had been split! This amazing news spread like wildfire through the community of atomic scientists. Experimenters in France showed that when a uranium atom splits, two or three extra neutrons are also given off, and an enormous amount of energy is released. Unlike radioactivity, this type of energy release from the nucleus ("nuclear energy") can easily be amplified simply by multiplying the number of neutrons. In fact, extreme amplification can happen automatically in an extremely short period of time – a tiny fraction of a second – through a process known as a "nuclear chain reaction".

The concept of a chain reaction can be explained by means of an analogy. Suppose a job pays two cents the first day, four cents the second day, eight cents the third day, and so on, doubling each day. How much will such a job pay after sixty days? A bit of arithmetic shows this Alice-in-Wonderland job will pay more money than has ever existed on the face of the earth: over forty quadrillion dollars, in just two months. That's a four with sixteen zeros after it – it's about two thousand times larger than the 2017 Gross National Product of the USA.

Something similar happens in a nuclear chain reaction, but much faster. When a uranium atom fissions, it releases energy and a few extra neutrons. Suppose two of the excess neutrons are absorbed by two other atoms, causing two more fissions. This time twice as much energy is produced, and twice as many extra neutrons appear. Continuing in this fashion, we have four fissions, then eight fissions, and then sixteen, in a "chain reaction" – just like the fabulous job described above. But neutrons move so fast that sixty generations of neutrons – that's sixty doublings – can take place in less than a millionth of a second. The energy from each fissioning atom is almost instantly magnified by a factor of many quadrillions. That is the awesome and horrific process that ended up destroying the cities of Hiroshima and Nagasaki in August 1945.

The military implications were quickly grasped. The neutron is that "detonator" that Rutherford joked might unleash a wave of annihilation that could destroy the world. With the discovery of atomic fission, it now seemed possible, after all, to build an incredibly powerful "atomic bomb". Would the Nazis be the first to achieve it? It was painfully clear to all that most of the neutron research had been done in Rome and Berlin, the two poles of the Fascist Axis.

The French Connection

It was 1939. The race was on to harness the power of the atom. First off the mark was the Paris group: Frédéric Joliot-Curie, Hans van Halban, Lew Kowarski and Francis Perrin. By the end of January they had shown that enough extra neutrons are released during atomic fission to sustain a chain reaction – at least in principle. But there are complications. If too many neutrons are captured by impurities, the reaction never gets going. Similarly, if too many neutrons escape without triggering additional fissions, the reaction fizzles out. Francis Perrin defined a "critical mass" of uranium to be the smallest amount of uranium needed to sustain a chain reaction.

The Paris group knew that slow neutrons are better than fast ones for provoking fission in natural uranium. Some years earlier, in Rome, Enrico Fermi had inserted a block of paraffin between a neutron source and a uranium target; the paraffin slowed the neutrons down, thereby increasing the yield of fission products.

To get a chain reaction going, and to keep it going, they would have to slow down not just the incoming neutrons, but all the subsequent neutrons released by fissioning atoms. The uranium would have to be surrounded by or intermixed with a "moderator" – a material that speeds up the fission process by slowing down the neutrons. Other materials ("neutron absorbers") could then be used to limit and control the chain reaction by absorbing any extra neutrons and preventing the chain reaction from getting out of control – or stopping the reaction altogether. The Paris group had worked out all of these important concepts by May of 1939.

Next began the search for a suitable moderator. They tried paraffin, but found that it captures too many neutrons. No good. Next they tried ordinary water; it was better, but not good enough. Too many neutrons captured. By then, World War II had erupted. Austria was annexed; the Sudetenland was occupied; Poland was invaded. The Nazis now had access to the uranium deposits of Czechoslovakia. The Paris group redoubled its efforts: what should they try next?

They wondered why water hadn't worked. Water is full of hydrogen atoms, whose nuclei are protons – the exact same size as neutrons. The Paris team figured that fast neutrons would ricochet off these protons like billiard balls colliding on a pool table, losing momentum with each impact. The neutrons would surely slow down. And indeed they do; but something else happens. Too many neutrons are captured by the hydrogen nuclei, and so the reaction simply grinds to a halt. Not enough neutrons are left in circulation to keep the chain reaction going.

When a neutron is captured by an ordinary hydrogen nucleus, it yields another hydrogen nucleus that is twice as heavy as normal. The nucleus of this new hydrogen atom has a proton and a neutron combined. It is a non-radioactive isotope of hydrogen that was first discovered in 1932 by the American Harold Urey; it is called "heavy hydrogen" or "deuterium". It occurs in nature in minute amounts, and can be extracted out of ordinary water with considerable effort.

The Paris group realized that "heavy water" – water made from heavy hydrogen – would be a perfect moderator. Having one extra neutron already, heavy hydrogen would be much less prone to capture another neutron. Thus neutrons could be slowed down by heavy water without too many of them being absorbed. With a little bit of luck, a chain reaction might just be possible.

The Paris group was convinced that heavy water had to be tried. But heavy water isn't easy to come by. It can only be extracted from ordinary water by a slow, painstaking process requiring lots of electricity. The only place it was being made was a large hydro-electric power station in Norway. In the spring of 1940, the French government was persuaded to get that heavy water out of Norway before Hitler's war machine could take possession of the precious fluid.

The French Minister of Armaments made inquiries. He learned that the Nazis intended to buy the entire stock of Norwegian heavy water – a strong hint that they had embarked on their own atomic research program. Once the Norwegians were informed about the possible military significance of this unusual substance, they entrusted it all to Jacques Allier, a French Secret Service man. He spirited it into France via England just days before the Nazis invaded Norway. A special bombproof shelter was built near Paris to house it. This entire stock of heavy water would eventually make its way to Montreal, Canada, as we shall see in due course.

There were only 200 kilos of heavy water – not enough for a chain reaction. The Paris group designed an exploratory experiment, and it was verified that with enough heavy water a chain reaction could indeed be sustained. The experiment had to be hastily dismantled when the Germans launched a lightning attack through Belgium into France. In the last frantic days just before the fall of Paris, Halban and Kowarski fled to England with the entire inventory of heavy water. They were told to try to reach North America, since Britain would surely be threatened with invasion also. It was considered essential that these fission experiments be continued.

The Fast Track

,Just two months earlier, the British had set up their own top-secret Committee of Experts to investigate the feasibility of an atomic bomb. Unlike the French, however, they were led to focus on the idea of a chain reaction using fast neutrons. No moderator would be needed.

