Nuclear Growth and Growing Pains

By John Benson

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1. Introduction

Your author probably has many opinions that are best termed "minority opinions." That is, these are not shared with the opinions of the main incumbent experts in a particular field. These include the intersection of nuclear-electric generation and renewable power generation. I consider nuclear-power a renewable form of generation, mainly because (1) there is no shortage of Uranium used as the active component in fuel, (2) although Natural uranium consists of 99.3% U_{238} and 0.7% U_{325}, and the latter is the only type usable for active-fuel in nuclear reactors, U_{238} can be "bred" into plutonium which is also usable for active-fuel. Plutonium is usually extracted from spent nuclear-fuel, purified and used to enrich new fuel elements. This process is much more complex than described in the last sentence, but there is no risk of running out of active reactor-fuel within the next few-centuries-to-millennia, which would be my definition of "renewable".

Yes, I will agree there are "issues" with nuclear power, the most serious of which is nuclear waste (mainly spent fuel), but we have the technology to deal with those. I'm not convinced we have the technology to deal with the greenhouse gasses currently being released into the atmosphere through burning fossil-fuel. Although intermittent renewables (like wind and photovoltaics) plus storage (mainly large battery banks) can cover our peak demand periods, and dispatchable renewables (hydro or geothermal) can cover much of the off-peak demand; in order to cover all demand, we still need to burn fossil fuel in most-to-all areas in the U.S. Now, if I can get off of my stump, we can continue with the rest of this paper.

2. Drivers of Nuclear Growth

Volatile geopolitical times bring considerable challenges, but also mean that more and more countries are looking to nuclear energy to boost energy security and meet economic and clean energy goals. How to turn that enthusiasm into action was a feature of discussion at the World Nuclear Fuel Cycle 2026 conference.[1]

The first panel of the two-day conference saw industry leaders set the scene, outlining accelerating plans for new nuclear deployment from countries with long-established nuclear programs to new-comer countries and new applications such as commercial-maritime propulsion.

Johnathan Chavers, Director of Nuclear Fuel and Analysis, Southern Nuclear, described the growth opportunities presented by increasing electricity demand – both from large load customers such as manufacturing and data centers, as well as residential customers – as unprecedented and transformational. Southern Company is itself investing $81 billion in energy infrastructure through 2030 to support this growth - and in nuclear, it is focusing on the existing installed capacity, he said, "because that's how we can respond the quickest. But we need to do what is necessary today to prepare ourself and preserve the option to grow nuclear".

[1] Claire Maden, World Nuclear News, "World Nuclear Fuel Cycle: How best to meet growing demand?" May 12, 2026, https://www.world-nuclear-news.org/articles/world-nuclear-fuel-cycle-how-best-meet-growing-demand

The vital role of existing capacity was highlighted by speakers across the conference. Japan shut down its nuclear fleet following the Fukushima accident of 2011. It has now restarted 15 of its fleet of 36 reactors, Shuji Yoneda, General Manager of the Federation of Electric Power Companies of Japan's Washington DC Office, said, with more restarts to come. But for the first time in 20 years, the Japanese government is projecting increases in electricity demand and envisages nuclear providing 20% of its electricity generation mix by 2040. As well as accelerating the restart process and extending the operating lifetime of those 36 plants, Japan will also need some 5.5 GWe of new nuclear capacity to reach that goal.[2]

Whether from existing capacity, new-build, or new applications, the entire value chain is central to sustained global nuclear growth, said Christian Di Lizia, EDF Senior Business Developer Relations with International Organizations. Standardization and replication of projects not only lead to speed, cost and quality improvements – they also attract finance. "Very often when we talk about financing projects, there's a kind of a tendency of thinking about reactor technology. It goes beyond that," he said.

2.1. Uranium Fundamentals

There is no shortage of uranium ore to fuel a growing nuclear sector, but for mining companies to be ready to meet this demand, exploration is a "must", Louis-Pierre Gagnon, Orano Canada's Director of Mining, said in the panel on A Deep Dive into Uranium Mining. As well as through its well-balanced and diversified pipeline of existing projects in Mongolia - where commissioning of the Zuuvch Ovoo uranium mine is expected to begin in 2028. In Uzbekistan, Canada, and Namibia, Orano is working to secure future supplies through exploration in those jurisdictions and also in new areas in Australia and Botswana, Gagnon said. Innovation in mining - such as Orano's SABRE (Surface Access Borehole Resource Extraction) technique, already in use in Canada, will also play a part in securing future supplies.

