WINDSCALE FIRE: EXAMINING THE CONTROVERSIAL CHAPTER OF NUCLEAR HISTORY

A literature review of the Windscale accident of October 10, 1957

Lappeenranta–Lahti University of Technology LUT

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Examiner: D.Sc. (Tech.) Elina Hujala

ABSTRACT

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This literature review provides a comprehensive examination of the Windscale accident, a significant event in the history of nuclear energy that occurred in United Kingdom on October 10, 1957. Through an in-depth analysis of historical documents, scientific literature, and archival records, the review provides a detailed analysis of the construction and the operation of the Windscale site, focusing on the events leading up to the accident; design flaws, safety concerns, political pressures; and its aftermath. The review highlights the lessons learned from the accident, the changes in safety practices and regulations, and the broader societal implications. By evaluating the impact of the Windscale accident on the nuclear industry, this review contributes to a better understanding of nuclear safety and the advancement of responsible nuclear energy development.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
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Windscale tulipalo: Ydinhistorian kiistanalaisen luvun tarkastelu

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Tämä kirjallisuuskatsaus antaa kattavan tarkastelun Windscale-onnettomuudesta, merkittävästä tapahtumasta ydinenergian historiassa, joka tapahtui Yhdistyneessä Kuningaskunnassa 10. lokakuuta 1957. Historiallisten asiakirjojen, tieteellisen kirjallisuuden ja arkiston syvällisen analyysin avulla tarkastelu tarjoaa yksityiskohtaisen analyysin Windscale-alueen rakentamisesta ja toiminnasta keskittyen onnettomuuteen johtaneisiin tapahtumiin; suunnitteluvirheisiin, turvallisuusongelmiin, poliittisiin paineisiin; ja sen jälkimainingeihin. Katsauksessa nostetaan esille onnettomuudesta opittuja asioita, turvallisuuskäytäntöjen ja määräysten muutoksia sekä laajempia yhteiskunnallisia vaikutuksia. Arvioimalla Windscalen onnettomuuden vaikutusta ydinteollisuuteen, tämä katsaus auttaa ymmärtämään ydinturvallisuutta paremmin ja edistämään vastuullista ydinenergian kehittämistä.

SYMBOLS AND ABBREVIATIONS

Constants

Celsius	temperature (SI)	[℃]
Curie	Curie’s constant	[Ci]
Foot	length measurement (Imperial)	[ft]
Kilometre	length measurement (SI)	[km]
Mile	length measurement (Imperial)	[mi]

Elements

^{9}Be	Beryllium-9
CO_2	Carbon dioxide
^{59}Co	Cobalt-59
^{131}I	Iodine-131
^{237}Np	Neptunium-237
^{239}Pu	Plutonium-239
^{240}Pu	Plutonium-240
^{210}Po	Polonium-210
^{106}Ru	Ruthenium-106
^{90}Sr	Strontium-90
^{232}Th	Thorium-232
^{3}He	Tritium-3
^{238}U	Uranium-238

Abbreviations

ACRS	Advisory Committee for Reactor Safety
A.M.	Ante meridiem
BEPO	British Experimental Pile
LM	Bismuth oxide
BNFL	British Nuclear Fuels Limited
BCDG	Burst Cartridge Detection Gear
CEA	Commissariat à l’Energie Atomique
NEA	European Nuclear Energy Agency (ENEA)
IRS	Incident Reporting System
INSARR	Integrated Safety Assessment of Research Reactors
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
INES	International Nuclear and Radiological Event Scale
INSAG	International Nuclear Safety Advisory Group
AM	Magnesium-lithium alloy
NRPB	National Radiological Protection Board
NII	Nuclear Installations Inspectorate
NDA	Nuclear Decommissioning Authority
NRC	Nuclear Regulatory Commission
NUSS	Nuclear Safety Standards
OSART	Operational Safety Review Teams
OECD	Organisation for Economic Co-operation and Development
P.M.	Post meridiem

PSA	Probabilistic safety assessment
RAPAT	Radiation Protection Advisory Team
SCSIN	Service Central de Sûreté des Installations Nucléaires
TMI	Three Mile Island
UK	United Kingdom
UKAEA	UK Atomic Energy Authority
US	United States
USA	United States of America
USAEC	US Atomic Energy Commission

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Introduction

One of the biggest, yet relatively unknown nuclear disasters took place on October 10, 1957, in Windscale, United Kingdom, 29 years prior to the infamous Chernobyl-4 disaster in the Soviet Union. The Windscale incident stands as the most significant nuclear catastrophe in Britain's history, earning a Level 5 classification on the INES scale (IAEA 2008). Nevertheless, despite its magnitude, the incident remains largely unfamiliar and rarely discussed, primarily due to the extensive classification and documentation surrounding the event. Understanding the incident is crucial for gaining insights into nuclear history and the evolution of nuclear energy safety.

The Windscale incident serves as a significant reminder of the utmost importance of nuclear safety protocols and practices. As the first nuclear facility in Britain, the Windscale project was initially received with great anticipation and commendation. It was meant to showcase Britain's capabilities and credibility as a nuclear ally, with nuclear science, despite its relative unfamiliarity and untested status during that era, being viewed as an exciting endeavour. However, inadequate planning and design of the power plant, coupled with emerging complications, pressing political challenges, and unattainable deadlines years after its construction, set Windscale on a path towards disaster. What was intended to be a source of national pride swiftly transformed into the nation's most catastrophic nuclear incident as a fire ignited in one of the facility's reactors.

This paper centres around a broad literature review of the Windscale accident. Subsequent sections of this publication will delve into the events that transpired prior to the accident, the accident itself, the measures taken to mitigate its impact, and the ensuing consequences. The discussion encompasses an examination of the political dynamics and influence exerted on the British atomic industry, the construction and design of the Windscale site, the trial-and-error process of British nuclear testing, the evolution of their nuclear science, the Windscale fire and its aftermath, the documentation pertaining to the incident, and ultimately draws conclusions regarding its effect on the nuclear industry practices prior to the declassification of the incident.

1 Windscale

The Windscale site is shrouded in relative anonymity today. The central focus of this chapter is to provide a comprehensive overview of the Windscale site, contextualizing the infamous accident that took place on October 10, 1957. Through an in-depth exploration, this chapter delves into the historical evolution of the Windscale Piles, unravelling the details of the construction process and development of this significant nuclear power plant site.

1.1 Britain’s international nuclear relations

Following the conclusion of the Second World War, Windscale emerged as a beacon of hope for the New Britain. This elevated status placed significant pressure on the project, as its success became pivotal not only for domestic prospects but also for the fate of a crucial international relationship. (BBC 2007)

1.1.1 USA’s nuclear secrets

By mid-1942, the Americans had achieved substantial scientific and technological advancements, showcasing their prowess on the global stage. The massive Manhattan Project was beginning to take shape, and the British were keen on partnership. British politicians and scientists hoped for a post-war atomic partnership, and even believed in Britain acquiring its own national atomic project. Despite their impressive scientific and technological knowledge, the Americans exhibited little interest in collaborating with the British, leading to the termination of information exchanges between the two nations.

The British got their chance to participate in the Manhattan Project following the Quebec Agreement signed in August 1943 by the American president Franklin Roosevelt, persuaded by the British Prime Minister, Winston Churchill. The agreement created a Combined Policy Committee, establishing arrangements for the joint procurement and allocation of uranium. Furthermore, a strict policy was implemented, prohibiting the sharing of atomic information with any third parties unless mutually agreed upon by both parties involved. (Arnold et al. 1995, 3–4.)

Despite the significant contribution of the British to the war-time atomic bomb project at Los Alamos, New Mexico and their extensive understanding regarding the atomic bomb theory and construction techniques (Fakley 1983), they were unable to access the top-secret American plutonium production reactors and fuel-processing facilities located at Hanford Site. Furthermore, the highly prized water-cooled graphite reactors remained beyond their grasp. In August 1946, the United States Congress Atomic Energy Act – the McMahon Act – destroyed the British' hope of a warm comradery relationship and co-operation between the two countries, as any sharing of classified atomic energy information, even with close allies, was prohibited (The National Archives 2008). William Penney, a highly talented young mathematician from Britain, was selected to lead the British atomic bomb development, having previously worked on blast effects studies at the Bikini Atoll tests for the Americans in 1946.

In the wake of these developments, Harwell, a research centre dedicated to studying the operation of nuclear reactors, was established within an airplane hangar at a former World War II airfield in Oxfordshire in August 1947. Its primary objective was to conduct research into the function of nuclear reactors (Science and Technology Facility Council 2020).

In order to keep pace with the rapidly advancing atomic industry and enhance diplomatic relations between the United States and Britain, it was decided that the construction of the Windscale reactors was essential. This strategic choice paved the way for a successful nuclear partnership, facilitating the confidential exchange of top-secret information between the two nations. (Mahaffey 2014, 158–160.)