Throughout 1939, the British were profoundly skeptical that a bomb was at all possible. They knew that an atomic explosion could not be achieved using slow neutrons, as the uranium would blow itself apart before the chain reaction had enough time to reach truly spectacular levels. On the other hand, a chain reaction using fast neutrons was thought to be impossible, because too many neutrons are absorbed by the existence of a non-fissionable type of uranium.

But then, in March 1940, Otto Frisch and Rudolf Peierls – two refugee German scientists living in England – hit upon a startling new idea. On three typewritten pages, they outlined how an atomic bomb could be built and detonated using only a few kilograms of a rare isotope of uranium – uranium-235 – and fissioned by fast neutrons. They warned that no man-made structure could possibly withstand the force of the resulting explosion; that no defence would be possible; that the intensely radioactive residues would remain deadly to living things for many years after the explosion; and that the Nazis were probably developing just such a bomb.

The basic idea is simple. Natural uranium is a blend of two main isotopes. The heavier, more abundant variety, is uranium-238. It frequently captures neutrons without fissioning. The other kind, uranium-235, almost always fissions. By slowing the neutrons down, as the Paris group was trying to do, one could minimize the neutron capture by uranium-238, while maximizing the fission of uranium-235. Slow neutrons are needed to keep a chain reaction going.

But Frisch and Peierls thought otherwise. They saw that if uranium-235 were completely separated from uranium-238, one wouldn’t need to slow the neutrons at all. A very powerful bomb could then be made from a grapefruit-sized quantity of relatively pure uranium-235. The Frisch-Peierls paper was communicated in great secrecy to British authorities. By April 1939, a Committee of Experts was appointed. They confirmed the claims made by Frisch and Peierls.

After more than a year of doubt and confusion, the British were finally on the right track – the fast track – towards an atomic bomb. During the summer of 1940, several research teams swung into action at four different universities. James Chadwick was asked to verify that a fast neutron uranium bomb would work. The heavy water team, newly arrived from France, was invited to continue its slow neutron research at Cambridge; however, their research was given a lower priority since it would not lead directly to a bomb – or so it seemed at the time,

The Committee soon became known as the M.A.U.D. Committee – a name inspired by a cryptic telegram from Neils Bohr in occupied Norway referring to “Maud Ray”, which British intelligence took to be a code name for “Radium”. Not until 1943 did they learn that Maud Ray was the name of an English governess who had once minded Neils Bohr’s children!

The most formidable task facing the M.A.U.D. Committee was to figure out how to “enrich” uranium by separating out and removing the unwanted uranium-238. As there are no chemical differences between uranium isotopes, the separation had to be based on the very slight mass differential between the two types of atoms. This ticklish problem now had top priority.

Some pure uranium metal was obtained from McGill University. From this metal, a highly corrosive compound was produced, called “uranium hexafluoride” or “hex”, which turns into a gas when slightly heated. The British demonstrated that when hex gas is diffused through a super-fine membrane, the lighter atoms pass through somewhat more easily than the heavier ones. The result is a very slight increase in the concentration of uranium-235. By repeating the process thousands of times, any desired degree of enrichment can be achieved, giving higher and higher percentages of uranium0-235. This cascading method is known as “gaseous diffusion”.

In principle, gaseous diffusion is relatively simple; but in practice, it is extremely demanding. As Frisch explained, “it was like getting a doctor who had, after great labour, made a minute quantity of a new drug, and saying to him: ‘Now we want enough to pave the streets.’ “ To complicate matters, any direct contact with the highly corrosive and toxic hex gas quickly destroyed metals, most lubricants, and rubber.

Nevertheless, by December 1940, the M.A.U.D. Committee had cranked out cost estimates and technical specifications for a large uranium enrichment plant based on gaseous diffusion. By early 1941, Chadwick “realized that a nuclear bomb was not only possible – it was inevitable.” He wrote, “I had then to start taking sleeping pills. It was the only remedy.”

In the summer of 1941, the M.A.U.D. Committee made its report. It was detailed and quite explicit. There were three conclusions. First, the Frisch-Peierls scheme for producing a uranium bomb was entirely feasible. Second, work towards building such a bomb should receive the highest priority. Third, close cooperation with America was of the utmost importance.

By the fall, Churchill had given the project his stamp of approval. “Although personally I am quite content with the existing explosives,” he wrote to his military advisers, “I feel we must not stand in the way of improvement.”

The New World

The battle of Britain raged throughout the fall of 1940 and the spring of 1941. The British pondered the wisdom of building their nuclear facilities across the ocean to avoid the ravages of the Luftwaffe bombardments. In August 1940, a British delegation – the Tizard Mission – was sent to North America to explore the possibilities of trans-Atlantic cooperation.

The Americans were told everything about the British effort. In turn, the visitors learned that work in the USA was proceeding along parallel lines, but with considerably less intensity. The US was not yet at war. Fermi, now at Columbia University, was pursuing slow neutron research rather similar to that of the Paris group, but using very pure graphite as a moderator. Like most scientists in the US he was extremely doubtful about the prospects for an atomic bomb, but he was hopeful that nuclear boilers might eventually be of great value as a commercial energy source after the war.

Some US researchers were investigating the problems associated with uranium isotope separation – not for bombs, but for boilers. A chain reaction using slow neutrons would be easier to achieve if the uranium were "enriched" – endowed with higher percentage of uranium-235. The presence of more fissile material guarantees many more fissions and many more neutrons. In that case, ordinary water might yet prove useful as a moderator, for neutron losses are more affordable.

In Ottawa the British met George Laurence, a one-time student of Rutherford's, then on staff at the National Research Council (NRC). Secretly and single-handedly, he had built his own slow neutron experiment in a room on Sussex Drive, using graphite as a moderator. In fact, he had anticipated Fermi's work at Columbia by several months. Although he never achieved a sustained chain reaction, his work placed Canada in the front ranks of experimentation in nuclear fission. This led to a regular exchange of secret information between Canadian, British and American nuclear scientists that was to presage later events.

Back home in England again, the British arranged for Canadian Industries Limited (CIL) to donate $5,000 in support of the Ottawa experiment. CIL was a branch plant of Imperial Chemical Industries, a large British company already deeply involved in supplying the UK nuclear program with money and expertise. The British also began urging the Americans to start producing heavy water, since the Cambridge group had proven that it was a far better moderator than graphite. Eventually, the Americans built four heavy water plants: the first one was located in Canada – at Trail, British Columbia – and the others were in the States.

