CANADA AND THE ATOM

CHAPTER TWO

DISTANT EARLY WARNING SIGNS

Gordon Edwards

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Distant Early Warning Signs

Almost accidentally, Canada had been drawn into the largest secret operation in human history. The object of the endeavor was to produce the most destructive weapons ever conceived. The scientific research may have been fueled by curiosity, but the secret project was fueled by fear: fear that Adolph Hitler would develop such weapons first and use them against innocent men, women and children. There was little doubt that he would do so if given the chance. It would be a logical extension of his tactic of terrorizing civilian populations from the air, as at Guernivca..

After the first atomic bombs had been built, they were used in exactly the same way that people feared Hitler might use them: to incinerate cities full of non-combatants in order to force an enemy to capitulate. It was a poor example for the world to follow. An unrestrained nuclear arms race ensued. Terror from the air, which had once been the hallmark of the German Wehrmacht, soon became an avowed policy of MAD – Mutually Assured Destruction – by Hitler's most implacable enemies: the western democracies and the Soviet Union.

There was an understandable zeal on the part of scientists and politicians to demonstrate that nuclear energy is capable not only or horrific destruction, but also of enormous good. Surely the amazing energy stored in the atomic nucleus could be used to fight poverty, disease and hunger – to make a better, more peaceful world, by providing safe, clean, cheap, abundant energy for all. The underlying causes of war itself might even be eliminated.

Such was the vision that inspired those who advocated the peaceful uses of atomic energy – a vision that was remarkably successful in capturing the imaginations of millions of people: Walt Disney even made a movie entitled "Our Friend, the Atom".

During the 1940's and 1950's, however, there were a number of omens – warnings that the vision of a nuclear-powered utopia might be an unrealizable dream. There were hints that nuclear energy might never be successfully divorced from its military roots; that atomic radiation may prove to be fundamentally inimical to a healthy and wholesome environment; that ultimately, nuclear accidents might prove as threatening as nuclear weapons; and that nuclear power may never become economic since the liabilities multiply faster than the benefits.

I. The Brotherhood of the Bomb

Two Japanese cities were instantly reduced to rubble by A-Bombs in August 1945, bringing World War II to an end. Three months later, in November, Canada's Prime Minister, Mackenzie King met with US President Harry Truman and British Prime Minister Clement Atlee in Washington DC. As leaders of the three powers that had cooperated to produce the first atomic bombs, they issued a Joint Declaration formally calling on the nations of the world to eradicate the use of atomic energy for destruction and to promote its use for human well-being. The three allies urged the newly formed United Nations to work toward this end.

In private, the same three leaders drew up and signed a secret agreement aimed at preserving a virtual monopoly over nuclear knowledge and materials. The new agreement pledged to maintain and expand two important wartime structures. One was the Combined Policy Committee, which would continue to coordinate the exchange of secret nuclear information among the three allies. The other was the Combined Development Trust, with an expanded mandate to pool and allocate uranium resources from every part of the globe. The three nations also agreed not "to use atomic weapons against other parties without prior consultation". Mutual consent would no longer be required when nuclear weapons are used, as had been the case under the Quebec Agreement, and not a word was said about eliminating nuclear weapons. It was a curiously contradictory stance – but it was a fair reflection of the schizophrenia of the time.

By the war's end, Canada had invested far more money on the nuclear project than all other government-funded R&D expenditures combined: developing uranium resources, hosting a multinational nuclear research effort , and establishing one of the world's most signfiicant nuclear establishments at Chalk River. Still more money would be needed to keep these enterprises going. There were only two possible funding sources: increased taxes, or military contracts. Canada opted, after the war, to commit itself to the peaceful use of nuclear technology, foregoing nuclear weaponry. But in fact, the only immediate customers for nuclear goods and services were military. Moreover, the 1945 agreement had tied Canada's nuclear program to two allies – Britain and France – with secret military ambitions to develop their own nuclear arsenals.

This quandary would become a recurrent theme throughout the nuclear age: can any fledgling nuclear program sustain itself without the support of the military?

A Parting of the Ways

As the war drew to a close, the Americans made it clear that they did not want the Paris group to remain a part of the Montreal team that would be running the Chalk River nuclear research site. General Groves had always regarded the French contingent as a security risk because of its multiple and diverse European interconnections as well as their leftist leanings, so they packed their bags and returned to liberated France. There they set to work building the foundations for France's own robust civilian and military nuclear programs, including a superior plutonium extraction capability based on the "solvent extraction" method developed in Montreal.

Following Japan's surrender, the future of the Chalk River complex was very much in doubt. Britain was determined to launch its own autonomous civilian nuclear program, which made the Canadians quite uneasy. Would the British, too, be withdrawing from Canada? The small pool-type ZEEP reactor was already running at the Chalk River site, using heavy water as a moderator and graphite as a neutron reflector, but the startup of the NRX reactor was still one or two years away. Ottawa did not want to be left in the lurch with such an expensive and demanding project on its hands.

Anxieties multiplied when, in October 1945, it was learned that Cockcroft, director of the Montreal/Chalk River project, was being recalled from Canada to direct the newly formed UK Atomic Energy Research Establishment at Harwell, England. For the next twelve months, he commuted back and forth across the Atlantic. He had to supervise the completion of NRX at Chalk River as well as the building of Britain's first two reactors, the GLEEP and BEPO "piles", in abandoned airplane hangars not far from Oxford. With no heavy water, and no industrial capability to enrich uranium, Britain had opted to use graphite as a moderator for its reactors, which were to be fueled with natural (unenriched) uranium.

But the British still needed the Canadians. British scientists had been at Los Alamos, so they knew how to build a plutonium bomb. They also knew how to enrich uranium, though they did not yet have the facilities to do so. However, much of the hands-on work of producing and separating plutonium without direct military control was being carried out in Canada – first in Montreal, then at Chalk River – and the British were determined to remain a vital part of that effort.

To assuage the Canadians' fear of imminent desertion, James Chadwick phoned C.J. Mackenzie in Ottawa in February, 1946, and recommended Wilfrid Bennett Lewis as a first-class replacement for Cockcroft. Walter Zinn had earlier been considered for the job. Zinn, a native-born Canadian who was in charge of the only other heavy water reactor in the world – Chicago Pile-3 (CP-3) at the Argonne National Laboratory – would have been a perfect choice. However, he was not available, as he was going to be busy designing an experimental breeder, the EBR-1 reactor – Chicago Pile-4 (CP-4) – at Idaho Falls. So W.B. Lewis was recruited instead. He ended up serving at Chalk River for 27 years, and came to be known as the "Father of the CANDU".

W.B. Lewis arrived in Canada from England in September 1946 to assume his new duties. Just one month earlier, the US Congress had passed the McMahon Act, making it a treasonable offence, punishable by life imprisonment or death, for any American to transmit information about nuclear technology to any other nation. This harsh piece of legislation was triggered in part by the sensational revelations by Igor Gouzenko of a Russian spy network in Canada, which burst into public view in February 1946. General Groves informed the US Congress that a British member of the Montreal team, Alan May Nunn, had successfully transferred sensitive information and fissile material – minute specks of uranium-235, uranium-233, and plutonium – to the Soviet Union. As a result, Britain was no longer to be trusted. In April 1946 Truman declared that the USA would not assist Britain to design, build or run a plutonium production facility in the UK.

Of course the McMahon Act contradicted both the Quebec Agreement and the Truman-Atlee-King agreement, but the US Congress knew nothing about those secret deals. The new Act created a gulf between the British and American programs – a rift that was deeply resented by the British, who realized that nuclear partnership with the USA was now an impossibility. The Americans acknowledged no debt of gratitude to the British, who had done most of the early work on the development of an atomic bomb. Nor did the Americans feel any obligation to share with Britain the atomic bombs they had at their disposal. Only research results would be shared.

The new reality made the Canadian connection even more important to the British. The Americans were willing to tolerate but not assist the Chalk River project, which included the production and chemical separation of the two new human-made fissile materials, plutonium and uranium-233.

Plutonium from Canada

In January 1947 Britain secretly decided to build its own atomic bombs. Plutonium was selected as the nuclear explosive of choice. It has a smaller critical mass, and is quicker and cheaper to produce than enriched uranium-235. The British chemistry team from Montreal, now working at Chalk River, consisting of about a dozen men, was asked to design a plutonium separation plant (or "reprocessing plant") to be built in Britain as soon as possible. Using some irradiated rods previously donated by the USA, the Montreal scientists extracted several milligrams of plutonium – about enough to cover the head of a pin. They had to base their blueprints for an industrial-scale plant on what data they could glean from this tiny sample.