1.1.2 Soviet Union's nuclear development

Soviet Union, getting its hands on every atomic secret Klaus Fuchs (German theoretical physicist, and an atomic spy) could provide them with, also joined the so-called 'atomic competition' (Mahaffey 2014, 158). Churchill had foreseen an impending Soviet military threat even before the end of the war, with the Cold War intensifying by 1948. The first Soviet atomic bomb test was detected in September 1949, alarming both the British and Americans. (Arnold et al. 1995, 6.) These events proved to be a crucial factor weighing on the demands of the British government, which will be discussed later in this work.

1.2 Construction of the power plant

Windscale, along with England’s first large-scale atomic piles, were established at the site of the Royal Ordnance Factory at Sellafield. This facility, alongside its sister factory at Drigg, had previously been responsible for the production of T.N.T. during the Second World War. The site stood in the county of Cumberland (now part of Cumbria) in north-west coast of England. In order to avoid any potential confusion with the nearby Preston-based Springfield Works – a uranium processing and fuel manufacturing establishment – the relatively unknown Sellafield was renamed Windscale. (Wakeford 2007)

Construction of Windscale commenced in September 1947, undertaking a monumental task that required a workforce of nearly 5,000 men, among whom were over 300 architects, surveyors, and engineers. (Arnold et al. 1995, 11.) To construct the two reactors, an estimated 4,000 tons of graphite were utilized, incorporating towering chimneys reaching a height of around 125 meters (410 ft). Additionally, a reinforced concrete box measuring over 2 meters (7 ft) on thickness, known as ‘biological shield’, was constructed. (BBC 2007)

The Windscale reactors operated on air-cooling, requiring the construction of four fans solely for shutdown purposes. In addition, eight massive blowers and two auxiliary (booster) fans were installed. Notably, the main blowers and shutdown fans remained operational even during temporary shutdowns, enabling the removal of residual heat. (Mahaffey 2014, 162.)

The pile and the graphite reactor design are illustrated in Figures 1 & 2.

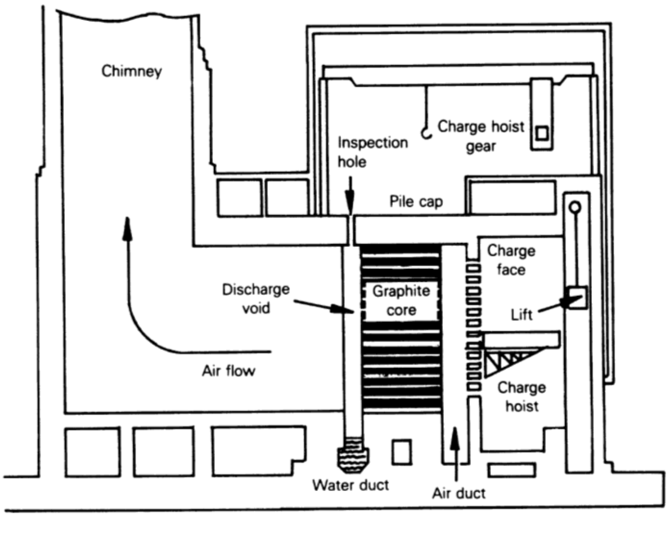

Figure 1. A section through a Windscale pile (Arnold et al. 1995).

Two nuclear reactors were built in Windscale: Pile No. 1 and Pile No. 2. The charge faces of the Piles were approximately 15 metres (50 ft) high and wide and contained 3,340 horizontal fuel channels in groups of four, over 7 metres (25 ft) long and open at the back of the pile. (Hill 2013) Each pile had scanning units – Burst Cartridge Detection Gear (BCDG) – on the rear face. BCDG was used to detect and scan for burst fuel cartridges with great accuracy.

Construction was notably fast, as Pile No. 1 became operational by October 1950, and Pile No. 2 by June 1951. (Arnold et al. 1995, 17.)

1.3 Reactor design

The primary objective behind the design of Windscale was to generate sufficient plutonium for the development of a nuclear bomb. The design concept drew inspiration from American scientists, and the reactors were constructed with an arrangement wherein uranium was positioned in hundreds of channels meticulously drilled through solid graphite block referred to as the core. (BBC 2007)

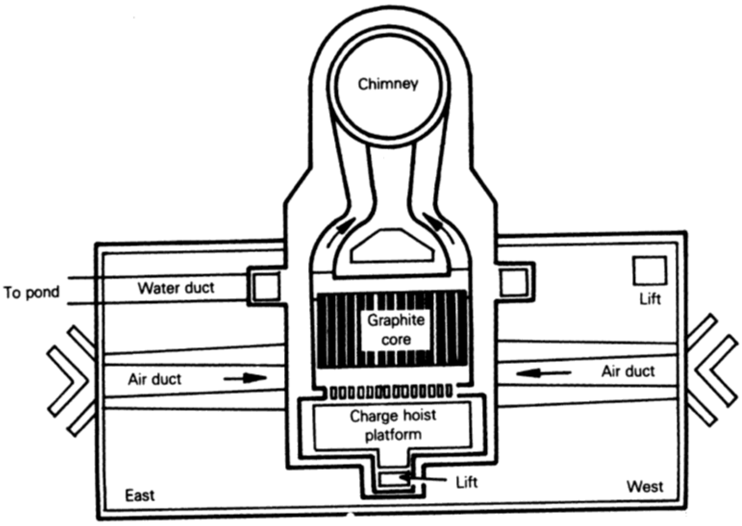

Figure 2. A plan of a Windscale pile (Arnold et al. 1995).

1.3.1 Graphite

Graphite, like diamond, is a crystalline form of carbon. While diamond reigns as the hardest material on Earth, capable of cutting through sapphire, graphite exhibits an entirely different characteristic – it is incredibly soft, to the extent that it can be easily cut with a butter knife. A substantial reserve of natural graphite was initially discovered in Cumbria, England, during the 1500s, situated approximately 21 kilometres (13 miles) north-east of the later Windscale site location. This discovery proved instrumental, with the British leveraging their expertise in utilizing this material for centuries, including its application within nuclear reactors. (Mahaffey 2014, 163–164.)

Upon learning of the British plutonium production initiative, the Americans became increasingly concerned about the reports that reached their ears. As a result, in 1948, a visitor from Los Alamos paid a visit to Harwell’s headquarters, offering valuable advice and guidance. The Americans informed the British of the Wigner growth that affects the graphite, expanding the size of the graphite blocks due to displacement of carbon atoms under the recoil action of neutrons colliding with them. (Mahaffey 2014, 164)

The knowledge obtained during the visit from Los Alamos proved invaluable in the redesign of the core, enabling each block to expand horizontally. However, British graphite exhibited different properties from the synthetic graphite used in the United States and expanded in multiple directions rather than just one. This expansion would result in the pile becoming warped and unusable within 2.5 years of use.

The solution was found by Canadian scientists, stating that British graphite would only expand at one fifth of the length of the American products, allowing the pile to operate for approximately 35 years instead. (Mahaffey 2014, 165.)

1.3.2 Nuclear fuel

The purpose of the Windscale nuclear reactors was to produce plutonium from the uranium fuel. The plutonium-239 (^{239}Pu) was chemically separated from worthless transmuted uranium-238 (^{238}U) and the waste by-products of nuclear reactions in a reprocessing plant, throwing the generated power overboard. The production of plutonium was maximized by having the fuel situated in a neutron-rich environment for a short period of time, maximizing the probability of undesirable plutonium-240 (^{240}Pu) being up-converted from the uranium. (Mahaffey 2014, 161.)

The plutonium was converted into metallic form, then sent to the Atomic Weapons Research Establishment at Aldermaston to be machined and assembled as a weapon. However, the activities at Windscale extended beyond the processing of weapons-grade uranium. By utilizing neutron radiation on specifically chosen materials in the form of ‘isotope cartridges’ inserted into the core channels, the facility also facilitated the production of additional nuclides. (Wakeford 2007, 211.)

The crucial steps contributing to both efficiency and safety of the piles were the design and integrity of the fuel elements. These fuel elements had to meet specific criteria: they needed to be efficient, mechanically robust, and possess a low neutron absorption rate. The cans also had to be finned for increased heat transfer. For these reasons, aluminium was chosen as the canning material.

Choosing aluminium for the canning material brought up its own set of issues: from structural design to chemical reactions of aluminium with uranium. Fortunately, these issues were all eventually solved, and the fuel element cans were finished. (Arnold et al. 1995, 14.)

The isotope cartridges consisted of bismuth oxide cartridges (LM cartridges) and magnesium-lithium alloy cartridges (AM cartridges). LM cartridges contained alpha-particle emitter polonium (^{210}Po) in combination with beryllium (^{9}Be) to act as a neutron source and trigger fission chain reactions, whereas AM cartridges, later, were purely used to produce tritium (^{3}He). Thorium (^{232}Th), neptunium (^{237}Np), and cobalt (^{59}Co) were also nuclides irradiated at the piles during their operational times. (Wakeford 2007, 211.)

As new cartridges were fed into the graphite core, old cartridges would fall into the skips of water baths placed below and be taken away (BBC 2007).