Originally the British felt that these slow neutron studies at Columbia, Ottawa and Cambridge, were irrelevant to the war effort. But nuclear boilers might have important post-war industrial significance, and Britain didn't want to be left out. Thus the research involving chain reactions with slow neutrons was still regarded as well worthwhile, but not urgent.

Then, near the end of 1940, everything changed. Two British researchers named Feather and Bretscher discovered an unexpected link between nuclear boilers and atomic bombs.

The atomic number of uranium is 92, and at that time, there was no element that had a higher atomic number. But when uranium-238 captures a neutron, it changes into a new element with atomic number 93 ("neptunium-239"), and thence into element 94 ("plutonium-239"), giving off two beta particles in the process. Because these are brand new human-made elements that are heavier than uranium, they are called "transuranic" elements.

On purely theoretical grounds, the two British scientists argued that plutonium-239, like uranium-235, could also undergo nuclear fission, and could also sustain a nuclear chain reaction. Uranium-235 is the only material in nature that can be used to make an atomic bomb, but plutonium-239 would be another, human-made nuclear explosive that could be manufactured at will. It would be created in copious amounts inside every nuclear boiler – because many of the stray neutrons are bound to be captured by uranium-238 atoms, thereby creating plutonium-239 atoms. Moreover, if heavy water is used as a moderator, the plutonium production is maximized.

This was an astonishing about-face. Atomic bombs can be made from the plutonium produced as a result of slow neutron chain reaction. As no self-sustaining chain reaction had yet been achieved, it was impossible to verify these amazingly accurate predictions. Accordingly, the military usefulness of plutonium was treated, at first, as just a hypothetical possibility. The M.A.U.D. report barely mentioned it.

Another potential military application of nuclear fission that was discussed from time to time, was to mass-produce fission products inside a nuclear boiler and use them as radioactive poisons to ruin the enemy's food supply by dropping them from airplanes onto enemy crops.

Breeding Plutonium

Early in 1941, tiny traces of plutonium were produced and meticulously studied in California. In March of that year, unbeknownst to the British, Glenn Seaborg showed that plutonium-239 fissions even more readily than uranium-235 – and with fast neutrons as well as slow ones. By July, Ernest Lawrence had obtained microgram quantities of pure plutonium-239 using his cyclotron – a gigantic electromagnetic device wherein charged atoms, fired through a strong magnetic field, are deflected into circular orbits determined by their respective masses.

When the Americans received a copy of the M.A.U.D. Report in October 1941, they were deeply impressed. Almost overnight, it changed their minds about the feasibility of building an atomic bomb. Overtures were made to the British to launch an integrated effort involving both countries. The idea was somewhat cooly received by the British, in part due to lax security measures by the Americans, who were still not at war, and so the opportunity slipped away.

At the end of November 1941, just one week before Pearl Harbor, President Roosevelt committed the USA to an all-out unilateral effort to build atomic bombs. The Americans elected to pursue three different methods for separating uranium isotopes: gaseous diffusion, centrifugal enrichment, and electromagnetic enrichment (based on the cyclotron). They also decided to explore a fourth option: producing and using plutonium for bombs.

When the British returned to the USA early in 1942, they were astonished at the momentum that the American effort had acquired. Although the British still had a significant lead in several aspects of bomb design, in gaseous diffusion, and in slow neutron reactions (thanks to their heavy water team) it was clear the Americans would soon outstrip them in all these areas. Besides, the Americans were placing more and more emphasis on plutonium – an area where British expertise was virtually non-existent. Fermi was now at Chicago, building a pilot plant for a large graphite-moderated uranium boiler to mass-produce plutonium. Seaborg and others from California had also gravitated to Chicago to investigate the complicated chemical properties of plutonium – the human-made element 94.

The full significance of element 94 was beginning to be appreciated. If the boiler concept proved valid, plutonium would be mass-produced as a byproduct. Being chemically different from uranium, it could be separated from the fuel by chemical means. Chemical separation was much easier than uranium enrichment. With plutonium, the inordinately expensive and terribly slow process of uranium isotope separation could be bypassed.

Slow neutron research, which the British had put on a back burner, suddenly had acquired great military significance. It now seemed imperative that the heavy water team (the off-shoot of the Paris group) be relocated in Chicago, where all the action was. Fermi's group would no doubt profit from their experience, and they would be in a better position to acquire some of the heavy water that the US was going to produce. They might finally get enough of the stuff for a self-sustaining nuclear chain reaction.

But the Americans had now become very security-conscious. They were in no mood to trust their atomic secrets to non-British foreigners (of the six senior scientists in the heavy water group, only one was British). They also suspected that the British might try to turn a profit after the war using US technology. These unvoiced suspicions were exacerbated when senior officials of Imperial Chemical Industries were sent to visit US top-security installations. Sensing the Americans' edginess, the British decided to back off.

Earlier, the M.A.U.D. Committee had suggested sending the heavy water team to Canada. It now seemed an excellent compromise: the European scientists would be close to Chicago, yet still within the British Commonwealth, and still safe from German bombs and rockets. With luck, they might obtain some of the heavy water from British Columbia to supplement the Norwegian stocks. And they would certainly be in a better position to learn about plutonium.

The Eldorado Story

Meanwhile, the Americans and British began to covet Canada's uranium supplies, which were among the largest in the world. Eldorado Gold Mines, a private Canadian company, owned a rich radium mine on the shore of Great Bear Lake in the Northwest Territories, close to the Arctic Circle. Since radium is a decay product of uranium, any ore rich in one is also rich in the other. Due to plummeting prices for radium, and the disruptions of the war, the mine was closed in 1940 and the Eldorado refinery at Port Hope, Ontario, on the shore of Lake Ontario, sat idle.

Radium had been regarded as a miracle substance ever since the Curies first isolated a tiny amount of it from tons of Czechoslovakian pitchblende ore. Radium glows in the dark, and it makes some other materials glow as well. It could cause nasty skin burns, which suggested an important medical use: killing cancerous tumours. Meanwhile, quacks sold bottles of radium in solution as a kind of tonic to be taken internally. Other edible products containing radium were marketed. The fact that hundreds died from radium poisoning did not noticeably dampen people's enthusiasm. A spectacular series of illnesses and deaths in a New Jersey luminous products factory should have made it perfectly plain that radium must be handled with extreme care and should never be ingested. Unfortunately, the lesson was not taken to heart; the commercial misuse of radium caused many gruesome deaths around the world.