In July 1947, after many aggravating delays, NRX was finally started up. It soon became known as the finest and most powerful research reactor in the world. It had a neutron density (or "flux") unsurpassed anywhere. For this very reason, it was a prodigious producer of heat, of radioactive isotopes, and of plutonium. The Chalk River team had also built a pilot reprocessing plant to separate plutonium, with the advice of the Montreal chemistry team. In 1949, plutonium was extracted for the first time from irradiated NRX fuel. The experience proved invaluable to the British military program. In fact all of the design and pilot work for the Windscale industrial-scale reprocessing plant, to be built in northern England, had now been accomplished in Canada.

By 1949, the British began hinting that Canada should build a more powerful reactor to produce even larger quantities of fissile materials. Canada had not been informed of Britain's decision to develop nuclear weapons, although the truth was suspected. But at the same time, the University of Saskatchewan was asking Chalk River to produce a human-made radioactive isotope, cobalt-60, for use in cancer therapy. The intense gamma rays from cobalt-60, being much more powerful than most x-rays, could be used to treat deep-seated cancers that x-rays cannot reach. W.B. Lewis agreed that a new reactor was desirable to keep the Chalk River project from stagnating. It would have to be more powerful and more versatile than NRX, and correspondingly more expensive. It could produce plutonium as well as cobalt-60 and other radioactive isotopes for a variety of uses. The cost, of course, would be difficult to justify.

In a secret progress report dated May 31, 1949, Lewis confided that "Plutonium may be regarded as a valuable product, and the plant designed to justify its cost by the revenue from the plutonium produced." C.J. Mackenzie had arrived at the same conclusion back in February, when he wrote "Costs are fantastic – we must begin to think in terms of [plutonium] production". And again, "A plutonium production unit was necessary for Canada." But would the US buy it?

In August 1949, the Soviet Union exploded its first atomic bomb, shocking everybody; it was at least two years earlier than anyone had anticipated. In February 1950, Klaus Fuchs, a German refugee physicist who had been sent by the British to work at Los Alamos, confessed to passing secret information about nuclear weapons design to the Soviets. Then, in June 1950, South Korea was invaded by the communist North. Many people saw these developments as alarming evidence that communism was on the march towards eventual world domination.

Bigger and better nuclear weapons were planned to help contain the “red menace”. Consequently, the US could make use of any extra plutonium that it could get. In August 1950, C.D. Howe received a letter from the US agreeing to purchase all of the plutonium produced in Canada. The exact terms were settled by December and the deal was accepted over the phone by the Chairman of the US Atomic Energy Commission, Gordon Dean. “He said he thought our price was perhaps a bit high,” wrote Mackenzie later, but he also indicated that this was more than compensated for by “our splendid cooperation and good will”.

On December 20, 1950, Howe informed Mackenzie that the order-in-council approving the new reactor had been passed. It would be called the NRU reactor (National Research Universal). For the next fifteen years, until the contracts expired in 1963, plutonium produced at NRX and NRU was routinely sold to the US military for bombs – about 250 kilograms in all, enough for 40 to 80 nuclear warheads. Kilogram quantities of plutonium were also made available to the British. In fact, the very first billet of plutonium metal produced in Britain came from a liquid solution of plutonium that was sent from Canada early in 1952.

A few months later, the first British atomic bomb was detonated on September 30, 1952. The blast took place in the Monte Bello Islands off Australia. Seven potential testing sites in Canada had also been considered, but were turned down for various reasons; the most promising candidate had been a site near Churchill, Manitoba. By then Canada knew what it was all about. Canadian scientists were present as honoured guests to witness the first British atomic explosion, which was fitting since the bomb likely did incorporate some of the plutonium from NRX.

On December 12, 1952, the first major nuclear reactor accident in the world took place at Chalk River, when the NRX reactor suffered a destructive partial meltdown following a series of violent hydrogen gas explosions. Of the hundreds of men brought in to clean up after the NRX accident, Jimmy Carter was one. He was part of a delegation of American nuclear engineers working under Admiral Hyman Rockover, the man who created the US nuclear submarine fleet.

In the late 40s and early 50s there were two reprocessing plants in operation at Chalk River, one to extract plutonium from irradiated uranium rods and the other to extract uranium-233 from irradiated thorium rods. A 1950 chemical explosion related to the reprocessing operation killed one man and injured two others. Both plants were permanently shut down in 1954 when it became clear that they were completely unaffordable.

While the British were assisting the Canadians in the construction of the ten times more powerful NRU reactor, the French were assisting Israel in the design and construction of its heavy water Dimona reactor. The Dimona plant bears some striking similarities to the Chalk River NRX reactor, which the French had helped design during their time in Montreal. And like NRX, the Dimona reactor is exceptionally good at producing plutonium, which formed the basis of the Israeli nuclear weapons program.

Although Canada chose never to build atomic bombs, Chalk River had become one of the best places on earth to learn about the basic properties of plutonium – how to produce it, and how to extract it from irradiated fuel. Nations who aspired to nuclear weaponry took note. The Canadian reactors had earned a well-deserved reputation as the best plutonium-producing reactors in the world.

To the Rescue

By 1945, Eldorado was in wretched financial condition. During the war years, it had been losing money steadily by selling uranium to the US army at prices insufficient to cover its costs. At the end of the war, an outstanding contract for 350 tons of uranium oxide was based on give-away prices guaranteed to lose the company even more money. Senior management had only the vaguest idea of what was going on; no one seemed to know all the facts. To make matters worse, future prospects were unclear. Would there be a market at all, now that the war was over?

William Bennett, C.D. Howe’s right-hand man in Ottawa, was asked to take charge of Eldorado’s affairs. For starters, he arranged a three million dollar government bail-out in the summer of 1946. Then, as he put it, “I went with my hat in my hand to see General Groves”. Upon verifying Eldorado’s plight by having the books inspected, Groves agreed to help out by re-negotiating the terms of the contract, increasing the price from $4.62 to $6.17 per pound.

Eldorado’s financial bind had been eased, but it was not enough. The grade of ore being mined at Port Radium was declining. The entire deposit might be exhausted within a couple of years. If Eldorado were going to stay in the uranium business at all, it would have to invest in exploration and development. That meant raising the price of uranium oxide to $12 per pound.

The British, who had just embarked on their own atomic bomb program, were in the market for uranium, but not at that price. They could get it far cheaper from the Congo. For that matter, so could the Americans. There were no new contracts in sight for Canada. In the spring of 1947, the Atomic Energy Control Board (created by Parliament the year before) recommended the creation of a government stockpile to absorb surplus production. In this way, all uranium mined in Canada “could be conserved for the general advantage of Canada.” But would Parliament approve the enormous expenditures required? It seemed unlikely.

The US army came to the rescue. In the summer of 1947, new contracts were signed at the new price. Military requirements for uranium were not diminishing after all. Prospects for the international control of nuclear weapons were receding, as the US and the USSR had reached a diplomatic deadlock. The US wanted to establish an international system of inspection and control before getting rid of its atomic arsenal. The USSR wanted to eliminate all nuclear weapons first, before agreeing to any system of control. Thanks to cold war intransigence, a nuclear arms race was just beginning, and Eldorado was finally going to make some money.

Over the next fifteen years, Eldorado profited handsomely from lucrative US military contracts. At first, Canadian uranium supplies were only a fraction of the Congolese production, and much more expensive to boot, but the Americans bought it anyway. Eldorado was greatly assisted by having access to privileged information. Through Canada’s position on the Combined Development Trust, Bennett was able to keep tabs on the newly discovered uranium resources of South Africa and Australia as well as those of the Congo and elsewhere. He learned that US military requirements greatly exceeded what could be obtained from these sources.

This was especially true after the autumn of 1949, when the US was stunned by the unexpected detonation of the first Soviet A-bomb, years before it had been considered possible. President Truman responded by authorizing the development of thermonuclear weapons, or “H-bombs”, a thousand times more powerful than the tiny A-Bombs that had been used against Japan. As a result, the uranium business boomed, and Canada got the lion’s share of the action.

H-Bombs derive their enormous power from nuclear fusion rather than nuclear fission. Instead of splitting heavy atoms like uranium or plutonium, nuclear fusion derives energy by combining or “fusing” very light atoms together – usually these are isotopes of hydrogen, hence the “H” in the term H-Bomb. Nuclear fusion is the same type of nuclear energy that has kept our sun burning for billions of years, along with all the billions upon billions of stars in our universe.