Another mine coming into operation shortly is Bannerman Resources' Etango project in Namibia. A key milestone for Bannerman has been the recently announced strategic partnership with CNNC Overseas Limited, the company's VP Market Strategy Olga Skorlyakova said, providing a "pathway-to-funding" and allowing the project to move forwards into construction: an early works program is already under way, and with a final investment decision - followed by the start of full-scale construction - expected in the second half of this year. First production is targeted in 2028.

Uranium producers rely on financing to be in place before they can proceed with new projects. Robert Willette, CEO of US-based in-situ recovery uranium producer enCore Energy Corp[3]*, said policymakers and regulators - as well as the market - have a part to play here. "Obviously, demand is there, and the resources are there. The real question comes down to a problem of capital formation. And what I mean by that is we have active engagement from utilities and other end users. The difficulty is that those discussions are oftentimes anchored in current market prices. And it's very difficult to have those when you're talking about long-term developed projects that really don't align with current market pricing," he said.*

[2] Gegawatt-electric (GWe): a unit of power equal to one billion (10) watts.
[3] enCore Energy Corp, Head Office, 13355 Noel Road, Suite 1700, Dallas, Texas 75240, T: 972.891.8664 https://encoreuranium.com/

This leads to a disconnect, where a company has to make long-term capital decisions "without having real visibility into what that future market's going to look like", he said. "Supply is not based upon current markets. Supply really responds to confidence in future markets and what that looks like."

Aligning end user contracting, permitting certainty, and policy support will bring the confidence that is needed to bring projects forward, he said. " I think when you get those aligned, you will see capital deployed," he said.

3. Chernobyl at 40

The section title event shaped the modern nuclear industry like no other, and its remnants remain today. However, since it happened more than 40 years ago, I thought it would be important for my readers to read this. However, note that nuclear safety practices (even 40 years ago) in the U.S. were much more rigorous than they were in the Soviet Union, and they are even more rigorous today. I exited the nuclear industry in the late 1970s because it was in decline, not for my own personal safety. Also, I still fully support nuclear power generation.

3.1. What Happened?

In April 1986 Chernobyl unit 4 was due to undergo a scheduled shutdown for routine maintenance. While this was happening, a test was also to take place to determine how long the power generation turbines would spin and supply power to the main circulating pumps following a loss of main electrical power supply. The scheduled shutdown process began on 25 April, with the reactor's power level gradually being lowered from its full operating power of 3200 MWt. (MWt is short for megawatts thermal - a measure of the plant's thermal power output, MWe - megawatts electrical - is a measure of its electrical output).[4]

At 01:00 on 26 April - with the reactor power down to about 200 MWt - preparations began for the turbogenerator rundown test. Just after 01:23, with the reactor parameters stabilised, the unit shift supervisors gave the go-ahead to start the test by closing down the turbine feed valves so that the turbines could start coasting. And for the next 30 seconds, the parameters of the unit remained within expected limits. Then the plant's operator pressed a button that should have stopped the reactor - even now, it's not entirely clear why the button was pressed, but it seems that this was because the turbogenerator rundown test had finished, or to begin the next stage of the reactor shutdown process. But - partly due to the design of the reactor itself, and partly because of the way it had been operated in the hours leading up to the test - this didn't happen. Instead, the reactor power increased rapidly. The sudden increase in heat production ruptured part of the fuel, ultimately leading to a steam explosion which destroyed the reactor core and released fission products into the atmosphere, followed by a second explosion three seconds later.

The accident caused the largest uncontrolled radioactive release into the environment ever recorded for any civilian operation. Large quantities of radioactive substances were released into the air for about 10 days.

[4] Claire Maden, Warwick Pipe and Alex Hunt, World Nuclear News, "Chernobyl at 40," https://www.world-nuclear-news.org/articles/chernobyl-at-40-the-accident-its-impact-and-how-it-changed-the-worlds-nuclear-energy-industry

3.2. Why did this Happen?

The International Nuclear Safety Advisory Group is an expert group convened by the International Atomic Energy Agency (IAEA) to provide authoritative advice and recommendations on nuclear and radiation safety. The group produced two definitive reports on the accident.