1.3.3 Cooling

To ensure safety and mitigate potential risks, uranium was encapsulated within aluminium cartridges, effectively sealing it off from air exposure. This measure served to prevent excessive heat buildup and the risk of fire. Notably, the most critical stage of the uranium extraction process lay in the graphite core, where the presence of cartridges necessitated immediate cooling. Failure to cool the core promptly could result in core meltdown and subsequent ignition. (BBC 2007)

The British knew that Americans had succeeded in water cooling their reactors at Hanford Site by having a continual flow of water run through the channels. This, however, had a serious weakness, as if the highly efficient water-cooling supply were to fail, by a broken pump or other means, the core itself would explode, resulting in a disastrous steam explosion. The Americans openly acknowledged this issue. There was no river like Columbia in Britain to be used as an open-loop cooling system, and using the salty seawater from the Irish Sea would result in destructive corrosion. (Mahaffey 2014, 161.)

The Americans had initially contemplated using gas-cooled piles, however, the gas would have had to be pressurized and leakages would have posed a possible danger. Additionally, the plutonium output would have been lower, and the fans or blowers used to circulate the gas would be very large. The Americans decided to go with water-cooling. (Arnold et al. 1995, 10.)

Terence Price, a reactor physicist at Harwell from 1947–60, stated the following:

> “The reactor would run very rapidly, and I mean very rapidly withing a second or so out of control. At Hanford in North America, there was a special 30-mile-long escape road built as part of the safety precautions. And we decided this country was far too small to have a reactor with such dangerous possibilities built anywhere, not even in Scotland.” (BBC 2007, 00:19:09.)

The British decided to go with air cooling instead. Air, at atmospheric pressure, would cool the finned fuel cans with reasonable efficiency, blowing straight through the core. The air would be blown through the core by huge fans, taking the heat up and out through enormous chimneys. Compared to gas-cooled pressurized design, air-cooled piles would be simpler in design and quicker to build as well. (Arnold et al. 1995, 10.)

A devastating discovery was made by Terence Price, one year into construction: the radioactive uranium could burn if any of the delicate aluminium cartridges were to burst, and the powerful air-cooling system would blow highly radioactive dust up the chimney over Seascale and beyond. This highly radioactive dust would the rain down on the nearby dairy farms of Cumbria. (BBC 2007)

The need for an air filter for the chimneys at Windscale was deemed urgent, but there were differing opinions regarding its necessity, with some perceiving at as an unnecessary delay. Although Price was backed up by physicist Sir John Cockcroft. Taking inspiration from the Americans at their Long Island facility in New York, who had installed filters between the atomic pile and air exhaust stack to prevent the spread of fission products in the event of an accident, Cockcroft ordered the same to be done at Windscale. Rebuilt would have been necessary for the Unit 1 chimney, since it had already been constructed to the height of 70 ft. The only appropriate location for the filters would be atop of the chimneys, which would not be an optimal set-up as the gas velocity would be higher and servicing and maintenance more challenging. Nevertheless, Cockcroft was adamant and in command, so the filters were built and hauled 400 feet up to the tops of the air stacks. The filters assemblies were aptly named 'Cockcroft's follies.' (Mahaffey 2014, 165–166.)

Although Cockcroft's safety measures proved successful in containing the majority of radioactive particles, there was one notable exception – a volatile fission product iodine-131 (^{131}I). It was largely unhindered by the filters because of its gaseous form. This was ignored as the production speed and the desire to amass a stockpile of weapons outweighed all but the most fundamental safety precautions. (Mahaffey 2014, 166–167.)

The strive to build a weapon arsenal, however, did not completely disregard all the safety regulations. Radiation detectors were installed in the chimneys to locate channels of fuel elements with burst aluminium cladding. This was done to prevent contamination in the affected channels. Such bursts did indeed occur several times during the Piles' operational time. (Wakeford 2007, 211–212.) The reactors were not being built as desired due to the deadline imposed by politicians, and the building had begun before the research work was complete.

Windscale was built in 5 years, only 10 days behind schedule. (BBC 2007)

2 Road to the disaster

Windscale, a source of great national pride for Britain, became the site of a significant incident that unfolded in the past. This chapter focuses on the events leading up to the accident, aiming to provide a comprehensive understanding of the occurrences that preceded and followed the fire that erupted in Windscale Pile No. 1 reactor on October 10, 1957.

2.1 Complications with scheduling

The urgent demand for Britain to establish itself as a nuclear power by 1952 was driven by the anticipation of the Soviet Union’s imminent completion of their first atomic bomb. However, this deadline presented formidable challenge for a field of science that was still in its infancy and largely untested. Regrettably, at Whitehall, the centre of the United Kingdom’s government, meeting the deadline outweighed the importance of ensuring the safety of the reactor.

Windscale was taken over by William Penney after enough uranium had been successfully extracted. Around the same time Britain received a new Prime Minister, Winston Churchill, who was determined that Penney’s atom bomb would restore Britain’s standing with the Americans.

2.1.1 Difficulties with design

The operation of the Windscale Piles was far from trouble-free. Despite a seemingly seamless commissioning process, issues began to arise during their operation, revealing shortcomings in the heavily criticized design and construction processes.

A serious operating problem arose in May 1952, during a scheduled shutdown of Pile No. 2. Over 140 cartridges were discovered hanging out of their respective channels or lodged in the outlet ducts, outside of the core. At least one of them had been damaged by contact with the BCDG. To ensure that the cartridges remained securely in place, an urgent and expedited design and manufacturing process was undertaken to develop a new type of graphite boat.

Later, in May 1952, Pile No. 2 experienced an unexplained and abnormal rise in temperature. To address this issue, the spread of heat within the pile was halted by the cooling air. An analogous, yet more serious accident occurred in September 1952, this time in Pile No. 1. (Arnold et al. 1995, 18.)

2.1.2 Insufficient production

It became evident to the scientists at the Harwell research laboratory that Windscale's plutonium production was insufficient to meet the demands for the atomic bomb. The two Windscale piles had generated less plutonium than originally anticipated in the design, and the third Windscale pile – cancelled because of the pressure to reduce the demand of uranium by Americans – was not in the picture to aid the process. The uranium cartridges located in the graphite core were not producing enough plutonium. The only way to resolve the issue and increase the plutonium output was to further heat the uranium. To do this, it was necessary reduce the amount of aluminium casing around it. However, there was a concern as the aluminium cartridges had already been manufactured and were located inside the reactor. (BBC 2007)

Recognizing the need to enhance the efficiency of the existing cartridges, Windscale's deputy general manager, Tom Tuohy, made the decision to trim approximately 4 millimetres (one-sixth inch) of aluminium from each fin. This action led to the removal of one of Windscale's safety features. Despite the numerous warning signs, the production of plutonium continued with no tolerance for any delays.

Britain reached a significant milestone on October 3, 1952, with the successful detonation of its first atomic bomb test, codenamed Hurricane, near Trimouille Island, Australia. The successful test yielded a release of 25 kilotons of raw energy, marking a momentous triumph for Windscale. However, the Americans had already developed a more advanced weapon – the hydrogen bomb – resulting in a megaton explosion, ten times the size of the British bomb. As the United States were unwilling to share nuclear secrets or engage in nuclear partnership with Britain, Churchill secretly instructed Penney to lead the development of Britain's own domestic hydrogen bomb. As a result, the personnel at Aldermaston were faced with the urgent task of producing a thermonuclear weapon. (BBC 2007)

2.1.3 Wigner release

The development of the hydrogen bomb (H-bomb), which necessitated the use of a new material called tritium in addition to plutonium, posed a significant challenge for Windscale.

The facility had initially been designed exclusively for plutonium production, and accommodating the new material required modifications. Notably, the reactors at Windscale had already exhibited unpredictable behaviour, marked by sudden and drastic increase in temperature within the graphite cores as energy accumulated, triggering alarms. This previously undocumented occurrence, referred to as the ‘Wigner effect’, prompted the invention of a novel procedure known as the ‘Wigner release’ to address this issue effectively. (BBC 2007)

The phenomenon known as the ‘Wigner effect’ was named in recognition of the contributions made by Hungarian physicist Eugene Wigner. This effect is characterized by the accumulation of potential energy stored in graphite, which is subsequently released when carbon atoms return to their original locations. The interaction between the high-speed neutrons and carbon atoms leads to displacement from their typical positions within the atomic lattice. Subsequently, at elevated temperatures, carbon atoms spontaneously fall back into place, resulting in the release of energy. This energy release phenomenon was aptly named the ‘Wigner release’.

Under certain conditions, if the energy released during the Wigner release reaches a critical level, the process can become self-sustaining, resulting in a progressive rise in graphite temperature. However, in the Windscale piles, the temperatures were not sufficiently high to induce spontaneous fall-back of carbon atoms. Consequently, displaced atoms accumulated in a specific hotspot, leading to an increase in core temperature through the simultaneous release of energy. This, in turn, facilitated further fall-back occurrences. (Hill 2013, 105–106.)