It turns out that a fusion reaction can only be initiated by raising the temperature to 50 million degrees or more, and that can only by achieved quickly by detonating a small fission-type A-Bomb, which is used as a “trigger” to ignite the fusion reaction in the H-Bomb. Thus every H-Bomb has a trigger made of plutonium. When warheads are eventually dismantled, the plutonium triggers are removed, whereupon the H-Bomb is no longer a Bomb – it is harmless.

Plutonium is created in uranium-fuelled nuclear reactors, so lots of uranium is needed when H-Bombs are being mass-produced. And so they were – beginning in the 1950s, the USA built an arsenal of over 30,000 nuclear weapons. Inside almost every American nuclear warhead is a bit of Canadian-origin material, as every atom of plutonium starts out as an atom of uranium.

For the remainder of the 20th century, Canada was to be the world’s largest producer and exporter of uranium. For the first three decades, 1940 to 1970, it was virtually all sold for bombs. For the following three decades, 1970 to 2000, it was all earmarked for peaceful purposes. As we shall see, however, even then some Canadian uranium continued to find its way into bombs.

The Great Canadian Uranium Boom

In the late 1940s and 1950s new mines opened up. Near the north shore of Lake Athabasca, fifty miles south of the Northwest Territories, just inside the provincial boundary of Saskatchewan, Eldorado founded the Beaverlodge mine, as well as a mill, a transportation system, and a town (Uranium City). Needless to say, it all had to be paid for. The US Atomic Energy Commission, under increasing pressure from the Pentagon to step up the uranium supply, obligingly agreed in 1952 to buy everything that Eldorado could produce for the next ten years.

In 1953, private uranium producers started getting into the act. C.D. Howe’s 1943 order-in-council forbidding private involvement in the uranium business was revoked in 1948. Ironically, the first major discovery was again by Gilbert Labine, who had recently severed his connections with Eldorado. The ore he found was close to the surface, and inexpensive to mine. This was the Gunnar mine, not far from Beaverlodge on Lake Athabasca. It was a rich find.

Even so, it was dwarfed by the discoveries made in Ontario. Along the north shore of Georgian Bay in the Elliot Lake area, seven large uranium mines would soon be located. Three more were opened up in the Bancroft area. There was a second mine in the Northwest Territories, several more in Northern Saskatchewan, and even one in Manitoba. Each of these private mines was required by law to sell its ore to Eldorado, who in turn sold it to the US to feed the burgeoning bomb program. The US obligingly sold back to Canada the small amounts of uranium metal needed to fuel the Chalk River reactors.

Annual exports of uranium oxide soared from about 200 tons in 1947 to more than 12,000 tons in 1959, easily surpassing those of the Congo, by a factor of three. In 1959, uranium was Canada's principal mineral export. In dollar value, it was the fourth most important export in the country, after lumber, pulp, and wheat. In just a few years – mainly in 1958, 1959, and 1960 – a billion and a half dollars' worth of uranium went south. It was all for bombs. Britain also placed orders for Canadian uranium in the mid-1950's to support its own weapons program.

The uranium bubble burst in November, 1959, when the US announced that no further purchases from Canada would be made after 1962. The news wasn't really unexpected – it was, after all, the end of the ten-year period that had been agreed to in advance – but it nevertheless came as a disagreeable shock to seventeen uranium companies. It threatened the viability of twenty-eight mines and three entire communities: Uranium City, Elliot Lake and Bancroft.

The Americans and the British agreed to stretch out deliveries of uranium until 1966, to soften the blow. Nevertheless, by 1962, there were only four uranium companies left in business. The population of Uranium City was cut in half. Elliot Lake fared much worse. Businesses failed, homes were deserted, mortgages were foreclosed. In order to save the uranium industry from utter extinction, the government of Canada created an expensive uranium stockpile. Government subsidies kept the surviving uranium mining companies in operation, producing uranium for which there were no customers. The government of Canada bought it all.

There has never been a civilian demand for Canadian uranium on a scale comparable to the military demands of the 1950s.

II. Radiation: The Unseen Killer

Early in 1945, Eldorado was warned by nuclear scientists from the Montreal Lab that radiation exposures at Port Radium and Port Hope constituted "a very serious industrial hazard". In the mine, the principal hazard was lung cancer caused by breathing a radioactive gas. In the refinery, there was a risk of cancers of various internal organs or of the bone due to chronic exposure to gamma radiation and ingestion or inhalation of radioactive dust and gas.

There were ample precedents for these concerns. For four hundred years it had been known that men who mine certain ores – uranium-bearing ores – suffered from a terrible curse; most of them died from fatal lung diseases. In the early decades of the 20th century, many radiologists suffered not only radiation burns from x-rays, but leukemias and other radiation-induced cancers. W.K. Roentgen, the discoverer of x-rays, died of bone cancer in 1923. Since its discovery by the Curies in 1898, radium had proven to be a superb carcinogen. Even minute amounts ingested into the body can cause fatal illnesses of the skeleton, the blood and the head. Marie Curie and her daughter Irene – both of whom worked with radium – died of aplastic anemia, a disease that is sometimes confused with leukemia.

The culprit, in all of these cases, was radiation. Specifically, it was ionizing radiation.

Hold Your Breath

Early in 1945, two scientists were sent from Montreal to Port Radium to investigate allegations that the radiation levels in the mine constituted a health hazard. The two men were Alan Nunn May and Bruno Pontecorvo. Ironically, both men were later discovered to be Soviet spies; May was implicated at the time of the Gouzenko revelations that emerged several months later, while Pontecorvo's Soviet involvement was not revealed until after the conviction of Klaus Fuchs in March 1950. Pontecorvo fled to Moscow and lived out the rest of his life there.

The levels of radon gas (specifically, radon-222) in the mine did indeed measure very high. Since this radioactive gas is a radioactive decay product of radium, it is constantly being created inside the solid ore body. In 1900, at McGill, Rutherford had discovered a different isotope of the same gas, namely radon-220, emanating from the naturally-occurring radioactive element thorium-232. As long as a radioactive ore body is undisturbed, only a tiny fraction of the radon escapes from the surfaces of the solid rock and finds its way into the atmosphere. Since radon has a short half-life, measured in days or hours depending on the isotope, most of the radon disintegrates long before it can reach the surface. But as soon as the rock is excavated, blasted, or crushed, as in the Eldorado mine, large amounts of the trapped gas are released into the air that the miners must breathe. Moreover, radon continues to emanate from the crushed rock at a much faster rate than ever before, since the exposed surface area of the ore, which was once solid and undivided, is greatly increased – by a factor of many millions.

Since radon gas is seven or eight times heavier than air, it can only be removed from an underground mine by utilizing powerful blowers. The Eldorado mine was not well ventilated to begin with, and in cold weather, the ventilation ducts were frequently blocked to keep the frigid arctic air out of the mine shafts. Consequently, radon gas would often accumulate and stagnate for many days, hanging in the dank subterranean environment.

Stagnation makes the hazard very much greater. As the radon gas hangs in the air, its atoms undergo radioactive disintegration, producing half-a-dozen different radioactive decay products, called "radon progeny". These are radioactive isotopes of polonium, bismuth and lead, and they are solids; however, as they are created one atom at a time, they behave very much like gases. Having an electric charge, they attach themselves to tiny dust particles or to droplets of water vapor floating in the air. When those attached particles are inhaled, the radon progeny lodge in the lung and deliver an extremely high dose of radiation to the delicate pink tissue.

Miners' Lament

The harmful effects of radon have been traced as far back as the sixteenth century. A document from 1546 indicates that miners in the region of the Erz Mountains, which straddle the border between Germany and Czechoslovakia, had an shockingly high frequency of fatal lung diseases. In 1879, Harting and Hesse demonstrated both clinically and anatomically that the principle disease, which was still afflicting miners in the area, was a malignancy of the lung tissue: in other words, lung cancer. Subsequent reports indicated that in Schneeburg (Germany) and Joachimsthal (Czechoslovakia), about half of all miners died of lung cancer. Of the rest, a large percentage died from other sorts of lung diseases.

By the 1930s, it had been proven that airborne radioactivity (radon) was the agent responsible for the excess lung cancer among miners. When Nunn and Pontecorvo reported the Eldorado measurements to their colleagues in Montreal, there was general agreement that the problem was a very serious one. As F.A. Paneth wrote in March of 1945, "the radon content seems to be so high as to be definitely dangerous to the health of those working in the mines."