Summary Report on the Post-accident Review Meeting on the Chernobyl Accident (INSAG-1) was published in 1986 following a review meeting which included a "frank and open" presentation from Soviet scientists and engineers who gave their account of the accident sequence, and more besides. This was updated in 1992 in the light of further information and published as "INSAG-7, The Chernobyl Accident: Updating of INSAG-1[5]".

INSAG-7 concluded that several major factors came together to cause the accident: certain physical characteristics of the reactor; specific design features of the reactor control elements; and the fact that the reactor had been brought to a state outside the specifications of operating procedures. And "most importantly", said the report, "the physical characteristics of the reactor made possible its unstable behavior".

3.2.1. What was it about the reactor design?

First, a little background on nuclear reactors. There are some components that all reactors have: nuclear fuel - usually based on pellets of uranium oxide which are arranged in fuel assemblies; a moderator, which slows down the neutrons released from fission so that they cause more fission, keeping the nuclear chain reaction going; control rods made of a neutron-absorbing material, that can be inserted or withdrawn from the core to control the rate of reaction, or to halt it; and a coolant, which circulates through the core to transfer the heat from it.[5]

The four units at Chernobyl were Soviet-designed RBMK reactors (RBMK is from reaktor bolshoy moshchnosty kanalny, which translates as 'high-power channel reactor'). Designed in the mid-1960s, the RBMK is a water-cooled reactor with individual fuel channels, using graphite as its moderator and is sometimes referred to as a light-water graphite reactor. RBMKs are unique amongst power reactors in having this combination of coolant and moderator.

Reactors cooled by boiling water will contain a certain amount of steam in the core. Water is a more efficient coolant and a more effective neutron absorber than steam, so an increase in these steam bubbles - or "voids" - will lead to a change in reactivity. In a reactor where the same water circuit acts as both moderator and coolant, an increase in these steam bubbles (voids) will mean the cooling is less efficient, but will also mean that fewer neutrons are slowed down. And because neutrons need to be slowed down in order to sustain the nuclear chain reaction, this leads to a reduction in power. This is known as a negative void coefficient of reactivity, or just a negative void coefficient, and it's a phenomenon that is a basic safety feature of most water-cooled reactors in operation today.

[5] INSAG-7 "The Chernobyl Accident: Updating of INSAG-1," A report by the International Nuclear Safety Advisory Group, 1992, https://www-pub.iaea.org/MTCD/publications/PDF/Pub913e_web.pdf

If the moderator and coolant are of different materials - like in the RBMK – an excess of steam in the core will reduce the cooling of the reactor, but as the moderator remains intact, the nuclear chain reaction continues. But in the RBMK, the neutron-absorbing properties of the coolant water are also an important part of the reactor's operating characteristics. Increased steam production means that fewer neutrons are absorbed, and this enhances the chain reaction, leading to an increase in the reactivity of the system. This is a positive void coefficient - and a positive void coefficient means that a coolant failure could lead to a strong increase in power output from the fission process.

Although there are other components that contribute to overall reactivity, at the time of the accident, the positive void coefficient in the reactor - which may have been generated in part from measures taken by operators to stabilize the reactor in preparation for the test - became large enough to overwhelm all other influences.

The design of the RBMK emergency protection system control rods may also have been a factor contributing to positive reactivity in parts of the core during an emergency shutdown - a positive scram effect.

3.2.2. Human Factors

The INSAG reports also found human factors to be a major element in causing the accident, particularly the actions of the reactor operators in the run-up to the test process. For example, too many control rods had already been removed from the reactor core by the time the test took place (only eight control rods were inserted in the reactor core, far below the minimum of 15 that, according to the operating policy, should have been in the core at all times), and the reactor had been operated for a time at a lower power than it should have been. These factors contributed, amongst other things, to a build-up of positive voids.

Why did the operators take those actions? Although INSAG-1 cited "a remarkable range of human errors and violations of operating rules" as the causes of the accident, by the time INSAG-7 was published, it had become clear that - far from recklessness or incompetence - the actions taken by the operators were symptomatic of the prevailing safety culture in the USSR at that time.