Eldorado Gold Mines was incorporated in 1926 by Charlie and Gilbert LaBine, two brothers from Renfrew County, Ontario. In that same year, Union Minière, a Belgian firm, forced the only operating American radium company out of business by undercutting their prices at every turn. The Belgians drove the price of radium down from $100,000 per gram in 1920 to $70,000 per gram, drawing on a large stockpile of radium that they had secretly extracted from a very rich mine in the Belgian Congo (as it was then known). In doing so, the Belgians eliminated all competition and by 1926 they had secured a world monopoly in radium.

By 1929, Eldorado was in financial difficulties. Its one and only gold mine in Manitoba turned out to be a bust. Acting on rumours and following hunches, Gilbert started poking around the shores of Great Bear Lake just below the Arctic circle. There, in May 1930, he discovered a rich deposit of pitchblende. The Canadian Department of Mines confirmed that the ore was very rich and could be mined at a cost as low as $50,000 per gram of radium. It seemed the Belgian monopoly might be broken. In 1931, work on the mine was started. In 1932, Marcel Pochon, a radium chemist from France, was brought across the ocean to direct the building of a radium refinery at Port Hope, Ontario, using a process developed by Canada's Department of Mines.

For the rest of the decade, rich radium ore concentrates were shipped south to the Eldorado refinery at Port Hope, where radium was extracted for sale on the world market. Hundreds of tons of refinery residues, containing the original uranium, were heaped up beside the docks, stored in old silos, and even dumped in the harbor. Uranium had almost no market value, whereas radium was exceptionally valuable.

The Congo ore proved far richer than anyone had guessed, and the Belgians were able to compete at a level that the Canadians could not afford. By 1938, the price of radium had dropped to $7,000 per gram. Eldorado was saved from bankruptcy only by forming a price-fixing cartel, with the Belgians as senior partners. Then the war intervened, closing off markets. In 1940, with large unsold inventories and huge mounds of waste material stored at Port Hope, Great Bear Lake, and Waterways, Alberta, Eldorado reluctantly decided to shut its mine down for five years or so. The Congo mine had also closed when Belgium was occupied by Germany in 1939.

Eldorado didn't know it yet, but the discovery of nuclear fission had made uranium a substance of immense importance. The Nazis, by conquering Belgium and Czechoslovakia, had acquired access to two of the richest repositories of uranium in the world. The other main sources were Canada and the Congo. Before the war, Eldorado's chief market for uranium was in Germany, where potters used uranium compounds to form a beautiful red ceramic glaze. Only a few other places seemed to want the stuff: local art schools (for color), Columbia University (for

Fermi's work), and the National Research Council (for Laurence's work). Behind the scenes, however, military planners were already weighing the question of long-term uranium supplies.

During 1939 and 1940, only small amounts of uranium oxide were ordered from Eldorado for fission experiments. But the demand grew. In May 1941, the Americans ordered eight tons. Later that year, the British ordered two tons through the Canadian National Research Council (NRC) for the sake of secrecy. Then, early in 1942, the US placed an order for sixty tons of refined uranium oxide. That was enough to justify re-opening the mine at Port Radium and re-starting the Port Hope refinery, which was the only plant equipped to refine uranium in North America. Eldorado's fortunes were about to take a turn for the better.

Canadian Collaboration

In March 1942, Gilbert LaBine asked Clarence Decatur Howe, the Canadian Minister of Munitions and Supply, for permission to reopen the Eldorado mine. The Minister's approval was needed, since fuel, aviation and manpower were all controlled during wartime. Howe already knew and admired LaBine. He had even appointed him to direct one of his many newly created crown companies, Polymer Limited. When C. D. Howe learned that the Americans were working on some new kind of explosive, he gave LaBine all the necessary permissions to obtain equipment and supplies. Operating in total secrecy, as required by both governments, LaBine began gathering the men and materials needed to produce uranium for bombs.

On June 15, 1942, Canada's Prime Minister Mackenzie King received a delegation from Britain. The British told the Prime Minister about their top-secret military project, code-named "Tube Alloys", for building the world's first atomic bombs. They impressed upon him the strategic importance of uranium, the only naturally occurring element that can be used to produce an incredible explosive – one so powerful that any country possessing it would win the war. King was deeply impressed. The British pointed out that a privately owned Canadian company had a mine in the Northwest Territories that was rich in uranium. They wanted to work with the Canadian government to establish complete control over that uranium.

The Prime Minister entrusted the matter to C.D. Howe and to C.J. Mackenzie, President of the NRC. Due to Mackenzie's familiarity with Laurence's fission experiments at the NRC, he was in a position to corroborate the British assertions and to support their request. Howe promised the British his complete cooperation. But what exactly should he do? To nationalize Eldorado as wartime emergency measure would generate unwanted publicity; moreover, private control would resume after the war. Instead, Howe proposed to recruit Gilbert LaBine to buy up shares in the company on behalf of the government. Once a controlling interest was acquired, ownership could be split three ways, with Canada a junior partner to the US and the UK.

The British were more than satisfied with this turn of events. Gilbert LaBine readily agreed to sell the government a million shares that he owned – one quarter of the total shares issued – while continuing to serve as president of the company. He also agreed to criss-cross Canada and the USA, secretly buying up another million shares – a task which took two years to complete. Meanwhile, the British ordered twenty more tons of uranium oxide from Eldorado.

On August 17, 1942, Malcolm MacDonald, the British High Commissioner in Ottawa, paid a visit to C. J. Mackenzie. He proposed moving the heavy water research group from Cambridge to Canada, creating a French-British-Canadian nuclear research team in the process. Mackenzie was very excited by this prospect. It seemed almost too good to be true. Canadian scientists would have an unprecedented opportunity to get in on the ground floor of a brand new technology, on the very cutting edge of science, working closely with some of the finest scientific minds in the world. It seemed an exhilarating opportunity that must not be missed.

Mackenzie had no trouble convincing C.D. Howe, who was both a close personal friend and the Minister responsible for the NRC. As Mackenzie said later, ‘it was amazingly simple”. He personally escorted the British High Commissioner to Howe’s office. After listening carefully to the proposal, Howe turned to Mackenzie and said, “What do you think?” Mackenzie said it was a good idea. Howe nodded his head a couple of times, and said, “Fine. Go to it.”