This was news to the Eldorado mining engineers, who had been routinely dismissing workers' complaints about the air quality underground. Their attitude was understandable, since radon gas is colorless, odorless, and tasteless. It is also chemically inert – it does not combine chemically with any other substances. Besides, the harmful effects of excess radon exposure are not apparent until at least ten years, or even twenty years or more, after exposure. Moreover, only sophisticated instruments can detect the presence of the gas and measure its concentration.

In order to be certain, the original radon measurements were replicated in August 1945. The diagnosis was confirmed: woefully inadequate ventilation. In October, large motorized fans were ordered for the mine. They were delivered the following May. Whether these measures were sufficient to rectify the situation would not be known for decades.

At least they had been warned, and some corrective actions had been taken.

Some Like It Hot

In a parallel development, during the spring of 1945, radiation measurements were taken at the Port Hope refinery by scientists from the National Research Council (NRC). The readings were high. Too high. Many workers were clearly being over-exposed, even by the standards of the time. Several areas of the refinery were so badly contaminated that they shouldn't have been used at all. Tests continued throughout the summer, and some efforts were made to reduce contamination levels. A follow-up conference on the subject of radiation exposure was organized at the Royal York Hotel in Toronto in September, 1945.

J.S. Mitchell, one of the British scientists working in Montreal, was the officer in charge. He opened the Toronto conference by announcing that recent findings had shown "that the effects of radioactive radiations on health are more, rather than less, important than was previously appreciated." He advocated much tighter restrictions on permissible exposures to gamma radiation. One-twentieth of a rem (0.05 rem) per eight-hour day, in his judgment, should be regarded as an absolute maximum. That's quite a high level of exposure – equivalent to two chest x-rays per day, using modern equipment. It amounts to more than 18 rems per year.

At the Toronto Conference, the necessity of preventing radioactive contamination was also emphasized. If minute amounts of radioactive materials are ingested, inhaled, absorbed through the skin, or lodged in pores and hair follicles, the worker will carry the radioactivity home and be continuously irradiated, day and night, for a considerable period of time. Company uniforms, on-site laundering, meticulous showering, dust suppression, improved ventilation, decontamination: all of these were necessary for health reasons. It was pointed out that some areas of the plant were so badly contaminated that they might have to be demolished.

Please Don't Lick The Brushes

Deaths caused by radium exposures were well known long before the Toronto Conference took place. At a scientific institute in Hamburg, Germany, a memorial had been erected in 1936 to the "X-ray and Radium Martyrs of All Nations" including of 169 researchers and staff people who had died of acute radium poisoning. Even the more subtle cancerous effects of radium had become quite evident as early as 1920. Ten years later, in 1931, H.S. Martland published his classic study on "The Incidence of Malignancy in Radioactive Persons," which documented the full scope of the radium dial-painters' tragedy.

Since the beginning of the 20th century, thousands of women – mostly teenagers – were employed in factories throughout Europe and North America to paint figures on dials and instruments with a radium-based paint. The dials glowed in the dark as the radioactive emissions from radium continually stimulated the phosphorous compounds in the paint. In Canada, such factories existed in several major cities. Their business increased dramatically during the two world wars, as the military ordered vast quantities of self-illuminating instruments for night-time use by pilots, divers and soldiers.

Over the years, more and more of these women became anemic. Many developed bone cancers. Some developed leukemia. Others developed head cancers – cancer of the sinuses and the mastoid, as well as the jawbone and the tongue. These are all extremely rare forms of cancer. Since the only thing the women had in common was their chronic exposure to radium, it seemed obvious that their cancers and related blood disorders were caused by radium exposure. Martland's carefully documented study removed all doubt.

It made sense. The women were using fine-tipped brushes to paint tiny luminous figures. In order to get a sharp point, they were told to touch the brush tips to their tongues. In this way, they swallowed minute quantities of radium. Over a period of years, it might add up to several micrograms. At $50,000 per gram, a microgram is about a nickel's worth. Apparently, that's what was killing them – a few pennies' worth of radium. They were never warned of danger.

Still, it was hard to believe. Everyone knew that radium could cause nasty burns that were extraordinarily difficult to heal. Everyone knew that radium could be used to kill or at least to quell the proliferation of cancerous tumours. But those effects were caused by large exposures. How could microscopic amounts of radium paint do any harm? Only gradually did scientists begin to understand.

Radium and Cancer

Radium is chemically similar to calcium. The body's digestive system cannot discriminate between the two elements. Therefore, when radium is ingested, most of it is not excreted – it is stored in the same places where calcium is stored: the bones, the teeth and the milk. But unlike calcium, radium is radioactive. It is an alpha emitter with a very long half-life.

A microgram of radium – one millionth of a gram – gives off thirty-seven thousand alpha particles every second. On the molecular scale of matter, each alpha particle is a positively charged, highly energetic, massive projectile. As this projectile hurtles through matter, it smashes molecular bonds indiscriminately by tearing electrons out of their orbits, leaving thousands of unstable chemical fragments in its wake. This violent process is called “ionization”, and therefore alpha radiation is called “ionizing radiation”. If ionization happens in living tissue, the cells are badly damaged. Very often they are killed, or altered in such a way that they can no longer function. But some of the damaged cells may still be able to reproduce. A few of these crippled cells may eventually become malignant. They are cancer cells.

Cancer is a disease resulting from the uninhibited and undifferentiated growth of a colony of cells. Normally, each cell in the body has a distinct function: it is a bone cell, or a blood cell, or a liver cell. Such a cell is “differentiated”; it has assumed a highly specialized role in the body.

When a cell is damaged in such a way that it “forgets”” its genetic programming, it becomes undifferentiated. It may begin to replicate itself with no regard for the larger organism of which it is a part. It simply reproduces for the sake of reproducing. One cell becomes two, those two become four, those four become eight, and so on. This is, in effect, an uncontrolled biological chain reaction. If not arrested, it proves fatal to the larger organism. It creates a parasitic growth – a malignancy – that will not stop until it destroys its host.

When radium accumulates in the bones, it stays there for a very long time, methodically blasting the surrounding cells with alpha particles. The blood-forming organs in the bone marrow are also bombarded with alpha radiation, leading to a variety of blood disorders. Once in awhile, very rarely, a cancerous cell may be created as a result of these repeated random injuries. Such a rogue cell may lie dormant for many years before spawning a cancer. If bone cells are so affected, the result is bone cancer. If white blood cells or cells in the blood-forming organs are damaged in this way, the result can be leukemia or some other form of blood cancer, such as myeloma or lymphoma.

In general, radiation-induced cancer is not actually observed until years or even decades after the original radiation exposure. The period of time between radiation exposure and the onset of cancer is called the latency period.

Radium decays into radon gas, even inside the body. One way of estimating the amount of radium stored in a person’s bones is to measure the amount of radon gas in that person’s exhaled breath. Radon produced in the bones dissolves in the blood and gravitates to the head. It seeps into the sinus cavity (near the nose) and into the mastoid cavity (behind the ears). There the radon decay products accumulate, irradiating the surrounding cells with alpha and beta particles, in some cases producing cancers.

Eldorado did not want to see its employees facing such a gruesome fate. In 1946, $68,000 out of a total capital budget of $81,000 was spent on health and safety, Another $32,000 was spent the following year. By 1949, radiation levels were much lower, ingestion levels were greatly reduced, a safety officer had been hired, and a rudimentary education of the work-force had begun.

Eventually, radium proved too hazardous to use. The market almost completely disappeared. In cancer therapy, radium was replaced by cobalt-60, a man-made radioactive isotope created by the NRX reactor at Chalk River. Eldorado quit producing radium in 1948.

From that time on, the radium in the ore was just another waste byproduct, to be carted to the local dump with the rest of the radioactive garbage.

Brave New World

The technology of nuclear fission created radiation hazards that dwarfed those encountered in nature. Before the end of 1945, many of the Japanese men and women who had survived the blast and the burns of the atomic bombs had died from acute radiation sickness – a hitherto unknown phenomenon.