"INSAG judges that factors leading to the accident are to be found in the safety features of the design, the actions of the operators, and the general safety and regulatory framework."

3.2.3. Raising the Alarm

Mass media in 1986 was very different to today. With no 24/7 online news, or social media, everyone got their news from traditional print media or broadcast news services. And in the Soviet Union, the media was controlled by the Kremlin.

Despite the scale of the accident, it took several days for word of the events at Chernobyl to become known outside of the USSR - and it was at a nuclear power plant in Sweden, more than 1000 km (621 miles) from the site of the accident, that the story began to emerge.

On the morning of Monday 28 April, Clifford Robinson, who worked as a measurement engineer in a chemistry lab at the Forsmark nuclear power plant, was about to begin his shift. He'd commuted from nearby Uppsala and arrived at work early. Passing through a radiation measuring station on his way into the controlled area of the nuclear power plant, an alarm sounded - which was strange, because Robinson had not yet been inside the controlled area.

At first, this was put down to an issue with the measuring device - perhaps an alarm level needed to be adjusted. "Completely wrong of us," Robinson said in a 2024 interview with Henrik Ekblom Ystén, published in Vi.

There was soon a long line of employees at the monitoring station.

"No one came out. The monitor was constantly beeping," Robinson said.

There was nothing to suggest a malfunction at any of Forsmark's three boiling water reactors - no abnormal radiation levels were observed inside the reactor buildings or from the stacks - but an alert was declared, with all personnel not required for the immediate operation of the plant evacuated. The local radio station was informed of the observations and the measures that were being taken at the plant.

Robinson asked to borrow a colleague's shoes, which he checked in the lab. "I discovered a lot of radioactivity and traces of substances that we normally don't have in Forsmark's reactors … whatever the emissions were, they didn't come from Forsmark."

As the day went on, Robinson recalled, more reports began coming in of elevated levels from other locations in Sweden, Norway and Finland, and the suspicion of an accident somewhere in the Soviet Union began to grow.

3.2.4. Confirming the Source

In 1986, the Swedish Radiation Protection Institute (SSI, from its Swedish name) was responsible for planning for radiological emergencies outside Swedish nuclear power plants and for advising and instructing local authorities, including in the event of an accident.

The first reports of increased radiation levels at Forsmark reached SSI at around 10:00 on 28 April[6], and an emergency task force was convened immediately. Over the next few hours, SSI started to receive information about abnormal radiation levels at the Studsvik research center, some 200 km from Forsmark, and at Sweden's other nuclear power plants. Research centers in Finland and Denmark confirmed to the SSI that increased background radiation and airborne contamination had been registered in both countries.

Sweden had a widespread radiation monitoring network, initially set up in the 1950s to monitor fallout from atmospheric nuclear weapons testing. At 12:15pm, the Swedish National Defense Research Institute - which operated the national air sampling stations - was notified of what was at that point still assumed to be a release from Forsmark. It analyzed a sample that had just been collected in Stockholm: from the radionuclide ratios it was clear that a reactor accident had happened somewhere. But meteorological data showed that the air flowing over Stockholm that morning had come from Latvia, Lithuania, Belarus and Ukraine - at that time, all part of the Soviet Union. By 13:00, the SSI had been notified that all Swedish reactors could be excluded: several plant sites in the USSR (Ignalina, Rovno, Chernobyl, Kursk and Novovoronezh) were emerging as the likely candidates.

That afternoon, Swedish diplomats had reached out to contacts in Moscow to try to find out more information about any accident - but were told their Soviet contacts had no information. Sweden then contacted the International Atomic Energy Agency to request

[6] Original Chernobyl explosions occurred on 26 April.

its help in finding out about the location -and extent - of the accident it was now clear had taken place.

Back in the Soviet Union, authorities were conducting emergency fire-fighting and response operations, although there had not yet been any announcements to the public. The first – brief - official report of the emergency came via the TASS official news agency later in the evening of 28 April. Five sentences, read out on the Вре́мя TV program, stating that an accident had occurred at the Chernobyl nuclear power plant.