Over the next few months, all the necessary arrangements were made. The British would pay the salaries of all the people they were sending over. The Canadians would pay for everything else. In scientific matters, Halban would run the show; administratively, Mackenzie would be in charge, acting for the NRC. C. D. Howe and the British High Commissioner would establish policy. Although the NRC was Ottawa-based, it was decided to house the nuclear research team in bilingual Montreal, where lab space and accommodations were both easier to obtain. A portion of the Medical Wing of the newly built Université de Montreal, situated on the slopes of Mount Royal, was leased and refurbished for this purpose.

The US authorities welcomed the joint venture. They expressed a hope that the Montreal team would maintain close communications with the Chicago team. The Canadians, who had just learned about the American-owned heavy water plant in British Columbia, argued very persuasively that the first six tons produced by that plant (one year’s output) should be earmarked for Montreal. It would add to the Norwegian inventory, which would be coming to Montreal, greatly accelerating the research. With some reluctance, the Americans agreed.

The Cambridge team started arriving in Montreal in late November and early December, months before the labs were ready. Temporary housing was provided in an old mansion on Simpson Street in downtown Montreal. It was so crowded that bathrooms were used as offices, and papers were stacked in the bathtubs. Despite the discomfort, spirits were high.

Several outstanding Canadian scientists joined the team, as well as a number of distinguished Europeans who were already in North America. The best-known Canadians were

G.C. Laurence from Ottawa, B.W. Sargent from Kingston, and G.M. Volkoff from British Columbia (who was actually born in Moscow). Of the Europeans, Bertrand Goldschmidt, a French chemist who had worked with Marie Curie in Paris, and then with Glenn Seaborg in Chicago, and most recently with Marcel Pochon in Port Hope, was a very welcome addition to the group. So was Pierre Auger, an esteemed French physicist; G. Placzek, a Czech physicist; F.A. Paneth, a German chemist; and J. Gueron, another French chemist. Lew Kowarski remained in England, stung by the fact that he had been offered only a relatively minor position in the Canadian lab. Most of the others agreed this was unfair, and a few remained behind in protest.

On December 2, 1942, the world's first self-sustaining nuclear reaction was achieved in a squash court underneath the west stands of Stagg Field, the University of Chicago football stadium, using solid blocks of uranium fuel and graphite moderator stacked in a carefully constructed pile. In honor of Fermi's historic accomplishment, for many years afterwards, nuclear reactors were called "piles" – especially by the British.

The age of nuclear fission had truly arrived. This thrilling news made the Montreal team even more eager to demonstrate how much better heavy water was than graphite as a moderator.

Some Rude Shocks

On January2, 1943, the Americans dropped an unexpected bombshell. It was a bluntly worded letter to Mackenzie. This letter, and the memorandum which followed ten days later, represented a surprisingly harsh turnabout on the part of the Americans. It put the Montreal effort on ice just as it was getting started. The project was set back, in the end, by more than a year.

The first shock: the Americans had decided to embark on their own intensive effort to produce plutonium using heavy water – the du Pont Company had already been contracted to do the necessary engineering work. The second shock: for security reasons, the Americans would no longer share any information on heavy water production, or the manufacture of uranium hexafluoride, or the method of electromagnetic separation (for enriching uranium), or the physical or chemical properties of plutonium, or the details of bomb design, or the facts about fast neutron reactions. The third shock: additional heavy water would be given to the Montreal group only if it would agree to direct its research along lines suggested by the du Pont firm.

The letter ended by saying that the assistance of the Montreal group would be greatly appreciated "in what is, after all, a joint aim – namely, the production of a weapon to be used against our common enemy in the shortest possible time under conditions of maximum security."

This blunt communication reflected the fact that the US Army had taken over the American atomic bomb project in the person of General Leslie Groves. Groves had instituted a strict policy of compartmentalization of information. No one was to have access to information, which he or she did not absolutely need to know. He regarded the Montreal group, in which so many different nationalities were represented, as a serious security risk. He also disliked the fact that some of the senior British men were representatives of International Chemical Industries.

Above all, Groves had decided that an all-out US effort was needed if atomic bombs were to be ready before the end of the war. He was not inclined to share heavy water, uranium, reactor-grade graphite, or even information, unless it would demonstrably shorten the time needed to construct atomic bombs and make them ready for use.

Seeing no alternative, the Canadians recommended compliance with the American demands; but the British refused to yield. They would not willingly submit to the unilateral dictates of the US military. Until this deadlock was resolved, the US would give neither information nor materials to the Montreal group. It was a frustrating time.

Still, a lot of solid work was done at Montreal in the spring of 1943. Important neutron measurements involving heavy water and very pure graphite (the latter being obtained from an Ontario firm) were carried out. The engineers and physicists jointly developed a number of imaginative design concepts for a boiler utilizing a heavy water moderator. In February, Goldschmidt visited his old friends in Chicago, and managed to bring back a sample of fission products. (Apparently the Chicago scientists didn't know about the new restrictions.) From this sample, the Montreal radiochemists painstakingly separated out three micrograms of plutonium, the new and exotic element 94. Further experiments were then done to evaluate and compare different methods for separating plutonium from the highly radioactive fission products.

The British wanted to force a change in US policy. Thus, when Halban was invited by Fermi to come to New York to discuss the supposed superiority of heavy water over graphite for use as a moderator, the British refused the invitation, thinking that sharing data might weaken their hand. The Canadians were furious. They felt the British were being far too stubborn.

Besides, the Canadians didn't feel the US position was altogether unreasonable, especially on security matters. On a trip to London, C. J. Mackenzie challenged the view that the Americans were giving the British a rotten deal. He pointed out how much the US was doing – far more than the British realized. Three entire cities were being built. At Oak Ridge Tennessee, uranium enrichment facilities were under construction; at Hanford, Washington, a series of graphite moderated boilers were being erected for plutonium production; at Los Alamos, New Mexico, bomb design and testing was underway, especially for the implosion mechanism needed for a plutonium bomb. The uranium bomb was much simpler in design and needed no testing.

By May of 1943, the British were muttering that they might have to "go it alone". They would need a secure supply of uranium from Eldorado. It must have come as a nasty jolt when they found that the US had completely tied up Eldorado's mining and refining capacity for years to come. It was a rude shock. How could this be? Hadn't C. D. Howe assured the British of joint control? Didn't he say that he, Howe, negotiated all contracts? In Washington, Churchill bitterly remarked to P.M. Mackenzie King that C. D. Howe "had sold the British Empire down the river."