The initial release of Wigner energy at Windscale caught everyone off guard, occurring unexpectedly after a considerable duration of pile operation. Fortunately, Windscale had a stroke of luck, as the pile had been shut down for a period before the energy release occurred. Had the pile been running at its peak capacity, the repercussions could have been dire due to the significant magnitude of the energy released.

To address the Wigner energy release issue, the solution of ‘annealing’ was chosen. This entailed operating the reactor at considerably higher temperatures for a duration of several hours to displace the accumulated atoms. The entire process was closely monitored by the operating staff. Still, the annealing progress was unpredictable, as it could commence in any part of the pile and sporadically spread to other regions. The process, as depicted in Figure 3, was not always successful, as it could only initiate in certain areas and the spread was confined to certain areas. Once the Wigner process was triggered, it became irreversible. (Hill 2013, 106–108.)

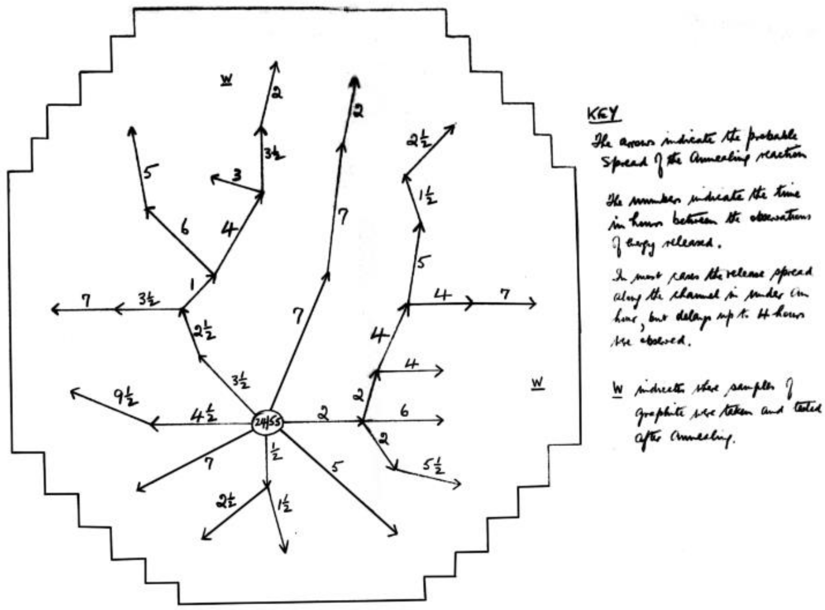

Figure 3. An example of anneal, in which circle 24/55 indicates the channel in the pile where the process had begun, the arrows depicting how the energy release propagated outwards (Hill 2013).

During the annealing process, the cooling fans of the reactor were deliberately switched off, and the reactor itself was shut down. However, as a precautionary measure, if the reactor began to overheat, the cooling fans would be briefly switched on to mitigate the temperature rise. (BBC 2007)

2.2 H-bomb

Situated in close proximity to Windscale, Calder Hall made history on October 17, 1956, by becoming the world’s first commercial nuclear power station. This remarkable achievement represented a major leap forward in harnessing nuclear energy for electricity generation. However, Calder Hall was designed to serve a broader purpose beyond its role as a power station. (BBC 2007)

2.2.1 Tritium

Calder Hall served as the replacement plutonium production facility for the Windscale reactors at the Windscale site. Calder Hall Piles 1 through 4 were large graphite reactors utilizing closed-loop cooling by carbon dioxide (CO_2), which meant they could not blow radioactivity into the atmosphere. The fuel cartridges used in the reactors, aptly named Magnox, consisted of magnesium alloy, and contained natural uranium. The magnesium alloy let the cans withstand higher operating temperatures than the aluminium ones at Windscale.

The Magnox reactors were the first commercial nuclear power reactors in the world, producing 60 megawatts of electricity each. Although, Calder Hall's main purpose was to help Windscale produce demanded material for the H-bomb program in complete secret. It converted ^{238}U into ^{239}Pu and manufactured tritium for Penney's H-bomb, unbeknown to the public. (Mahaffey 2014, 181.)

In Geneva, the world leaders had agreed on a nuclear bomb testing ban treaty by 1959 (IAEA 2015). Britain was running out of time to produce and test the new H-bomb; no delays were acceptable at Windscale. If Britain failed to produce the new bomb it could mean a possible end for British hopes for nuclear collaboration with USA.

Windscale was venturing into unknown scientific territory. Recently developed AM cartridges used for tritium production contained enriched uranium and lithium-magnesium, which were prone to ignition at high temperatures. Senior scientists sounded the alarm. Around the same time, readings taken around Windscale produced alarming results. High levels of radioactivity were discovered around Seascale by a Windscale research scientist Frank Leslie. Some of the radioactive cartridges had burst open by getting stuck, lodged in the back of the reactor. The radioactive dust was unable to be stopped from being blown out over Cumbria by the huge filters on top of the chimneys. Both senior scientists' and Leslie's alarms were kept quiet and ignored. The leaking cartridges were somewhat dealt with make do and mend. (BBC 2007)

2.2.2 Attempt No. 1 – Short Granite

Anthony Eden, the British Prime Minister succeeding Winston Churchill, was accused of misleading the Parliament following the political disaster of the Suez Crisis in 1957. Earlier, in 1955, Britain had launched the world’s first civil nuclear power program; an ambitious objective to build 12 twin-reactor stations within 10 years to generate 1,500 – 2,000 megawatts of electricity. The plan was tripled in size in the aftermath of the Suez Crisis, setting the goal to 5,000 – 6,000 megawatts. (Arnold et al. 1995, 23.)

Following Eden’s resign, Harold Macmillan stepped up to take the position of the new Prime Minister. Macmillan was convinced he could deliver *The Great Prize* because of his friendship with the American President Dwight D. Eisenhower. For that to happen, Britain would have to prove itself a nuclear equal. British H-bomb needed to have a megaton yield because American bomb had the same. Fortunately, Windscale had met its target in delivering tritium.

On May 15, 1957, Britain’s new H-bomb, code-named Short Granite, dropped just offshore from Malden Island in the middle of the Pacific Ocean. The result was an embarrassing explosion of just 300 kilotons. Penney’s H-bomb failed to produce a megaton blast, being barely bigger than the atom bomb five years earlier. The British’ first attempt at making a sufficient hydrogen bomb had failed. (Mahaffey 2014, 171–172.)

2.2.3 Attempt No. 2 – Orange Herald

Penney had a backup plan: another bomb called Orange Herald. Though marketed as one, Orange Herald was not an H-bomb, just a massive atom bomb the British were convinced would produce a megaton explosion. The government did not tell the media about this. Huge quantities of plutonium, along with tritium, needed to be produced. The Americans were not deceived into thinking Britain was now their equal, so Macmillan ordered Penney to prepare another H-bomb test. (BBC 2007)

Following the earlier measure of removing aluminium from the cartridges to increase production, Windscale received an order to further boost tritium production by a staggering 500%. To meet the demands for the H-bomb, new aluminium cartridges were made to house uranium and lithium-magnesium. Some aluminium casing was once again removed to boost the production by increasing the heat of the reaction. The amount of lithium-magnesium was doubled in the cartridges, which caused scientists to express alarms over the danger of a nuclear accident.

Under the increased strain, Windscale persevered until the completion of Orange Herald. The facility had reached its operational limits, but the atomic bomb was successfully prepared. On May 31, 1957, the new bomb detonated on the shores of Maiden Island, mirroring the previous test. The detonation ended in a successful 720-kiloton blast, enough to be classified as one megaton. (BBC 2007)

2.3 Sputnik 1

As a part of their ambitious space program, the Soviet Union successfully launched Sputnik 1, the first man-made artificial satellite, into Earth’s orbit on October 4, 1957. This groundbreaking achievement positioned the Soviet Union at the forefront of the Space Race, leaving United States in a vulnerable position and igniting concerns about their relative capabilities. British Prime Minister Macmillan took notice of the situation and wrote to President Eisenhower to accept Britain as its nuclear ally, confident that the successful nuclear bomb test of Orange Herald 5 months prior would help Britain’s case.

The very same evening fire started at Windscale. (BBC 2007)

3 Fire in Pile No. 1

The Windscale fire posed a significant threat to the new and glamorous civil technology in Britain. This chapter focuses on recounting the events surrounding the accident, offering valuable insights into the happenings in the days leading up to and during the incident.

3.1 Annealing

On the Sunday night of October 6, 1957, Windscale Pile No. 1 was overdue for a process of annealing. The reactor was heating up more than it should. As the last anneal in July 1957 had failed to release energy in the front lower part of the graphite, the core had a significant and dangerous Wigner energy build-up that needed to be released. The Wigner release had been done eight times in the past. Pile No. 1's production was halted, and it was cooled down. The anneal was scheduled to the morning of October 7.