The sickness begins one or two hours after exposure to 200 rems or more (equivalent to seven thousand chest X-rays). Weakness, nausea, and vomiting come first. Headaches and dizziness follow. After two or three days, there is an apparent recovery, and for two or three weeks, the victim feels he has been spared. During this period, however, pernicious changes occur in the blood and in the blood-forming organs. One day, rather suddenly, the victim feels he has come down with an acute infectious disease. Chills, fever, fatigue, and shortness of breath occur. The hair falls out all over the body. Ugly purple splotches appear on the body, caused by hemorrhages under the skin. The nose and gums begin to bleed profusely. There is bloody diarrhea, too. I=Virulent infection is often a complication, especially inside the mouth.

Anyone exposed to 200 rems or more of whole-body radiation in the space of a few hours ("prompt exposure") will experience these symptoms, and will require hospitalization. Over half of those exposed to a dose of 200 to 400 rems will survive. With larger doses of 500 to 600 rems, the survival rate is drastically reduced because of severe gastrointestinal damage (the lining of the gut becomes detached). At about 700 rems, mortality approaches 100 percent. At doses of 1000 to 1500 rems, a person will die in a few days due to massive internal bleeding. At doses of 10,000 rems or more, the central nervous system is incapacitated, ensuring death within one day accompanied by violent seizures and convulsions.

The sides of the NRX reactor were barricaded behind a wall of shielding material almost four meters thick, to safeguard workers from prompt radiation exposures that could exceed 10,000 rems. First came a one-meter thickness of graphite; then, one-third of a meter of solid iron; and finally, a two-and-a-half meter slab of concrete. During operation, radiation passing through this shield (mainly neutrons and gamma rays) would dissipate its energy by agitating the atoms, generating up to 150,000 watts of heat in the graphite layer alone. Very little radiation penetrated into the reactor room. Nevertheless, in 1948, when the NRX power level first exceeded a million watts, extra shielding was added to reduce residual radiation even further.

Activation Products

Air from the NRX building had to be vented through a stack seventy meters high because of radioactive contamination. Argon-41 was the main culprit. It is an intense gamma emitter with a short half-life (110 minutes). Gamma rays are like X-rays: they are so penetrating, they can deliver a whole-body dose even at a distance. Despite the high stack, Lewis noted in December 1948 that "Gamma rays from the invisible cloud of argon-41 are presumed to cause the observed fluctuating level of up to three times the normal radiation background" in those laboratories which were not shielded.

As Fermi learned long ago, when non-radioactive atoms capture neutrons, they often become radioactive. Such radioactive materials, produced by neutron capture, are called "activation products". Since there are so many neutrons flying around inside a nuclear reactor – especially in a Canadian reactor – there are a great many activation products created: in the structural materials, in the coolant, in the moderator and even in the air, if it circulates too close to the reactor core. Argon-41 was one of these.

Activation products were regarded as a nuisance, but not a serious problem, by the Chalk River pioneers. In fact, they represented a golden opportunity. By deliberately activating a variety of foreign materials, all sorts of radioactive isotopes could be created for use in medicine, science and industry. For example, cobalt-60 was first used as a substitute for radium in cancer therapy in London, Ontario and in Saskatoon, Saskatchewan, in 1951. It was manufactured in the NRX reactor, where control rods made of non-radioactive cobalt-59 would slowly "cook" into radioactive cobalt-60. Canada was and is the world's largest supplier of cobalt-60. Eventually, a host of other radioisotopes were fabricated for a wide range of applications. Producing and selling radioisotopes and ancillary equipment was Chalk River's sole source of revenue for many years, if we include plutonium for bombs as the principal commodity in this category.

Fission Products

In terms of radiation exposures, however, the real challenge at Chalk River was reprocessing spent fuel. When a fuel rod is removed from a nuclear reactor at the end of its useful lifetime, it is so radioactive that it can kill a man at a distance of one meter in less than a minute. He would not die immediately, but over a period of days or weeks, from acute radiation sickness.

Starting in September of 1943, when Canadian and British scientists first began handling intensely radioactive fuel rods from US reactors, George Laurence arranged for all the scientists and technicians to have regular blood tests at the Royal Victoria Hospital in Montreal. In April 1945, Cockcroft reported findings of abnormal white blood cells "with reference to the early detection of radiation damage." The following month, colonies of rats and mice were started in order to study, in them, the same phenomenon that had already been observed in humans.

The extraordinary radioactivity of spent fuel is due to the presence of fission products – those broken pieces of uranium and plutonium atoms left over after fission. There are about three hundred different fission products created inside every nuclear reactor. Their combined radioactivity is billions of times greater than that of all the radium produced before the outbreak of the war. (Unlike radium, however, they are not alpha-emitters; they are beta and gamma emitters. Almost none of them exist in nature.)

When plutonium separation began at Chalk River in 1949, the extreme radiation fields associated with the spent fuel made it a uniquely hazardous operation. The job could be done only by remote control, behind very thick shielding. Moreover, the equipment itself became so badly contaminated that even routine maintenance was dangerous, and sometimes impossible.

First, the aluminum sheath would be removed from the spent fuel rod by remote mechanical strippers. Next, the rod would be dissolved in acid, releasing radioactive gases and vapours into the air (krypton, argon, cesium and iodine isotopes). Then, the solution would pass through a number of solvent extraction columns, where plutonium would be chemically separated from the uranium and the fission products. The corrosive acid solution, loaded with fission products, would enter a high-level radioactive liquid waste storage tank. There it would be constantly cooled to prevent spontaneous boiling caused by radioactive heating.

To reduce the volume of the less contaminated solvent before adding it to the waste tanks, an evaporation process was used. In December 1950, there was a violent explosion in Building 224 at Chalk River, killing one man, sending four to hospital, injuring several others, and spraying them all with the contaminated liquid. According to a report, the men "were kept under observation and treatment for several days".

Establishing Standards

In September 1949, physicists from Canada, Britain and the US attended a "permissible dose" conference at Chalk River. As Gordon Butler of the NRC expressed it, the purpose was to establish guidelines for the "maximum permissible exposure for continuous contact with an injurious agent"; namely, atomic radiation. Since exposure of atomic workers was unavoidable, the three atomic powers decided to lay down some rules or guidelines. They decided on an annual permissible exposure to gamma radiation for atomic workers, which is about sixty times larger than the unavoidable background radiation that humans have received from time immemorial in the form of "cosmic rays" from the depths of outer space and radioactive minerals in the earth's crust. The standard was five rems per year. It was about two-and-a-half times more stringent than the limit of 0.05 rem per day suggested by J.S. Mitchell to Eldorado at the Toronto conference in 1945.

A similar tripartite conference on radiation was held at Harwell in Britain in August 1950. It was obviously important to learn more about the new radioactive substances which were being created in such enormous quantities, and the health hazards which each one poses. Late in 1950, a few British, American and Canadian scientists got together to form the International Commission on Radiological Protection (ICRP). Scientists from France, Sweden and Germany were also invited to join the ICRP, whose deliberations would be based on the recommendations from the Chalk River and Harwell conferences.

III. Accidents Do Happen

An Unpleasant Excursion

It wasn't Friday the thirteenth, but it might as well have been. On Friday, December 12, 1952, around three o'clock in the afternoon, at Chalk River, Ontario, the NRX reactor was about to undergo a low power test. Experimenters had disconnected the cooling water from one fuel rod; in the upcoming experiment, it would be cooled only by air. Several other fuel rods would be cooled using ordinary low pressure water hoses instead of the usual high pressure coolant. At the very low power levels foreseen for the experiment, these arrangements were considered adequate.

The start-up procedure would involve gradually raising the level of heavy water in the reactor vessel (called a "calandria"). As the depth increases, more and more neutrons are slowed down, leading to an increase in the fissioning of the uranium-235 atoms in the fuel rods. At a certain point, a chain reaction would be achieved; the reactor would "go critical".

Just before the experiment began, a technician down in the basement opened three or four valves by mistake. These valves were supposed to remain closed to prevent air pressure from lifting the control rods out of the reactor. If three or four of the control rods unexpectedly lifted during start-up, the chain reaction would accelerate and might go completely out of control.

The heavy water level began rising in the calandria. Red warning lights began flashing on the instrument panel. The supervisor grabbed the phone and told the man in the basement to stop doing whatever he was doing. He then ran down to the basement, leaving his assistant in charge. He quickly saw what was wrong and re-closed all the valves. Upstairs in the control room, the warning lights went off. It seemed that the control rods had returned to their normal positions. But they hadn't. For some never-to-be-explained reason, they jammed. They dropped only slightly – enough to extinguish the warning lights, but not enough to quench the neutron activity.