The truth of the matter was that Howe had left Gilbert LaBine alone to do his job without interference. He had done the same with the heads of some twenty-odd crown companies that he'd created. And LaBine did what he thought was intended: he acquired control of the company on behalf of the government of Canada, and sold Eldorado's goods and services under a blanket of military secrecy. Both allies had been asked to state their future uranium needs, but the British had not responded, so nothing was put aside for them.

As previously mentioned, the US had ordered 60 tons of uranium oxide early in 1942. That summer, the order was increased to 350 tons. But then, in the fall, 1200 tons of high grade ore was discovered in a warehouse on Staten Island, stored in steel drums. It had been shipped there from the Congo in 1940 by the Belgians to circumvent the Nazis. The Americans bought it all up, and interrupted deliveries on their Canadian contract so that Eldorado could begin refining the Congolese ore. That winter, with the Port Hope refinery working full blast on the Congo job, the US ordered yet another 500 tons of Canadian oxide. This, together with 195 tons still undelivered from the previous contract, represented about three years of Eldorado's production. C. D. Howe, who was nominally in charge, knew nothing about these American contracts.

It was an awkward situation. Heavy water was soon to be produced at Trail, British Columbia, uranium oxide was being produced at Port Hope, Ontario, but the Americans owned it all. And none of it was available for the Montreal lab. At the same time, the only manufacturer of uranium metal was the USA. The Canadians and the British were snookered.

In the summer of 1943, the US Army started exploring for uranium "in more than twenty foreign countries and in thirty-six states." Several claims were registered in the Great Bear Lake region of Northern Canada. As a result, Eldorado stock began climbing in value, and unwelcome newspaper articles appeared, some of them speculating on the possible military implications of all this. In July, C. D. Howe discussed the matter with General Groves, who agreed that the US was acting foolishly. The last thing they wanted to do was to call attention to the uranium traffic.

In September 1943, C. D. Howe passed an Order-in-Council reserving to the crown "all radioactive substances" found in the Northwest Territories. By Christmas, LaBine had finally finished buying up a controlling interest in Eldorado for the government. On January 28, C. D. Howe announced in the House of Commons that Eldorado had become a crown company. "In the interests of military secrecy," he said, he hoped there would be no embarrassing questions. There were none.

The Quebec Agreement

By the summer of 1943, work in Montreal had almost ground to a complete halt. Morale was at a very low ebb. The Canadians were getting fed up with the lack of cooperation from the

Americans, the imperious demands of Halban, and the unrealistic posturing of the British. They were sorely tempted to call the whole thing off.

In July, when General Groves came to Ottawa, C. J. Mackenzie emphasized that heavy water was the best choice for producing plutonium, and therefore the Montreal Lab should be given a high priority. Groves concurred, anxious as he was not to lose any bets. He said he did favour cooperation, but insisted that the US could not just "give away" industrial know-how that was costing the taxpayer so much to acquire. He also stood firm on the question of security.

At about the same time, in London, England, senior American officials were engaged in frank discussions with the British. Some major misunderstandings about British motives were cleared up. Winston Churchill drafted a series of propositions on nuclear cooperation, which the Americans promised to relay to the President. This was to become the basis for the Quebec Agreement, signed by Roosevelt and Churchill at Quebec City on August 19, 1943. Operation Overlord, the Allied invasion of Europe through Normandy, was approved at the same meeting.

The World War II Atomic Bomb project, known as the "Manhattan Project" to the Americans, was called "Tube Alloys" by the British. The Quebec Agreement stipulated that Britain and the USA must share resources "to bring the Tube Alloys project to fruition at the earliest moment." The leaders agreed that "We will never use this agency against each other," that "We will not use it against third parties without each other's consent," and that "We will not either of us communicate any information about Tube Alloys to third parties except by mutual consent." It was agreed that "any post-war advantages of an industrial or commercial nature" would be decided at the discretion of the US President.

Although Canada was not a signatory to the Agreement, C.D. Howe was given a seat on the Combined Policy Committee. This was a six-person trilateral body, headquartered in Washington, set up to oversee the "full and effective collaboration" promised in the Agreement. As it would take some months to hammer out details, a scientific subcommittee was struck to advise the Policy Committee on technical matters. James Chadwick and C.J. Mackenzie were both on the subcommittee, which first met on September 10, 1943, at the Pentagon.

Progress was slow. By December, 1943, the Combined Policy Committee had ruled that British scientists could join in three aspects of the US effort: the gaseous diffusion project, the electromagnetic project for separating uranium isotopes, and the bomb development work at Los Alamos. This led to a mass exodus of British nuclear scientists to North America. But nothing was said about the Montreal Lab.

The next agenda item was the creation of a Combined Development Trust to control and allocate world supplies of radioactive ores. The US had asked the Belgians to reopen the Congo mine to meet the needs of the US bomb program, but they had flatly refused. Perhaps an international Trust would be a more acceptable vehicle. As Canada had not signed the Quebec

Agreement, she did not sign the Declaration establishing the Combined Development Trust either. Nevertheless, one of the six trustees would be a Canadian.

There was still no decision on the Montreal Lab. The delay seemed incomprehensible. The plant at Trail, BC, had started producing heavy water in June 1943. Now it was 1944, and the Montreal team still hadn't received an ounce of it. In fact, the Americans were secretly holding back several tons for their own heavy water reactor being built at Argonne, near Chicago. Behind the scenes, the Chicago group opposed giving the heavy water project to the Canadians; they wanted it for themselves.

The Canadians knew nothing about all this. However, they realized that the Montreal project would be more acceptable to the US if it were headed by a prominent British scientist instead of Halban. There was a good deal of unhappiness over Halban's leadership anyway. He seldom consulted others, hoarded important technical information, and treated the Canadians as subordinates.

To replace Halban, Mackenzie favoured Dr. John Cockcroft, who had once been a research assistant of Sir Ernest Rutherford's and a member of the M.A.U.D. Committee. He was now one of the key scientists in the field of radar, yet his knowledge of nuclear physics was exceptional. He was also an exceptional team worker.

In the meantime, Chadwick worked hard to secure an endorsement of the Montreal Lab from the Combined Policy Committee. He answered every objection, refuted every argument, overcame every obstacle. Finally, he prevailed. On April 13, 1944, in Washington, DC, the Combined Policy Committee decided that a large-scale pilot plant – a nuclear reactor – would be built in Canada, using heavy water as a moderator. The US would supply the needed materials.