The Wigner release controls were operated by the pile control engineers and their scientists, who acted under the supervision and direction of the pile physicists (Arnold et al. 1995, 42). The 1,800 cubic metre (62,000 cubic ft) core temperature was monitored by mere 66 thermocouples, placed in selected fuel channels at three depths in the reactor face. This was highly inadequate, as for monitoring the anneal, a comprehensive map of the temperature distribution throughout the graphite was required. Despite this, there was no concern regarding the instrumentation, as the operation team had formerly conducted similar assessments. Additional 13 uranium-temperature monitors were located in the control room, along with seven in the crane room, on top of the pile. (Mahaffey 2014, 172–173.)

3.1.1 First anneal

On the Monday morning of October 7, the main blowers were shut down initiate the process to achieve criticality in the lower portion of the core. Withdrawing the controls and reaching criticality took seven and a half hours, due to the need to work on faulty thermocouple connectors. The fission reactions were concentrated towards the lower front of the core, the goal being bringing the temperature up to 250°C in the core section.

The early Tuesday morning of October 8 began well. The graphite temperatures read between 50° and 80°C, with the exception of one thermocouple reading 210°C. This was where the annealing had started. The pile operators sat back to keep an eye on the process as it slowly spread out. In a successful Wigner release the temperature would rise across the entire core as the stored energy gets released. Here, though, the temperatures were falling, and only one channel, 20-53, was releasing its stored energy. It was also known that uranium does not anneal; that was the job of the graphite. In an unusual turn of events, two of the uranium thermocouples in the core displayed a reading of 250°C. Despite this anomaly, the operating crew seemed to have everything under control. (Mahaffey 2014, 173.)

3.1.1 Second anneal

At 9:00 A.M., several hours later, the operators determined that reheating the reactor by restoring it to criticality was necessary. The initial annealing process had not achieved the desired temperature distribution as planned, prompting the need for further action. (Mahaffey 2014, 173–174.) The decision presented a choice between leaving the stored energy in the reactor, risking a potential fire, or proceeding with a second Wigner release to further elevate the core temperature. Given the absence of negative consequences from a prior instance of a second Wigner release done in the past, the decision was straightforward. Still, strict measures were implemented to ensure that temperatures did not rise above the maximum allowable limit. (BBC 2007)

Although the reactor had been brought back to operation at low power, there was a sense of unease as an unexpected temperature increase to 380°C was detected by one uranium thermocouple. While Pile No. 1 had experienced its fair share of challenges, this type of erratic behaviour was not characteristic. Nonetheless, the annealing process had to continue as planned, leading to the subsequent shutdown of the fission process at 7:25 P.M.

By Wednesday morning, October 9, the situation appeared to have stabilized. In an attempt to lower the temperatures and increase the ventilation in the core, the shutdown fans were switched on, and the inspection ports located atop the core were sealed. Despite these measures, the temperature readings from the graphite thermocouples started to escalate uncontrollably around midnight, presenting a new set of challenges to be addressed. (Mahaffey 2014, 174.)

3.2 Fire in the core

On the early morning of October 10, one thermocouple read an extreme temperature of 400℃. The thermocouple was located in the middle of aforementioned channel hole 20-53 in the core, 20 rows up from the bottom and 53 rows across. Air dampers were opened but the temperature continued rising to 412℃ in mere 15 minutes. The dampers were opened again at 5:10 A.M., at which point some radioactivity was indicated in the filter by the smokestack radiation monitor. Alarm was raised as the stack on Windscale Pile No. 2, running on full power to produce plutonium, indicated increasing radiation levels. The cause of the problem was believed to be a burst rogue uranium cartridge in Pile No. 2. (Mahaffey 2014, 174.)

The situation did not improve as the pile operators continued their attempts at bringing the annealing back under control. The opening and closing of air dampers did not yield any results, and by 1:30 P.M. the uranium temperature was rising over 420℃ with the stack radiation being higher than usual.

Ron Gausden, Windscale Site's Pile Manager, arrived at the scene after being called in, and instructed the pile crew to open the dampers and turn on the shutdown fans in the attempt to bring down the temperature. This, however, was not effective either. (Mahaffey 2014, 174.) Against all assumptions, fire was rapidly burning inside channel 20-53. The aluminium casing that had been trimmed caused the cartridges to catch fire more easily, and the additional heat from the second Wigner release resulted in them bursting and igniting. (BBC 2007) Gausden, unaware of this, directed the operators to turn on the main blowers at 2:30 P.M, hoping to be utilise BCDG to locate the issue. The increased airflow from the now operational blowers caused the fire to spread throughout the hundreds of channels. Radioactivity was pouring out of the chimney as the fire was soon burning out of control.

Gausden contacted Tom Hughes; the Assistant Works Manager, the Acting Works Manager, and the Works Manager; via telephone. The Windscale operation was severely understaffed for this sort of emergency, with only 52 professional posts vacant of the 784 available. (Mahaffey 2014, 175.)

The control room crew made their way to the refuelling platform on the elevator, heading towards row 20 on the loading face to take a look at what was happening behind plug 53.

Each hole was sealed with a metal cylinder when the bio-shield, built to protect the workers who would push the fuel into the graphite pile with long poles, was not in use. After a worker pulled out the plug in 20-53, the team finally had the chance to look inside the graphite pile. Anticipating darkness in the fuel channel, illuminated solely by their flashlights, the scientists were met with a surprising and unsettling sight: a vivid red glow emanating from all five holes behind the plug, illuminating the area.

The crew was suddenly struck by the alarming realization that the pile had been ablaze Tuesday, October 8. (Mahaffey 2014, 175.)

3.3 Damage control

With no predetermined emergency plan in place to handle fire, the scientists at Windscale were initially at a loss regarding the appropriate course of action. Gausden made the decision to remove all the fuel around the burning channels in hope of making a firebreak and stopping the fire from spreading any further in the core. As the crew attempted to remove the fuel around the fire, they quickly realized that the cartridges would not budge as the high temperature caused them to swell and get stuck inside the core. Dressed in protective gear, the men continued their fight with the fire. They pushed out with the fuel with heavy rods, dumping it into the cooling pool at the back of the core. The graphite in front of the pile was now a mess of flames, reading over 1,200°C. (Mahaffey 2014, 175.) As the fire zone extended to 120 channels, two or three channel rings had been cleared to serve as a firebreak (Arnold et al. 1995, 50).

The deputy general manager, Tom Touhy, was contacted via telephone at 5:00 P.M. Tuohy had been home at the time, taking care of his sick wife and children down with the flu. After arriving at the scene in minutes, Tuohy took notice of the grim situation by seeing the crew struggle to dislodge the fuel cartridges out of the back of the pile. The rods used by the men were luminescent yellow on the ends, and had molten uranium dripping from them. (Mahaffey 2014, 175.)

Tuohy came across a group of scientists arguing about the best way to extinguish the fire and by 7:00 P.M. decided to take a better look at the reactor himself. Looking down from the inspection plate in the crane room, Tuohy could see the glowing front of the reactor, flames shooting from the fuel channels. At 11:30, to Tuohy’s growing horror as he observed the situation through the viewing port, the concrete wall situated several feet behind the back of the pile was hit by blue flames. This meant that the flames were intense enough to cause the nitrogen in the air to become ionized, making it possible to burn through the concrete wall. (Mahaffey 2014, 175–176.)

Between 4:00 and 5:00 A.M. on Friday, October 11, the fire had failed to be smothered by a large tank of carbon dioxide. Water was desperately suggested to be pumped into the fuel channels. This was a last resort. There was a risk of catastrophic consequences by using water to put out the fire, as it could cause the reactor to blow up by reacting with the enriched uranium cartridges. (BBC 2007) There were no firehose taps present in the building as the idea of flooding the reactor with water was so far removed, so the works fire brigade had to be called in with pumper trucks. Water was forced through the holes in the loading face just before 9:00 A.M. It flowed deep into the fuel channels through jury-rigged nozzles on minimum pressure, two feet above the apex of the flame. (Mahaffey 2014, 176–177.)

Much to the relief of everyone involved, the reaction between water and graphite did not lead to an explosion. However, it had little effect and the fire kept raging on. After following the situation for about an hour, Tuohy had a brilliant idea. The blowers, previously used to cool the men on the loading face, were turned off as everyone had evacuated. The fire died out rapidly due to the lack of air flowing through the channels. Around noon, Tuohy was able to report on the situation being finally under control.

No official warning about the fire was given to Seascale residents. The water was kept on for additional 30 hours after the fire had died down. (Mahaffey 2014, 177.)

4 Aftermath

As the fire finally subsided, Pile No. 1 was left in ruins. This chapter delves into the aftermath of the Windscale fire. It examines the profound effects that the incident had on the British government and the civil nuclear programs, shedding light on the enduring repercussions that unfolded as a result.