Using the basement phone, the supervisor told his assistant in the control room to "Push buttons number 4 and number 1." That was a mistake. He had meant to say "Push buttons number 4 and number 3", which would have returned the system to normal, but in the excitement of the moment, he got his numbers mixed up. He immediately corrected himself, but it was too late. The assistant had promptly put the phone down and gone to do as he was told.

When button number 1 was pressed, four more control rods were lifted out of the reactor. The power began to multiply. Within twenty seconds, the assistant saw that it was getting out of control. He reached for the shut-off switch that would slide all the control rods into the reactor at once and shut down the chain reaction completely. Due to a lack of air pressure, however, only one of the withdrawn control rods was forced back into place, and very slowly at that. The power level was climbing even faster. The assistant picked up the phone and yelled for the supervisor to do something. But there was nothing he could do.

Forty-four seconds had elapsed since button number 1 was pushed. The power level was still surging. A physicist in the control room reached over and activated an emergency switch to dump the heavy water moderator. With no moderator, the chain reaction would sputter out. About thirty seconds after the dumping began, the power level finally returned to zero, after peaking at a level almost five times higher than the reactor had been designed for. Everyone heaved a sigh of relief. But when the supervisor glanced through an open basement door, he saw water gushing out of the calandria into the sub-basement area. A quick check showed that it wasn't heavy water; it was ordinary water, and highly radioactive. That meant the coolant was leaking and the fuel was overheating.

Four minutes after button number 1 was pushed, a dull rumble was heard, and water spurted out through the top of the reactor. Something in the air triggered the radiation alarms. There was a frantic phone call from the adjoining plutonium separation plant. There, radiation readings were so high that the monitoring instruments had gone completely off-scale. A siren was sounded, warning everyone to stay inside with doors and windows closed.

A series of explosions followed. During one of these blasts, the four-ton gasholder dome on top of the calandria was thrown four feet through the air, where it lodged in the superstructure. Gas masks were issued to those in the control room, to prevent them from inhaling the airborne radioactive particles. Before long, the NRX crew was forced to retreat to an adjoining, less contaminated building.

At 3:45 pm, the entire Chalk River area was evacuated – buildings and grounds – except for emergency personnel. Tons of radioactive water were flooding into the basement of the reactor building. Had the flow of cooling water been interrupted, the molten metallic fuel inside the reactor might very well catch fire, releasing even more radioactive vapours into the air. Also, as Mackenzie wrote later, "it was feared that further explosions might occur if the flow were not maintained – at least until the heat from radiation and fission products died down." Gradually, over a period of many hours, the reactor quieted down.

The NRX accident was, technically, a runaway accident (or, as it is quaintly called, a "nuclear excursion"). In such an accident, the normal control system fails to limit the power of the chain reaction to safe operating levels. If the emergency shut-down systems fail to terminate the power surge fast enough, the core of the reactor (the calandria and everything inside it) will be severely damaged. Large quantities of fission products and activation products (including plutonium) will be released from the damaged fuel into the plant atmosphere.

The worst part of the power surge occurred when the water inside the low-pressure coolant hoses started to boil. Because of its lower density, steam captures far fewer neutrons than ordinary light water does; so when the coolant boils, its almost as if another control rod were suddenly withdrawn. The neutron activity increases dramatically, driving the whole system towards a catastrophic failure.

Coping with the Consequences

The cleanup began the next day, and lasted for eighteen months. A pipeline one and a quarter miles long was used to pump a million gallons of radioactive water from the NRX basement into a shallow trench some distance from the Ottawa River. The amount of radioactivity disposed of in this way was equivalent to about seven times the total amount of radium produced in the entire world up to that time.

Inside the NRX reactor building, radiation levels were so high following the accident that workmen could stay for only very short periods of time in "hot" areas. Because the harmful effects of radiation are cumulative, a very large workforce was needed to dilute the total radiation dose to acceptable individual levels of exposure. Hundreds of men from the Canadian Army, the Royal Canadian Air Force and the Royal Canadian Navy were ordered to help dismantle and decontaminate the crippled reactor.

Admiral Hyman Rickover, who used the high neutron flux of the NRX reactor to test fuel for his fleet of nuclear submarines, ordered men from the U.S. Navy and the U.S. Naval Radiological Defense Laboratory to help out with the cleanup. One of these was Jimmy Carter, who would later be U.S. President at the time of the 1979 Three Mile Island reactor accident. It wasn't just a friendly gesture on Rickover's part; it was a rare opportunity to train his men to function in a severely contaminated environment.

The calandria was impossible to decontaminate. It was so radioactive that it could give a man a lethal dose of radiation at a distance of one meter in less than an hour. A crew of about seventy men used long ropes to lift and guide the big vessel onto a skid. None of the men was allowed to get within fifty feet of it.

The calandria was then towed off-site by a grader connected to the skid by means of a long cable. A relay team of drivers was used so that no one driver would get too high a dose. Two cars escorted the cortege, at a respectful distance, in front and behind. The entire area was evacuated except for the removal crew. Guard posts were vacated, gates stood open, buildings were deserted. As the funereal procession passed by, all the radiation monitors inside went right off-scale. The calandria was buried in sandy soil on company property at a considerable distance from the NRX building. One face was left uncovered to allow access for scientific studies.

A year and a half later, the NRX reactor had been rebuilt, with a new calandria and new design features that would make it safer as well as more powerful. The Chalk River scientists had learned many things from the dreadful experience. They were justifiably proud that they had dealt with the mess as well as they did. There were no immediate fatalities from the accident.

The NRX accident was not a catastrophe, like the Chernobyl disaster which happened thirty years later. To be sure, there were many superficial points of comparison. Both incidents began with a low-power experiment. Both involved operator error that disabled some safety systems. In both cases, a sudden power surge was followed by violent explosions. In both cases, the boiling of water in one or more fuel channels contributed to the power surge. But there the similarity ends. At Chalk River, there was no raging fire to disseminate clouds of radioactivity into the atmosphere. Moreover, it was a very much smaller reactor – about one-half of one percent as large as the Chernobyl reactor.

It was not a catastrophe. But it was a warning.

Too Hot to Handle

On May 24, 1958, a damaged fuel rod was being removed from the NRU reactor by a remote-controlled overhead crane. It wasn't the first time; during the previous month, six cracked fuel rods had been removed. The fuel was metallic uranium sheathed in aluminum. Because the aluminum cladding was damaged, fission products had escaped into the cooling water. The sudden sharp increase in radiation readings had automatically shut the reactor down. The damaged rod would have to be replaced.

But this rod was jammed. In an effort to pry it out, the pressure tube was accidentally damaged, and the coolant water ran out of the channel. Without adequate cooling, the fuel temperature rose sharply. The metal softened and separated. A three-foot length broke off and remained lodged in the fuel channel. The rest of the rod was pulled free by the crane.

As the long piece of rod was swung across towards a water-filled spent fuel bay, it burst into flames. Its temperature had reached the ignition point of 1200°C, driven upwards by the radioactive heat of the fission products in the fuel. Several small pieces of burning fuel fell onto the top deck. Then a large three-foot section broke off and plummeted into the maintenance pit.

There it lay, burning, filling the atmosphere of the reactor building with tiny radioactive cinders. These hot particles were so minute that many of them remained airborne for weeks following the accident. Wherever they made contact, they bonded themselves – to walls, ceilings, clothing, instruments, equipment, anything – as if they had been welded on.

As soon as the fire started, a workman jabbed at a switch to close the ventilation dampers so that radioactivity could not escape from the building. In his haste, he accidentally jammed the switch open. As a result, a radioactive plume escaped from the building. Four days later, radioactive fallout was found clinging to soil and vegetation up to a mile away from the plant.

While the fire was burning, the airborne contamination within the reactor hall was too high to be measured with accuracy; the instruments all went off-scale. Readings taken one hour later a hundred yards from the building were as high as 200,000 disintegrations per minute for each cubic meter of air. Even twelve days later, the same level of atmospheric contamination was measured in air samples taken from within the reactor hall.

A relay team of running men, carrying buckets of wet sand from outside, extinguished the fire in the maintenance pit by hastily dumping their loads as they ran past, completely smothering the burning fuel. The small fires smoldering on the reactor deck were allowed to burn themselves out. Within 24 hours of the accident, most of the visible debris had been removed. The extremely radioactive fuel fragments were gingerly hoisted out by the overhead crane. Each crane operator was limited to a two-minute working time, because, even in the cab of the crane, the radiation levels were between five and ten rems per hour. About forty men used long-handled tools to shovel the radioactive sand into metal cans. Radiation readings at the can surfaces were up to 200 rems per hour. In spite of the one-and-a-half minute working time prescribed for each man, fourteen of them exceeded the five-rem annual exposure limit for atomic workers.