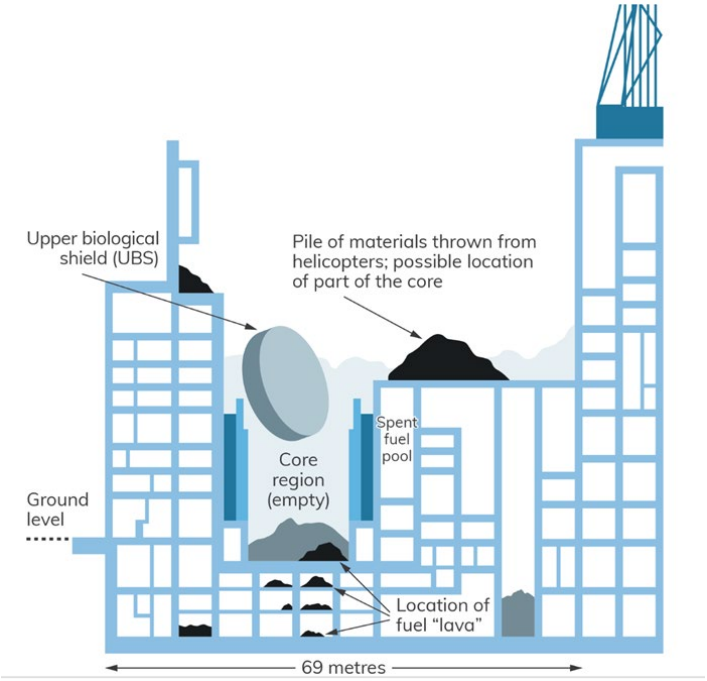
The report said only that one of the nuclear reactors had been damaged; that the effects of the accident were being dealt with, assistance was being provided for those affected, and a commission had been set up to investigate the incident.

It was not until 14 May that President Mikhail Gorbachev acknowledged the accident in a televised address.[6]

The official announcements to the Soviet people may have been a long time coming, but inside the Soviet Union, awareness of the accident had been growing. Radio Free Europe/Radio Liberty's Ukrainian Service made its first mention of the news on April 29.

3.3. The Impact

The first of the two explosions that rocked unit 4 at the Chernobyl plant in the early hours of April 26, 1986 is now known to have been a steam explosion which blew open the reactor and blew the roof off the reactor building, releasing fission products to the atmosphere. Moments later, the second explosion - likely caused by the production of hydrogen from zirconium-steam reactions (nuclear fuel rods are clad in zirconium alloy) - threw out fragments from the fuel channels as well as hot graphite. The plume of smoke, radioactive fission products and debris rose about 1 km into the air. Here's a World Nuclear Association graphic showing the rough layout of the reactor after the accident:

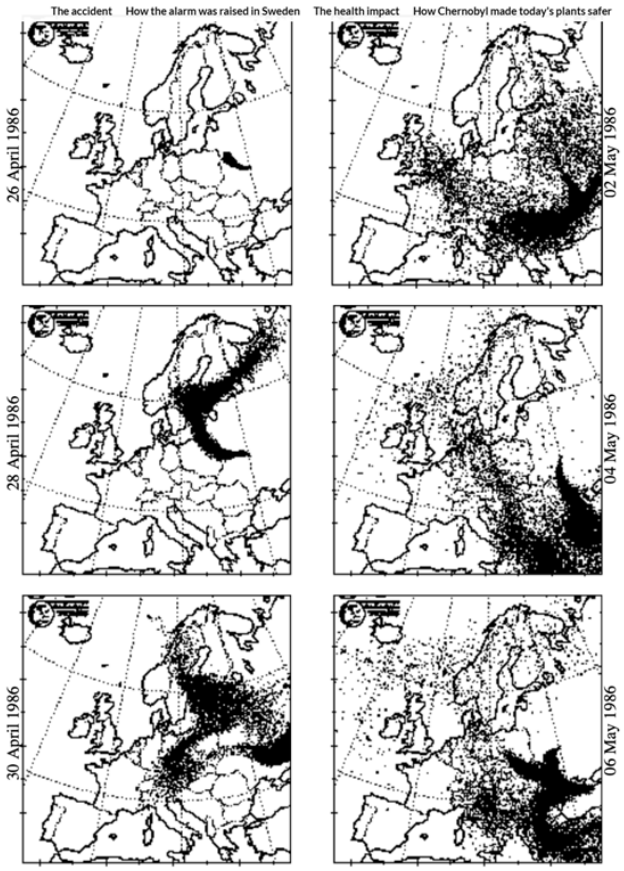


Fires started in what was left of the Reactor 4 building and other parts of the site, releasing clouds of steam and dust - most of these fires had been put out within a few

hours. But a serious fire which involved the reactor's graphite moderator burned for days, finally being extinguished by 9 May.