4.1 Safety concerns

The destruction of Pile No. 1 led to the catastrophic meltdown of approximately 17 tons of uranium, with an additional 5 tons being consumed by the fire (Arnold et al. 1995, 74). Although the pile's chimney only captured a small portion of the uranium and fission products emitted during the fire, the pile itself, along with its filters, effectively trapped a significant amount of other fission products, including strontium-90 (^{90}Sr) (Arnold et al. 1995, 54). However, the primary concerns revolved around the volatile fission product ^{131}I present in the fuel. The filter packs, no longer referred to as 'Cockcroft's follies', managed to capture some of the ^{131}I; nonetheless, an estimated 20,000 curies of this hazardous substance escaped from the top of the stacks, dispersing over nearby dairy farms. The widespread release of ^{131}I constituted the most substantial radiological hazard resulting from the accident. (Mahaffey 2014, 178.)

As north-east wind blew the radioactive dust and vapor inland over Seascale (see Figure 4), the immediate concern was contaminated milk, an exceptionally huge risk for infants and young children. The authorities, following extensive environmental monitoring, determined that a ban on milk distribution should be implemented in the west Cumbrian coastal stretch extending from 10 km north of Windscale Works to approximately 20 km to the south. Seventeen farms in the Windscale area were forced to stop milk distribution (Arnold et al. 1995, 58). Iodine-131 had deposited on grass ingested by cattle, resulting in the substance swiftly transferring to their milk. The ban on this milk prevented a significant increase in the collective welfare of the local population and limited individual thyroid ^{131}I doses, which, if contained in larger amounts, could cause thyroid cancer. (Wakeford 2007, 214.)

One fortunate aspect was that ^{131}I had a relatively short half-life of just eight days. As the reactor was shut down in preparation for the upcoming Wigner release on October 6,1957, the production of ^{131}I came to a halt, triggering its decay process. Eight days after the accident, half of the initial ^{131}I had undergone natural decay, marking a significant reduction in its presence. (Mahaffey 2014, 178.)

Within two or three days of the accident, Pile No. 2 continued its operation in perfect condition. After the Authority Executive decided that the continuation of its operation would be unwise, the pile was permanently shut down five days after the accident. (Arnold et al. 1995, 75.)

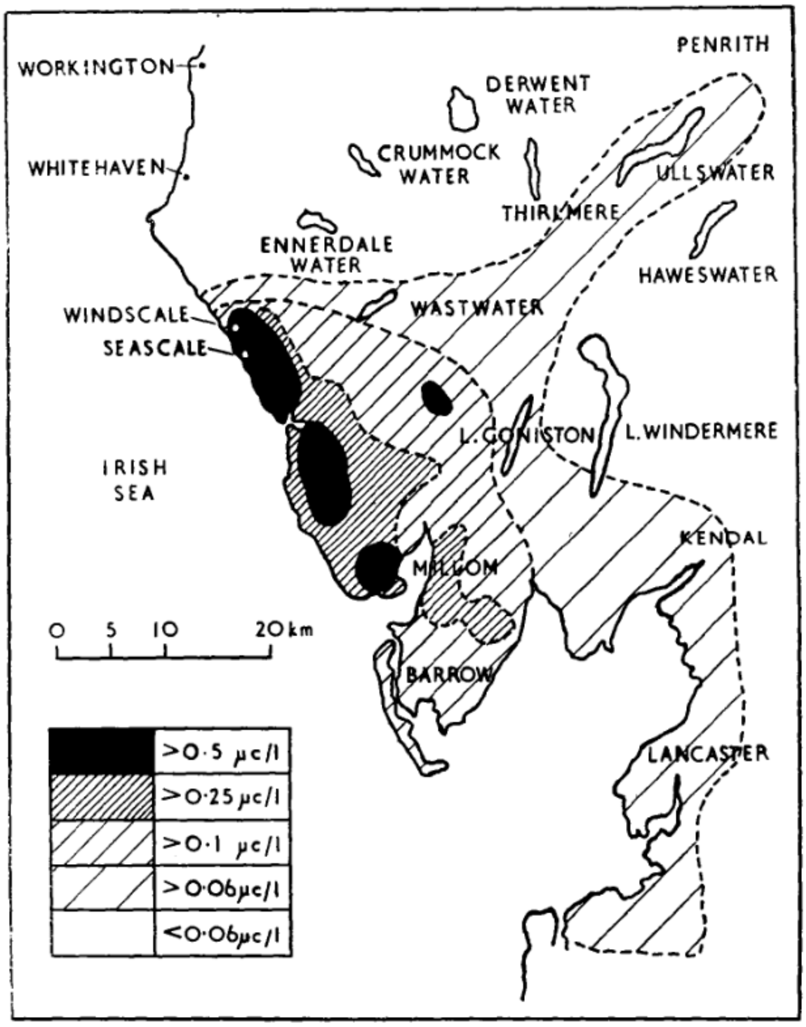

Figure 4. A map showing the milk contamination ^{131}I contours in Windscale and its surrounding area on October 13, 1957 (Loutit et al. 1960).

4.2 Clean-up

With Pile No. 1 completely cooled down, the focus shifted towards the cleanup and remediation of the area to ensure the plant’s safety. To tackle the issue of contamination, measures were taken to pump out the contaminated water, and selected uranium cartridges in the unaffected portion of the core were removed. The air filters were removed on October 20, once it was determined that the radioactivity on them was decreasing rapidly. In order to prevent the release of dust into the atmosphere, the stack opening was sealed with tightly fitted timber planks treated specifically for this purpose. Concurrently, the cooling pond, where the discharged cartridges were transported via skips, underwent a thorough purging process, and was replenished with fresh water, allowing for discharge of the contaminated water into the sea. (Arnold et al. 1995, 73–74.)

By the start of November, all accessible uranium cartridges had been successfully removed from the core. The rods contained within these cartridges were then extracted from their protective casings and transported to the chemical separation plant for further treatment. This adjustment in operations resulted in a two-week postponement of fuel discharge for Calder Hall reactor No. 1 to accommodate the handling and processing of these fuel elements.

Inside the Pile No. 1 core, within approximately 2 metres (6 ft) of the charge face, both graphite and metal seemed to be undamaged. However, the charge hoist on the pile was badly contaminated, which limited the access to it for the time being. There were no attempts to remove the debris from the air and water ducts, nor to clear the blocked channels. Out of 180 tons of uranium fuel contained in the pile, around 22 tons failed to be recovered, including the 5 tons that burned in the fire and 17 melted tons that remained in the core. (Arnold et al. 1995, 74.)

In order to avoid fission products in the core generating residual heat and overheating the graphite, leading to a possible district hazard, the pile was secured by capping the stack and plugging the holes in the biological shield made from concrete. Monitoring equipment and alarm systems were also installed to detect any potential anomalies.

By 1960, most of the pile area was cleaned up, after extensive decontamination of buildings and the removal of the topsoil from their immediate vicinity. (Arnold et al. 1995, 74–75.)

4.3 Political cover-up

The fire at Windscale became a major source of embarrassment for Britain’s Prime Minister Harold Macmillan. The timing of the incident was particularly unfortunate, as it transpired just days before a crucial meeting where President Dwight D. Eisenhower of the United States was set to declare Britain as a suitable nuclear ally for America. (BBC 2007) Within days of the accident, the UK government initiated an inquiry into the accident, chaired by

Sir William Penney. The Penney Committee submitted its report to the government in a timely manner after the accident, on October 26. (Wakeford 2007, 212.)

As the United States finally agreed to collaborate with Britain as nuclear partners, Prime Minister Harold Macmillan returned to Britain to find Penney's report awaiting him on his desk. The report revealed that the Windscale fire was a consequence of the political pressure to develop a megaton bomb. However, as Britain's relationship with America and the delicate negotiations with them to re-establish nuclear weapons cooperation were at risk, the full details of the incident could not be disclosed. Macmillan promptly ordered the recall of all copies of Sir William Penney's report, releasing only a summarized version to the public. The testimony provided by the scientists involved at Windscale was deemed highly sensitive, leading to the tapes being withheld from public access for several decades. The complete Penney Report was eventually made public in 1988, thirty years after the incident. (Wakeford 2007, 212.)

4.3.1 Key notes from the Penney Report

Penney's report was made public in January 1988.

Wigner release process (nuclear heating) been previously carried out eight times in Pile No. 1 before the end of 1956. The anneal of all the graphite in the Pile had not always been successful, e.g., in April 1956, one attempt was entirely unsuccessful, and two others were partially successful (some graphite pockets remained un-annealed).

Double Wigner release process had been utilized on three consecutive occasions before the accident. In 1954 and 1955, a second Wigner release was only initiated 24 hours after the last regional burst of temperature, whereupon all the graphite temperatures were seen to decrease. In 1956, all graphite thermocouples, except for one, were showing a decrease.

The original procedure plan included carrying out Wigner releases after 20,000 cumulative megawatt days. The figure, however, was later increased to 30,000 megawatt days. Before the accident it was decided that the next Wigner release should be due in October 1957, at 40,000 megawatt days.

There was no Pile Operating Manual, so the entire Wigner release process fell entirely to the Pile Physicist and his two deputies due to their specialized expertise. The only existing instruction appeared to be a memorandum sent by the Pile Manager to Mr. Gausden on November 14, 1955: in the event that the highest uranium temperature reaches 360°C, it was essential to provide clear and specific operational instructions to the operator overseeing the Wigner energy release in order to ensure efficient and safe progress (see Appendix 1). Although, in Penney and his team's interview with the Pile Manager, the team learned that should not be an initial cartridge temperature higher than 250°C in the first instance of a Wigner release.