Two days following the fire, after the fuel fragments and most of the sand had been removed, officials reported that "radiation fields as high as one thousand rems per hour were measured two feet above the reactor deck and above the maintenance pit. Readings of one hundred rems per hour at waist level were found in many parts of the main floor." The NRU building was still extremely hot. Within a week, an improvised vacuum system – a commercial Vacublast unit with an exceptionally long hose – was being used to remove as much of the remaining debris as possible. The suction nozzle was manipulated from a distance using long-handled grippers. Long poles with adhesive-coated tips were used to retrieve pieces of paper that kept clogging the vacuum hose.

All the radioactive garbage was eventually trucked to a burial site. According to the official account of the cleanup, "much more contamination was spread on the roads used for transportation of debris than escaped directly from the building. The roads were cleaned quickly by vacuuming, washing with fire hoses and, when necessary, removing part of the road surface" – to be buried also as radioactive waste.

During the first two weeks following the fire, three hundred men took part in the cleanup. They worked in closely timed relays to a maximum exposure of three rems each. It soon became clear that the cleanup of the building could not be carried out without outside help, "if these men were to remain within the permissible annual radiation limit."

By June 6, sixteen instructors had been brought in from the Civil Defence College in Arnprior, as well as fifty-eight RCAF instructors from across Canada. Some of these men had earned "ABC" teaching certificates: they were qualified as instructors in Atomic, Biological and Chemical Warfare. They all had experience in handling radioactive materials and reading radiation monitoring equipment. They were all familiar with the use of protective clothing and respirators.

Over the next few weeks, these older, more experienced men supervised the work of hundreds of teenagers – unseasoned army recruits from Camp Petawawa – escorting them in groups of fifteen into the contaminated area. There they scrubbed and mopped what appeared to be immaculately clean walls and floors, sometimes five, ten, or fifteen times. They were dressed in airtight plastic suits carefully taped to their rubber boots. Their heads were enclosed in bulky army respirators equipped with carbon filters. About 25,000 rubbers and 10,000 respirators were decontaminated in the month of July. It was not unusual to find as much as 200 millirems per hour surface contamination on used suits.

The entire cleanup involved over six hundred men and took six months to complete, although there was almost no physical damage to the reactor. All surfaces were scrubbed at least three times to reduce contamination to levels deemed acceptable (about 500 counts per minute). When no amount of effort would do the trick, a residual contamination level of up to 5000 counts per minute was accepted. To wash high walls, ceilings and the overhead crane in some spots up to ninety feet above the floor, a firm of professional steeplejacks from Ottawa was employed.

All of the contamination originated from a relatively small portion of a single burning fuel rod. Chalk River officials later estimated that the radioactivity of the fission products in the three-foot long section that fell into the maintenance pit was equivalent to about 200,000 grams of radium – about seventy times the amount of radium available worldwide before 1945. The amount of plutonium in the same segment (fifteen grams) was, even by the most conservative estimates, sufficient to kill tens of thousands if inhaled into the lungs in the form of finely divided particles such as those which filled the atmosphere of the NRU building.

Fortunately, no one was killed during the accident itself or the cleanup that followed. It was, however, another warning.

Other Omens

The NRX accident was the first serious nuclear mishap in the world. However, by the time the NRU incident happened, a few others had already occurred. In November 1955, during a low-power start-up operation, Walter Zinn's experimental breeder reactor (the EBR-1 reactor) experienced a nuclear excursion in Idaho which resulted in the partial melting of the uranium fuel. In October 1957, Britain's Windscale-1 reactor released so much radioactivity into the air that abnormally high fallout readings were recorded all over Northern Europe. Like the Chernobyl accident in 1986, the Windscale accident involved a raging fire in the graphite moderator. The Windscale plant had no containment building whatsoever; it was a military reactor whose sole purpose was to produce plutonium for bombs.

A truly catastrophic accident occurred in the Soviet Union in 1957. It remained a closely guarded secret in the West until a Soviet biologist, Zhores Medvedev, who had emigrated to England, revealed some of the details in 1976. Medvedev casually referred to the disaster in one of his scientific publications, and was astonished to learn that nobody in Europe or North America knew anything about it. Medvedev reported that hundreds of people were killed and thousands hospitalized when a cloud of radioactive fission products contaminated a huge area near the Ural Mountains. The release resulted from an enormously violent explosion, either in a reprocessing plant or in a buried tank full of high-level radioactive liquid wastes left over from reprocessing.

Medvedev's account, which was first greeted with disbelief, was subsequently substantiated by the US Central Intelligence Agency, by visitors to that region of the USSR. Medvedev cited over one hundred technical papers in the Soviet scientific literature dealing with radioactively contaminated soil, lakes, rivers, animals, insects, birds and fish. The Soviet accident resulted in about thirty villages being wiped off the map, creating a radioactive "no man's land" – a zone that remains uninhabitable to this day.

Accidents in the west were less catastrophic. In 1961, the SL-1 reactor (Stationary Low-Power Reactor Number One) at Idaho Falls was destroyed by a sudden power surge caused by operator error. The central control rod was being withdrawn by hand when it was suddenly driven upwards out of the core with such force that the workman was impaled against the roof. Two other men were killed as well. The exposed portions of the three bodies were so radioactively contaminated that their heads and hands had to be severed and buried separately with other radioactive wastes.

IV. Hunting for Profits

The economic feasibility of generating electricity from nuclear energy has always been problematic. On August 13, 1945, in the same press release that revealed the existence of Chalk River, it was stated that the surface temperature of uranium metal in a nuclear reactor is "too low at present for this heat to be used for the generation of power." In other words, it's not hot enough to boil water in large amounts.

Addressing the Manitoba Chamber of Mines in October 1949, C.J. Mackenzie (then president of the Atomic Energy Control Board) made the very same point. "There is no indication," he added "that atomic power will become generally competitive with ordinary central power plants for many, many years. The existing reactors can make fissile material for bombs quite efficiently, but in the general power field there are years of research work ahead."

In February 1951, addressing the Canadian Club in Montreal, Mackenzie reacted to the overblown vision of unlimited cheap power from the atom which might make war itself obsolete. "The power is there all right," he said, "but at the moment it is not cheap and I am afraid that even in 1951 the fear of war is not obsolete. However, perhaps another fifty years is all that is needed."

Making It Work

How does one coax power from the atom? By August 1951, W.B. Lewis had pieced together some important parts of the puzzle. To get steam, higher operating temperatures are needed. That means running the reactor hotter. If so, zirconium instead of aluminum should be used to encase the uranium fuel, since it is more heat resistant. Moreover, at a pressure of one thousand pounds per square inch (about 70 atmospheres), the coolant can be heated to a temperature of three hundred degrees Celsius without boiling. This superheated water can then be forced through thousands of small tubes inside a special boiler, called a “steam generator”, filled with ordinary unpressurized water. On contact with those blistering hot tubes, the unpressurized water will boil. Finally, the steam can be used to spin an electricity-generating turbine.

In January 1952, these ideas were discussed with several Ontario Hydro executives. They were interested. More meetings followed. On April 1, the Atomic Energy Control Board (AECB) created a new crown corporation, Atomic Energy of Canada Limited (AECL), to pursue commercial prospects in this field and to assume ownership of Chalk River. Mackenzie was made the president of AECL, while remaining the president of AECB. In June 1953, Ontario Hydro and AECL began a joint study on the feasibility of building Canada’s first nuclear power plant.

Representatives from the UK visited Chalk River in October 1953. The British confided that they were building dual-purpose plants to generate plutonium for bombs as well as electricity. Similar plans were afoot in the USA. The year before, three groups of American power companies reported to the US Atomic Energy Commission that no existing reactor design could produce economic electric power, unless plutonium were produced as a byproduct and sold to the military. Accordingly, one of the first commercial reactors envisaged was the Enrico Fermi plant, a breeder reactor located thirty miles from Detroit, which (it was hoped) would produce weapons-usable plutonium along with electricity. The plant suffered a partial meltdown in 1966, less than a year after start-up, and never operated again.