The most significant radioactive releases from Chernobyl occurred over a period of about 10 days. There was an initial large release following the explosion - principally made up of the more volatile radionuclides (for example, the reactor's entire inventory of xenon-33 was released during the accident), iodine and compounds of elements such as cesium and tellurium. The radioactive release rate fell quickly, but about a week later, as the graphite fire continued, emissions again began to rise and there was another period of intense emissions - this time, involving some of the less volatile elements such as cerium, zirconium and lanthanides embedded in fuel particles.

Those radioactive particles ejected into the atmosphere must eventually come back down - and where they come down is influenced by things like the size of the particles themselves (larger, heavier particles are deposited closer to the accident site, while smaller particles will be more widely dispersed). The weather conditions also play a part - and in the ten days or so after the accident, when the significant releases occurred, the meteorological conditions were changing frequently (see graphic below).



The initial radioactive plume - the one that was detected in Sweden - was tracked as it moved over the Soviet Union and Europe, with north-westerly winds initially taking it towards Scandinavia, the Netherlands, Belgium and the UK. Later, as the winds shifted, the plume moved to the south. All that time, the composition and characteristics of the radioactive materials in the plume were changing, for example due to radioactive decay,

chemical transformations, and changes in particle size. The pattern of deposition was also irregular: rainfall caused a significant increase in deposition.

The plume spread far and wide - activity from Chernobyl was detected as far away as Canada, Japan and the USA - but only certain territories in the former Soviet Union, and a few parts of Europe, experienced significant contamination.

With four reactors in operation in 1986, two more RBMK units already under construction, and plans for a second phase of six further reactors, Chernobyl had looked set to become the largest nuclear power plant in the world. The town of Pripyat, about 3 kilometers from the plant, was founded in 1970 as a showpiece city to house the Chernobyl workforce.

In an article published in February 1986 - just two months before the accident - the town's mayor, Vladimir Voloshko, enthused about a town with a population drawn from all over the Soviet Union, with streets abounding in flowers, apartment blocks standing in pine groves, schools, libraries, shops, sports facilities and playgrounds conveniently close to each residential area. The average age of the population was just 26. The photo below, courtesy of Chornobyl Nuclear Power Plant SSE (Chornobyl is Ukraine's preferred spelling), gives an idea of how it looked before being abandoned:

The decision to evacuate Pripyat was not taken until late on 26 April. An announcement was issued at 11:00 the next day, with evacuation beginning at 14:00 that afternoon - around 36 hours after the explosion. Residents were told to take their documents, vital personal belongings and some food, "just in case" - and to make sure they had turned off the lights, electrical equipment and water, and shut the windows before leaving.

The evacuation was to be temporary. According to the OECD Nuclear Energy Agency's report issued ten years after the accident, the evacuation was completed in about two and a half hours. The residents never returned.

In early May, an exclusion zone with a radius of 30 kilometers from the Chernobyl plant was declared, leading to more evacuations. The zone was subsequently expanded to include some highly contaminated areas further out from the plant as well as Pripyat's 49,000 residents. The old town of Chernobyl, with a population of 12,500, lay about 15 kilometers to the south-east of the power plant. Between 115,000 and 135,000 people are thought to have lived within the 30-kilometer radius of the plant. Setting up the exclusion zone meant the evacuation of more than 100,000 people from Belarus, Ukraine and Russia.

Meanwhile, at the plant itself, work went on to tackle the fires and attempt to bring the situation under control. There were about 600 emergency workers on site at Chernobyl during the night of the accident: they received the highest doses of radiation, according to UNSCEAR. (UNSCEAR is the United Nations Scientific Commission on the Effects of Atomic Radiation, the UN body with a mandate from the General Assembly to assess and report levels and health effects of exposure to ionizing radiation.)