Penney and his team proposed several possible reasons for the direct cause of the accident. The most likely possibility, in their opinion, was that the failure of one or more of the fuel element cans was caused by the rapid increase of temperature of the fuel elements due to the second Wigner release. The second possibility included a failure of a lithium-magnesium cartridge, as the oxidation of lithium-magnesium could have initiated the fire by adding further heat to the already intensely heated piles due to Wigner release. (Penney et al. 2017, 781–785.)

> "We consider that the evidence points to the initiation of the fire being the result of the failure of the can of a fuel element giving rise to oxidation. We also consider that the origin lay in the region of the Pile just below the middle plane and towards the front." (Penney et al. 2017, 785)

However, the team considered that the lithium-magnesium cartridges were not the direct cause of the fire, as no temperature as high as 400°C was recorded in the graphite structure and particulate matter was only captured a cyclone filter at the top of the stack, prior to ignition of any lithium or magnesium.

Another consideration had been an ignition of a portion of a graphite block at an early stage. However, the available data suggested that the oxidation of graphite proceeded slowly at temperatures below 400°C, making this impossible. The ignition of a graphite block would have required temperatures above 450°C. As there was no evidence of the temperatures exceeding 400°C, Penney and his team did not accept this as an explanation for the accident.

Penney and his team determined that a lack of an operating manual and the insufficient instrumentation for the safe and effective running of Wigner release were the primary contributors to the accident. Based on the evidence acquired by the team, it was clear that the division of responsibility between different technical branches were not clearly defined, and the operations staff at Windscale lacked adequate technical guidance. In their view, the heavy responsibilities laid upon the Windscale organization were too heavy to be carried and served as one of the lessons of the accident. (Penney et al. 2017, 785–793.)

Still, Penney and his team neglected to mention that the fire had originated in hole 20-53 due to the overheated lithium diffusing through aluminium in an AM cartridge. This caused the adjoined fuel to be set on fire. Penney also did not take any accountability for himself or the questionable engineering of the isotope production cartridges. (Mahaffey 2014, 180.)

Penney believed the scientist team at Windscale had started the second nuclear heating "too soon" and applied it "too rapidly". Penney's conclusion gave Macmillan the opportunity he was looking for. A White Paper was published, leaving out a lot of the detail present in Penney's report. A new phrase, which Penney had not used, had been inserted into it:

> "The fire at Windscale had been caused by *an error of judgement* by the Windscale men."

The blame was put on the scientists working at Windscale to cover up the truth. (BBC 2007) The Windscale site was renamed Sellafield, as if to get rid of the bad smell and negative associations that came up with the name Windscale. (Mahaffey 2014, 179.) Today, Sellafield is owned by the Nuclear Decommissioning Authority (NDA).

4.4 Response from around the world

The Windscale accident sparked a response of both interest and alarm among scientists worldwide, as its coverage was quickly spread by the international press and radio. The countries that showed the most interest in the news, with reason, were the United States, Italy, Japan, France, and Belgium. (Arnold et al. 1995, 94.)

As the country with the most experience and qualification in graphite moderated reactors, America was well qualified to advice and assist with the situation. The Americans reacted very quickly and offered their help on October 12, wanting all the technical information regarding the accident. A team of five U.S. Atomic Energy Commission (USAEC) scientists and engineers arrived in England for a three-day conference at Risley. A comprehensive report of the accident, including all pertinent pile records were given by the British, who, in return, received substantial information about operating experience from the Americans. This included their research centre at Brookhaven, New Work and the plutonium-producing reactors at Hanford, Washington State. The British had previously owned some unclassified American pertaining to graphite and had participated in conferences in the US on graphite and reactor safety in 1953 and 1956. Further conference on graphite had been in the process of being arranged, when the Windscale fire intervened. Until these post-accident discussions, the Hanford reactors had always been under the strictest secrecy, preventing the Americans from sharing any details about the operation of graphite reactors. In January 1958, a second conference regarding the health physics and medical aspects of the accident was held when nine American scientists arrived in England for thorough discussions. (Arnold et al. 1995, 94–95.)

In Europe, the Italian government had approached the British Embassy in Rome on October 12, asking for information on the Magnox reactors. Italy was in the process of procuring Magnox reactors from Britain, which would be used at their first nuclear power station at Latina. The Latina contract was signed in November, which meant the British' reassurances were satisfactory for the Italian government. The Magnox power station was also bought by the Japanese, becoming the Tokaimura nuclear station. Tokaimura and Latina are the only nuclear stations ever exported by Britain. (Arnold et al. 1995, 95.)

France was the European nation exhibiting the most enthusiasm for graphite reactors, second only to Britain. A graphite-moderated, air-cooled reactor at Marcoule, owned by the French Commissariat à l'Energie Atomique (CEA), was getting two more carbon-dioxide-cooled reactors built along it. After the Windscale accident, the French, surprisingly, had not asked for information regarding the accident. Since Windscale was a defence plant, it was likely that they may have withheld in anticipation of a refusal. Even though the atomic relations between the British and the French were faint because of Britain's existing commitments to the United States, the relations between Authority and French CEA scientists were great. The British decided to invite the French to unclassified talks in February and give an account of the accident, providing information about their health and safety aspects along with various administrative problems. This was greatly appreciated by the French participants. (Arnold et al. 1995, 96.)

The Belgians asked the British for advice about Wigner energy after the accident, as they too had a graphite-moderated reactor at Mol, albeit smaller. The reactor was similar to British Experimental Pile (BEPO) at Harwell. The Belgians were invited to witness the next anneal of BEPO at Harwell in the spring of 1958, as their Mol reactor required annealing before the end of 1959. (Arnold et al. 1995, 95–96.)

As the radiation fallout from Windscale was not believed to pose a substantial public health risk for most of Britain, estimated to be limited to an area of 500 square kilometres (200 sq. miles) around Windscale, no warning was issued to other countries about the potential airborne hazard. This was not considered strange, as it was not expected to pose any threat to other countries. There was no existing international apparatus for exchanging information regarding nuclear accidents like what is available today. Britain was not a member of the European Communities when the Euratom Treaty was signed in March 1957. Additionally, the International Atomic Energy Agency (IAEA) in Vienna was just founded in June 1957, along with the European Nuclear Energy Agency (ENEA – now NEA) being later created in 1958. Within a day or two of the accident, increased radioactivity was detected in parts of Northern Europe. This led to close co-operation between Authority health physicists and overseas scientists at working level. (Arnold et al. 1995, 96–97.)

5 Analysis and impacts

The Windscale accident had a notable impact on the atomic industry, albeit somewhat curtailed by the strict classification measures. The limited accessibility to crucial information hindered the ability to draw comprehensive lessons from the incident and share them with the world. This chapter examines the post-effects of the accident, focusing on the period prior to the declassification of most Windscale documents in 1988. It sheds light on the challenges posed by the strict classification measures and the potential implications of the suppressed information, while also examining the lessons that the world could have learned from the events of October 10, 1957.

5.1 After Windscale

The far-reaching political implications arising from the devastating fire at the Windscale Piles led to their permanent shutdown. Consequently, the UK Atomic Energy Authority (UKAEA), responsible for managing nuclear operations in Britain, underwent substantial changes. However, it is noteworthy that the impact on the eight upcoming UKAEA-owned Magnox reactors, which featured more advanced designs and were employed for electricity generation at Calder Hall, and Chapelcross in Southern Scotland, as well as the weapons production program, remained relatively limited. (Wakeford 2007, 212.)

The official information regarding the Windscale fire was marred by incompleteness and misleading statements, a realization that only dawned upon the public years after the accident. The official statements released by the Authority inaccurately conveyed that the radioactive emissions had been harmlessly carried out to sea. In stark contrast to these claims, the reality was far more concerning. The prevailing wind had transported around 20,000 curies of ^{131}I inland, dispersing it across a significant portion of Northern Europe, as depicted in Figure 5. In the 1980s, it was revealed that the fire had released a considerable amount of the dangerous alpha-emitter ^{210}Po into the atmosphere due to the reactor's irradiation of material to produce bomb triggers. The National Radiological Protection Board (NRPB) of British government, in 1983, confirmed findings of an analysis published by British nuclear scientists. This analysis indicated that the Windscale fire, initially assumed to pose no hazard to the public, could potentially lead up to 30 additional cancer-related deaths due to radioactive exposure. An official inquiry into the Windscale fire had also made a report in 1958, however, it was classified, and the full text was not published at the time. (Patterson 1986, 2.)