Although heavy water reactors are the best plutonium-producers, the Canadians opted for electricity alone. In 1954, AECL and Ontario Hydro teamed up with Canadian General Electric to build the NPD reactor (Nuclear Power Demonstration) at Rolphton, not far from Chalk River. NPD was an amalgam of the NRX and NRU designs, but much more complicated. It was a high-pressure system, unlike its precursors. It was decided, after lengthy debate, to utilize over a hundred individual pressure tubes, instead of a single large pressure vessel, to prevent the coolant from boiling as it floods past the hot fuel. (If the coolant boils, there could be a power surge like the one during the NRX accident in 1952.)

In a flash of insight, the NPD fuel channels were positioned horizontally instead of vertically. Several short stubby fuel bundles were used in each channel instead of one long thin rod. Refuelling was much easier as a result. Fresh fuel bundles could be inserted at one end, while spent fuel bundles were removed at the other, without even shutting the reactor down. This distinctive feature, called “on-line refueling”, would prove to be one of the major advantages of the Canadian design compared with others.

Two other innovations deserve mention. First, a ceramic fuel made from uranium oxide was used instead of uranium metal. Oxides can't burn the way metals can, so the NRU accident could not be repeated. Ceramics are more resistant to warping, and they melt at a much higher temperature than metals. Fuel integrity was therefore greatly improved. Second, heavy water was used as a coolant (as well as a moderator). NRX and NRU both used ordinary light water as a coolant; it was cheap but inefficient, since light water absorbed a lot of neutrons. Heavy water captured few neutrons, but it was so expensive ($30 per pound) that its use as a coolant would be unaffordable unless the system were leakproof.

NPD was designed to generate about twenty million watts (20 megawatts) of electricity, requiring eighty megawatts of heat. The waste heat – sixty megawatts' worth – was dumped in the Ottawa River. The reactor was too small to be economical. Beginning in 1954, plans were made for another plant, ten times larger (200 MW). That larger reactor was built at Douglas Point, on the shore of Lake Huron, near the town of Kincardine. Many features incorporated into NPD were, in fact, conceived for the larger Douglas Point plant, the first to be called a CANDU reactor (CANadian Deuterium Uranium) – destined to become the generic name for a long line of power reactors.

C.D. Howe told the House of Commons about the decision to build NPD in March 1955. At that time construction was well underway. Nobody seemed to mind.

Priming the Pump

During the 50s and 60s, the Canadian government spent lavish sums promoting nuclear power. It was hoped that private industries would step in and take over, once they saw what a good investment it was. However, Ottawa was forced to shoulder most of the financial load, as other investors shied away.

By the end of the war, Canada had spent more on the atomic bomb project than on all other research and development programs combined. Just maintaining Chalk River was an expensive undertaking. And there were the capital expenses: building NRU, repairing NRX, creating NPD. Then, in 1956, Canada gave India a $10 million gift: a copy of the NRX reactor, called CIRUS (Canada-India Reactor, with US heavy water). It was justified as Third World Aid under the Columbo plan. With a bit of luck, it would stimulate purchases later on from India and other Third World countries.

When Diefenbaker swept to power in 1957, government spending on nuclear power sharply increased. In 1958, the Nuclear Power Plant Division of AECL set up shop in Toronto. In 1958 and 1960, two new "zero power" reactors called PTR (Pool Test Reactor) and ZED (Zero Energy Deuterium) went into operation at Chalk River. In June 1959, before NPD was even finished, an order-in-council was passed authorizing the building of the first CANDU – a 200 MW plant, to be located at Douglas Point on the Bruce Peninsula off Georgian Bay. Ottawa paid the $70 million needed to build it, with the understanding that Ontario Hydro would buy it when it became a reliable source of power. (It never did. It is now mothballed.)

In October of 1959, the Conservatives were persuaded to build a brand new AECL research complex in Manitoba. Ten thousand acres of land were acquired beside the Winnipeg River to accommodate the buildings for the nuclear centre. Another two thousand acres were set aside at Pinawa, eight miles east, for a residential community of about six hundred people, similar to Deep River in Ontario. Of course, Ottawa paid for it all.

During the summer of 1960, a parliamentary committee inquired into the operations and finances of AECL. In a brief prepared for the occasion, Lorne Gray, the second AECL president, gave the first recorded argument for nuclear electricity. He noted that electrical demand in Canada had been doubling every ten years, and would likely continue to do so. While admitting that nuclear electricity was more expensive than power from conventional sources, he argued that the latter would become increasingly expensive, due to rising fuel prices and the scarcity of good hydro sites. The cost of nuclear power, on the other hand, would go down due to experience and innovation. “At some time,” he concluded, “The two cost trends will cross, and nuclear power will be cheaper than conventional power. Very few, if any, deny this. The difference between the optimists and the pessimists is the date they consider this crossover will take place.” It was a very theoretical argument, with very few facts to support it. But the parliamentarians were convinced.

On June 4, 1962, the first nuclear-generated electricity was fed into Ontario Hydro’s grid by NPD. For two or three years, many problems were encountered: defective joints, faulty valves, a failure in the first attempt to change fuel at full power, and unexpectedly high losses of heavy water coolant. These resulted in frequent shutdowns (“outages”) which made the plant completely uncompetitive in economic terms. Nevertheless, many valuable lessons were learned, and heavy water losses were gradually reduced to acceptable (i.e. affordable) levels.

In October 1962, Ottawa announced that it would build a CANDU-style nuclear reactor at Whiteshell, to be called WR-1, which would use an organic oil instead of heavy water as coolant. Such a design, it was felt, would alleviate problems of corrosion and contamination, as well as the expense of heavy water leaks.

After ousting Diefenbaker’s Conservatives in 1963, Pearson’s Liberals out-did their predecessors in promoting nuclear power. Expecting rapid growth in nuclear power, Canadian technologists felt their heavy water needs would soon outstrip US production. In December 1963, acting on advice from AECL, a government contract was awarded to a private company, Deuterium of Canada Limited, to build a heavy water plant at Glace Bay, Nova Scotia. About $70 million in government funds (two-thirds of it federal) were invested in the plant.

Exactly two weeks after the Glace Bay decision, agreement was reached to sell India a power reactor similar to Douglas Point, to be called RAPP-1 (Rajasthan Atomic Power Project). Being the first genuine sale of a nuclear power plant, the deal was greeted with great jubilation. Over a period of several years, Canada loaned $33 million to India to help finance this reactor and its twin, RAPP-2, ordered in 1966.

In August 1964, Ontario Hydro and AECL agreed to build two large (500 MW) CANDU reactors at Pickering, just three miles east of the Metropolitan Toronto Boundary. Costs were split three ways – between Ontario Hydro, the government of Canada, and the government of Ontario. Ottawa’s contribution was $116 million, thirty-five percent of the total. Also in 1964, Canadian General Electric sold a small (125 MW) CANDU-type plant to Pakistan. The government of Canada loaned Pakistan $47 million to help pay for the plant. This loan was to be repaid over a fifty year period, interest-free, following a ten-year period of grace.

By now, AECL was predicting a voracious world-wide demand for CANDU reactors, even though the first CANDU (Douglas Point) had not yet started up. Warnings were issued that the availability of heavy water could become a critical constraint. In 1965, Ottawa approved AECL's plans to build a CANDU-style reactor in Quebec, Gentilly-1, to experiment with the use of boiling light water as a coolant instead of pressurized heavy water. As with WR-1, the objective was to reduce heavy water requirements. AECL paid about $100 million for the plant, on the understanding that Hydro Quebec would buy it once it started producing electricity competitively. (It never did. It is now mothballed.)

Meanwhile, AECL was still urging Ottawa to increase the heavy water supply. Accordingly, plans for a second heavy water plant were announced early in 1965. When the first two bidders for the contract backed out, Ottawa panicked and over-reacted by doubling the projected size of the Glace Bay plant. Not long afterwards, authorization for the second plant was also given. It would be located in Cape Breton, on the Straight of Canso.

Throughout the 1950s and 1960s, as Ottawa poured more and more money into nuclear power, nobody seemed to doubt that the investment would pay dividends. It was the Age of Euphoria. Walt Disney's movie, "Our Friend, The Atom", portrayed nuclear power as a force capable of transforming the earth into a kind of terrestrial paradise. A comic book published in the 1960s by the Canadian Nuclear Association was suitably inspirational: "In time it is possible that nuclear power will lead to temperature-controlled, germ-free cities and a better life for all mankind."

Yet there were still no returns on these massive investments of taxpayers' money, except from the military contracts.