There was a hitch, however. No information was to be transmitted about the chemical properties or even the biomedical hazards of fission products, or of plutonium. The Montreal team would have to figure it all out for themselves. The Americans did agree, however, to donate a few irradiated fuel rods from the US plants to provide a source of data.

Choosing Chalk River

As soon as news of the decision reached Britain, Cockcroft was released from his other duties and put in a bomber bound for New York. He was in Montreal by the end of April, ready to take charge. Halban graciously stepped down to become head of the Physics Division. The place was now bubbling with enthusiasm.

The first necessity was to find a firm to design and build the pilot plant. The natural choice was Defence Industries Limited (DIL), a crown company involved in munitions manufacture, whose key staff was drawn from the private company Canadian Industries Limited

(CIL). On May 18, the DIL Directors were briefed on the nature of a nuclear chain reaction and the basic requirements for a heavy water moderated pilot plant – the first nuclear reactor ever to be built outside the United States of America.

At first the DIL Directors were reluctant to accept the job, given the hazardous nature of the enterprise. While the plant could not explode like an atomic bomb, because it used only slow neutrons, it was nevertheless clear that an uncontrolled chain reaction would result in a very violent and destructive release of energy, which could blow the plant to kingdom come and scatter radioactive fission products over a very large area. It was pointed out to Dr. Mackenzie that, in case of such a nuclear catastrophe, the effect on the future public relations of CIL would be most deplorable. Mackenzie retorted that CIL would surely not escape blame if DIL refused the contract on that account and some less capable firm did the job; that could be interpreted as evasion of responsibility. On May 26, DIL somewhat reluctantly accepted the contract.

The next priority was to choose a site. For both security and safety reasons, it would have to be isolated. After scouring the shores of Georgian Bay, Lake Superior and the La Tuque region of Quebec, a secluded spot on the Ottawa River was selected in mid-July. It was 200 miles northwest of the capital, near a small village named Chalk River. A townsite for the employees was chosen at Indian Point, on a beautiful bay a few miles away.

By the summer of 1944, the Montreal group had decided on the basic design features of the pilot plant, to be called NRX (National Research eXperiment). The fuel would consist of 175 metal uranium rods, each with a thin coating of aluminum. The coating, or "cladding", would protect the fuel from chemical reactions and prevent the escape of fission products. These rods would be suspended in an aluminum tank full of heavy water, surrounded by graphite to reflect escaping neutrons back into the tank.

Since NRX would generate ten million watts of heat, the fuel would have to be cooled to prevent it from melting and releasing fiercely radioactive fission products. Even with proper cooling, radiation from fission products would be so intense that massive biological shielding would be needed to protect workers at all times, even when the plant was shut down. Moreover, reliable shutdown systems would be needed to halt the chain reaction immediately if it began to get out of control. These various safety concerns greatly complicated the design.

The NRX fuel rods were to be housed in double-walled tubes, through which ordinary "light" water would be pumped at very high speed to cool the fuel. The tubes had to be thin, so as not to absorb too many neutrons, but also strong, to prevent a loss of coolant. The heavy water moderator would fill the space outside these tubes. In between the tubes would be hundreds of adjustable "control rods", made of neutron-absorbing materials. When inserted into the tank these control rods would soak up neutrons, thereby slowing down or stopping the chain reaction.

Because of neutron activation – transmuting non-radioactive atoms into radioactive ones – all of the internal structures, including the cooling tubes, the control rods, and the reactor vessel, would become intensely radioactive. Thus, maintenance could only be done by remote control or following a very lengthy shutdown.

It was considered prudent to build a much simpler, much smaller plant, using the same fuel, moderator and reflector as NRX, but not powerful enough to need cooling, and not radioactive enough to prevent workers from approaching it. It would be called the "Zero Energy Experimental Pile" (ZEEP). Cockcroft sent for Lew Kowarski, a member of the original Paris group who had remained in England, to supervise the operation. He arrived in Canada in late July to take charge of ZEEP, accompanied by the other members of the Cambridge team who had stayed behind – partly because of personal difficulties with Halban.

The Canadian government had offered to pay the whole shot. However, the initial cost estimate came as something of a shock. It included the NRX nuclear reactor, the ZEEP nuclear reactor, two chemical extraction plants, a huge water purification plant, and a maze of labs and offices. It also included an entire planned community at Indian Point – the newly-created village of Deep River – complete with hospital, school, shopping centre, recreational hall, and administration building. After some hesitation, Ottawa bravely gave the final go-ahead on August 19, 1944, just six days before the liberation of Paris.

Planning Ahead

Meanwhile, back at the Montreal Lab, there were about a hundred very busy scientists – over forty Canadians, an equal number of British, and twelve others, including five French citizens. During the fall of 1944 and the spring of 1945, much of their effort was directly related to solving the detailed design problems of ZEEP and NRX. There was time, however, for other types of advanced research.

The Americans suggested that provision be made for thorium rods to be inserted in the NRX reactor. It was known that thorium-232 atoms change into fissile uranium-233 atoms by neutron capture, just as uranium-238 atoms change into fissile plutonium-239 atoms. Uranium-233 does not exist in nature. It is a brand new human-made isotope of uranium that can be used as a powerful nuclear explosive. It is therefore worth investigating, said the Americans.

The Montreal Lab designed two chemical extraction plants – called "reprocessing plants" – to be built at Chalk River in order to extract nuclear-weapons-usable materials from a hot acidic solution of radioactive fission products. One plant was intended to extract plutonium from irradiated uranium rods, the other was to extract uranium-233 from irradiated thorium rods. In both cases, the solid metallic rods had to be dissolved in boiling nitric acid so that the nuclear explosive materials could be chemically separated out of the hot chemical bath, leaving large volumes of highly radioactive and corrosive liquid wastes to be stored in large tanks onsite.

The British were beginning to plan for the post-war period. Having no heavy water in England, they settled on using graphite as a moderator for British reactors. Accordingly, a Graphite Group was formed at the Montreal Lab in December, 1944, to work out the details. By the end of the war in August 1945, all the basic design work had been done for what was to be Britain's first major experimental nuclear reactor at Harwell, called BEPO. All of the graphite used in the first few British reactors came from Ontario.