Acute radiation sickness was confirmed in 134 of the emergency workers: 93 of those received higher doses and had more severe acute radiation sickness. Twenty-eight of those died over the next days and weeks. In addition to the deaths from radiation sickness, three further deaths were immediately associated with the accident: one person was killed by the explosion itself, and another suffered a coronary thrombosis. A third person died early on the morning of the accident from thermal burns.

About 600,000 people (including about 240,000 military servicemen) received special certificates confirming their status as recovery operation workers under laws passed in Belarus, the Russian Federation and Ukraine. Over the next few years, these workers - known as "liquidators" - carried out tasks such as decontamination of the reactor block, reactor site and roads, as well as construction of the "sarcophagus" to cover the damaged reactor, a town for reactor personnel and waste repositories.

3.3.1. Broader Horizons

Even as the emergency teams continued their efforts to bring the situation at the plant under control, radioactive material emitted as a result of the accident was starting to be detected around Europe.

Here's just one example: In 1986, David Drury had recently begun working at the Heysham 2 project in north-west England, which was still in commissioning. He remembers arriving at work on 28 April to be met by operators complaining of intermittent, and seemingly spurious, alarms from the whole-body monitoring systems that had begun the previous day.

They had already confirmed that nothing had happened at the plant - or its sister plant next door, Heysham 1 - to cause the alarms.

"And so this was kind of a bit baffling, but then we started to get reports of potential fallout coming across in the atmosphere from Eastern Europe and from Ukraine, from the Chernobyl nuclear accident," Drury recalled to World Nuclear News.

"I can remember really clearly listening to the commentary on the radio... And certainly, for us as nuclear workers, nuclear professionals, it was kind of almost a sense of, let's say, disbelief, but also wonder, that we could be experiencing some consequence

thousands of miles away as a result of an accident that happened or an event on one of the nuclear power stations in Eastern Europe."

3.3.2. Isotopes and Impacts

The explosions at Chernobyl released over 100 radioactive elements into the air.

When it comes to considering the effects of that radiation, it's not just the amount of radioactivity released that is important, but also its distribution over time, and the chemical and physical forms of the radionuclides released. The types and amounts of radioactive or hazardous material released to the environment following a nuclear accident is known as the "source term". For Chernobyl, the source term was initially estimated from air sampling and ground deposition within the former Soviet Union.

As time passed, more information continued to become available from deposition data measured around world, and from analyses on core debris and material deposited in the reactor building itself. By the time the OECD Nuclear Energy Agency (NEA) reviewed the radiological and health impacts of the accident in 1996 - benefiting from ten years of refinements to those initial evaluations - there was what the agency described as a "fairly accurate estimate" of the total radioactivity released from the accident. And in an update published 15 years later, in 2022, the NEA said those estimations remained valid.

Radioactive elements including plutonium, iodine, strontium and cesium were released during the accident. Two of those - iodine-131 (I-131) and caesium-137 (Cs-137) - are of particular importance, because they are responsible for most of the radiation exposure received by the general population.

Iodine-131 has a short radioactive half-life (eight days), but it can be transferred to humans relatively rapidly from the air and through consumption of contaminated milk (milk becomes contaminated when cows and goats graze on grass on which the isotope has been deposited) and leafy vegetables. Iodine becomes concentrated in the thyroid gland, so I-131 is of particular significance in infants and children because of their intake of milk and dairy products. But its short half-life means that I-131 is not a long-term environmental issue.

Cesium is longer-lived, with a half-life of 30 years. Deposited on soil, it migrates downwards, and contamination levels in soils decrease only slowly as it is taken up through the roots of plants. And when taken up by food-plants, it enters the food chain…

Final author's comment: One of the main differences between 1986 and now, is that, for a several of decades, we have used extensive computer-modeling to test all large power generation designs before actually building anything, including exploring paths to self-destruction. This absence was especially true in the USSR, which lagged behind the U.S. in computer-tech. Thus, with this dearth, the designers in the late 1970s made their best-guesses, which were dead wrong. In the U.S. in the late 70s, I was already using similar computer-modeling, and my colleagues were modeling whole nuclear plants.