Early in 1945, a Future Systems Group was formed in Montreal to brainstorm on other possible reactor designs. They investigated a variety of liquids and gases for use as reactor coolants. They searched out materials that resist corrosion, conduct heat and tolerate prolonged radiation exposure. In the end, they anticipated almost every major conceptual development in nuclear boilers for the next quarter century and beyond.

In particular, they perceived that economic deposits of uranium are relatively scarce. Accordingly, if fission energy is to last for more than a few decades, they saw the need to "breed" man-made substitutes for uranium-235; either plutonium-239 (bred from uranium-238) or uranium-233 (bred from thorium-232). They anticipated the future use of "advanced fuel cycles", in which plutonium and thorium would supplant uranium as the principle nuclear fuels.

They were thus led to conceive a futuristic type of nuclear boiler, fueled by concentrated fissile material, fissioned by fast neutrons rather than slow ones, and surrounded by a blanket of "fertile material" such as uranium-238 or thorium-232, in which "fissile materials" would be "bred" by neutron capture. In principle, more fissile material can be created in the blanket than is consumed in the fuel. This could greatly extend the supply of nuclear fuel. Such advanced boilers are called "fast breeder reactors", because they use fast neutrons to breed fissile material. Fast breeders have since been built in the USA, the USSR and France, with mixed results.

The Montreal Chemistry Division also did groundbreaking work. In July 1944, the Americans delivered a few irradiated rods of natural uranium (containing plutonium-239) and of thorium (containing uranium-233). The Montreal team knew little about the US method for separating plutonium, except that it was based on precipitation. After dissolving spent fuel in a chemical bath, the Americans would convert the dissolved plutonium into a solid that can then be harvested, leaving the fission products in solution.

Precipitation had one big disadvantage: it could only be done in batches. It was a stop-and-start operation. The Montreal team wanted a process that would run continuously, mass-producing plutonium for bombs. Over two hundred different solvents were studied, to strip plutonium away from the fission products, creating two liquid fractions that (like oil and water) do not mix. The plutonium-bearing fraction could then be separated mechanically and continuously and plutonium could be extracted from it at will.

As fission products are lethally dangerous even at a distance, the irradiated rods could not be handled directly; all work upon them had to be done behind a shield of thick concrete. The

Montreal Health Section developed instruments ("dosimeters") to record individual levels of radiation exposure. They also began studying the biological effects of atomic radiation. Looking beyond, they foresaw that NRX and ZEEP would produce large quantities of human-made radioactive isotopes, some of which might be useful as substitutes for radium in cancer therapy or as "radioactive tracers" for use in science, medicine and industry.

The sixteen months between the Combined Policy Committee's decision and the dropping of the atomic bombs on Japan were happy and fruitful times at the Montreal Labs. The basis was laid for three post-war nuclear programs: the Canadian, the British and the French. The British made detailed plans for their post-war nuclear industry through research carried out at Montreal and Chalk River. Both the British and French gained a distinct post-war advantage in reprocessing technology (extracting fissile materials, particularly plutonium, from irradiated nuclear fuel) based on the Montreal experience. That advantage persists to the present day.

End of an Era

News of the atomic bombing of Hiroshima reached Ottawa just before noon on August 6, 1945. As a member of the Combined Policy Committee, C.D. Howe expected it. In a prepared statement released that day, he said: "It is a particular 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 development." Three days later, on August 9, Nagasaki was A-Bombed.

Using all three methods of isotope separation, the Americans had produced enough uranium-235 for just one bomb: the one used on Hiroshima. They had also produced enough plutonium-239 for just two bombs: the one tested in the desert at Alamogordo in July, and the one dropped on Nagasaki. There were none left in the arsenal. However, there was an enormous establishment at work churning out materials for more bombs. The postwar nuclear arms race had already begun.

On August 13, 1945, at an Ottawa press conference, one of the best-kept secrets of the war was discussed: Canada's participation in the atomic bomb project. The first public account of the Montreal Lab and the Chalk River complex was given. The press release described NRX (about half finished) as "a pilot plant for the production of atomic bomb materials", specifically plutonium. The construction force was over 2000 men, and growing; it included some 250 prisoners of war. The nuclear program was costing Ottawa more than all other scientific or industrial research and development activities combined.

On September 5, ZEEP started up. It was the first operating reactor in the world outside the USA. The next day, September 6, just one month after Hiroshima, a Soviet cipher clerk in Ottawa named Igor Gouzenko revealed the existence of a large Russian spy ring in Canada. One of its missions was to obtain information about the atomic bomb project. A British scientist – a member of the Montreal team – was one of the spies.

It was a shocking revelation, but hardly a surprising development. The Soviets had known since 1940 of a large secret project involving atomic fission, because most nuclear scientists in the West had suddenly stopped publishing any papers on related atomic research. And, when two Soviet scientists announced their discovery of spontaneous fission in June, 1940, their report was met with an unnatural wall of silence from the West. Nonetheless, the Gouzenko affair tended to confirm Groves' worst suspicions and feed the emerging paranoia of the cold war period. In turn, the Soviets saw the Japanese Atomic Bombings as an ominous warning directed at them, as was intended by the Americans.

At that time Harry Truman was US President, and Clement Atlee was British Prime Minister. Neither of them knew anything about the atomic bomb before coming to office. In his diary of October 11, 1945, Mackenzie King wrote: "How strange it is that I should find myself at the very centre of this problem, through Canada possessing uranium, having contributed to the production of the bomb, and being one of the three countries to hold most of the secrets."

On November 15, the heads of the three governments met in Washington and issued a frank statement, a Joint Declaration, solemnly recognizing that the Atomic Bomb represents a level of destruction "hitherto unknown, against which there can be no adequate military defence, and in the employment of which no single nation can in fact have a monopoly." Accordingly, the Joint Declaration included an impassioned appeal from the Bomb-making countries for international action to eliminate the use of atomic energy for destructive purposes and to promote its use "for peaceful and humanitarian ends."

British Prime Minister Clement Atlee offered his opinion that nuclear weapons would not be relinquished unless war itself was renounced. In his view, although people can easily understand that

> "rivers as strategic frontiers have been obsolete since the advent of air power, it is infinitely harder for people to realize that even the modern conception of war is now completely out of date. The only course which seems to offer a reasonable hope of staving off imminent disaster for the world is joint action by the U.S.A., U.K. and Russia based upon stark reality. We should declare that this invention has made it essential to end wars."