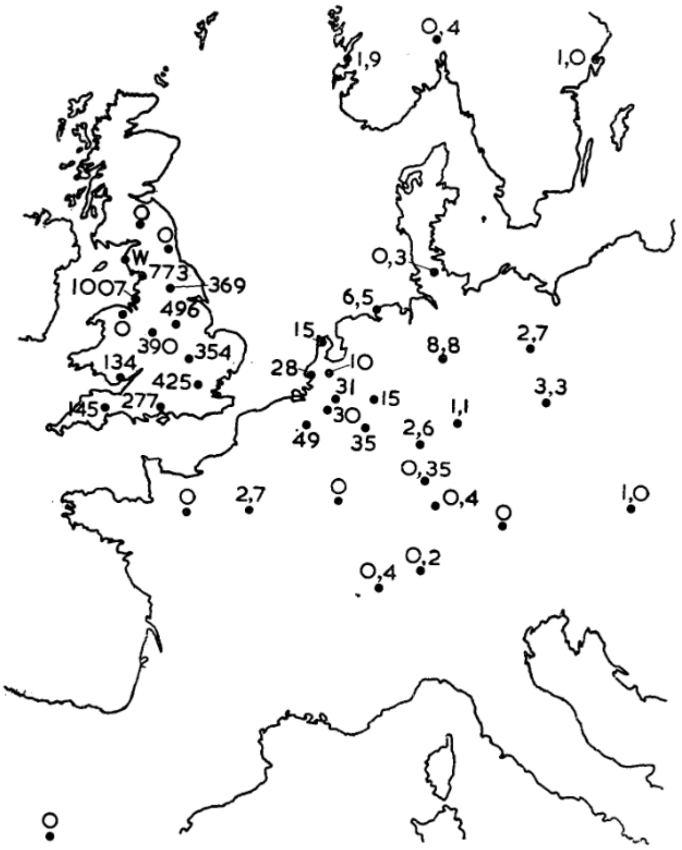

Figure 5. A map displaying the time integral of the concentration of ^{131}I in the air (micro-microcurie-days per cubic metre) in Europe following the Windscale accident in October, 1957 (Loutit et al. 1960).

The establishment of the NRPB in 1970 was instigated by a committee chaired by Sir Alexander Fleck investigating the wider implications of the accident afterwards. NRPB was subsumed within the Health Protection Agency as the Radiation Protection Division since 2004. (Wakeford 2007, 212.) Another indirect result of the accident was the formation of UK’s Nuclear Installations Inspectorate (NII), a part of the Health & Safety executive responsible for regulating the safety of nuclear installations in the UK. (Jones 2008, 5.)

The Windscale site, now Sellafield, houses massive aging concrete stacks. British Nuclear Fuels, operating since 1971, conceded that something had to be done about the two inoperative reactors. This was difficult, as Pile No. 1 was heavily contaminated. The dismantle and disposing of its radioactive rubble without exposing workers and the public to too much radiation would pose a serious technical challenge. (Patterson 1986, 3.) Calder Hall was shut down in 2003 (Institution of Civil Engineers 2023), and as of 2023, nothing has yet been done to the former nuclear reactor site.

5.1.1 Further uncertainty

At the time of the radioactive leak, the scientific understanding surrounding the Windscale accident was relatively limited. The dissemination of information regarding both the accident itself and its scientific aspects was largely confined to specialist media channels. Even today, the circulation of comprehensive details regarding the event remains relatively restricted. Despite being classified a Level 5 incident on the International Nuclear and Radiological Event Scale (INES) and making a significant dent in UK's nuclear policy, Windscale is hardly talked about.

The lack of awareness among the British population about the Windscale reactors is evident in the New Scientist article addressing the Windscale Fire, published on October 17, 1957:

> "One of the two seven-year-old reactors had been shut down, and whatever work was being carried out on it – apparently it was being used for experiments of some kind – started a fire in at least two fuel channels in the centre of the reactor which was fierce enough to carry vapourised fission products the whole distance up the 400-foot chimney and through the filters at its top."

The article emphasizes the importance of conducting a comprehensive investigation of the accident to ensure that any deficiencies in the reactor design will not be replicated in the future. The shortcomings of the reactor at Windscale are attributed to its design, which was formulated almost a decade earlier when scientific knowledge about fission was considerably limited. It also raises the question of how certain it is that the UKAEA will not repeat the errors made following the outbreak of the fire. The article's concluding words bring out the nation's concerns:

> "Public confidence has been severely shaken by what appeared to be attempts to minimise the gravity of what had taken place at Windscale, and even more by the extremely late hour at which any precautions to safeguard public health were put into effect. The escape of fission products may have been small, but night calls by police two days after the first leaks occurred suggest an unfortunately belated awakening to the degree of contamination that might in fact be involved."

This concern regarding potential accidents was not unfounded, as demonstrated by an incident in 1973 at B204, a Magnox reprocessing plant B205's pretreatment section built by British Nuclear Fuels Limited (BNFL) at Windscale site in 1969. Before the accident, 100 tons of spent oxide fuel had been reprocessed there. The accident released radioactive ruthenium-106 (^{106}Ru), a notorious fission product present in radioactive waste, gas into the plant and resulted in B204 being shut down. Some radioactivity was released into the operating area, exposing 35 workers to the gas. None of the radioactivity, fortunately, was released into the surrounding countryside. (Nature 1978; Sneddon 2010, 51.)

Sneddon, in his work (2010), quotes Dr T.J. Thompson, a leading scientist of the EBR-1 fire accident investigation at America’s first nuclear power reactor in 1955 as follows:

> “… at the time, nuclear power programmes were thought to be safe and economical methods of generating electricity that appealed to countries seeking to promote the rapid development of their electric power systems.”

These accidents had little effect on non-nuclear countries’ attitudes to nuclear power and their optimism, as they were downplayed and outright denied by the relevant government bodies. The general awareness of the accidents outside the nuclear sphere was very low when it should have been significantly higher. (Sneddon 2010, 52.)

5.1.2 INES rating

Despite the initial assertion that the Windscale accident had limited impact, its severity was ultimately recognized with a Level 5 classification on the INES scale (Sneddon 2010, 50.). INES was developed by the IAEA and the NEA (see Figure 6) in May 1990, to classify nuclear power plant events and later all installations linked to the civil nuclear sector (IAEA 2017). All nuclear and radiological incidents are classified by INES by considering three areas of impact:

People and the Environment
Radiological Barriers and Control
Defence-in-Depth

The People and the Environment area of impact considers the location of the event, the widespread of the radioactive material from the location of the accident, and the radiation doses received by people in proximity of the accident. The Radiological Barriers and Control area of impact pertains to circumstances that do not have any immediate impact on humans or the environment. It is applicable only in large facilities where unanticipated high radiation levels and leaks arise within the installations. The Defence-in-Depth area of impact covers the preventive measures that did not function as intended in events that did not have a direct impact on people or the environment.

It is worth emphasizing that the Windscale fire was not a minor incident, as its significance is reflected in its classification on the INES scale. Only a handful of events, including the Kyshtym accident in Soviet Union in 1957 (a Level 6 incident), the Three Mile Island accident in the United States in 1979 (a Level 5 incident), and the Chernolyl-4 accident in Soviet Union in 1986 (a Level 7 incident), the Goiânia accident in Brazil in 1987 (a Level 5 incident), and the Fukushima Daiichi accident in Japan in 2011 (a Level 7 incident), have been classified as high or higher than the Windscale fire (IAEA 2008; Statista Research Department 2011).

Figure 6. A representation of the INES levels as a pyramid (Simopt, s.r.o. 2021).

5.2 Changes to nuclear practices

Safety priority of nuclear science was scarce in the first years of nuclear development. Little attention was given to safety criteria that the power plant designs were supposed to meet, and there was nothing to compare the designs to. Construction and operation were given little attention, and even to achieve sufficient safety levels, detailed design approach was essentially given no review. (Sylves 1982)

A first version of the general design criteria was issued in 1965 by the US Atomic Energy Commission (AEC). The second, more relevant, version was issued by the Advisory Committee for Reactor Safety (ACRS) in 1967. This was a decisive step towards the improved safety regulation in the nuclear field. In the same year, in an international meeting in Vienna, Austria, the concept of probabilistic safety assessment (PSA) was introduced for the first time. (Tanguy 1988, 52.)

Safety practices had not reached full recognition before 1957 as they were independent from nuclear developments. This came later. For organizations participating in the development of the peaceful nuclear energy applications, safety was already a primary concern, though not fully autonomous. Tanguy brings up François Cogné in his bulletin, who, in his paper ‘Progress in Nuclear Safety’ (paper in French, in *Revue Générale Nucléaire*, No. 1 (1984)), mentions that there had been no dedicated focus on safety in the first two Geneva conferences in 1955 and 1958.

Between 1957 and 1967, main safety functions, such as containing the radioactive materials, controlling the chain reaction, and cooling the core, were established. The emphasis placed on safety of the design was a primary factor in this period. Other concepts that were introduced included Defence-in-Depth, involving having multiple layers of protection and redundancy to meet the criterion of a single failure; and the provision of the fundamental design for safety features, relying on postulated initiating events. At that time, the most significant external events, including earthquakes and floods, were presented. France emphasised on having multi-barrier systems to keep the radioactive materials and the environment separate, along with an assessment of the possible challenges of this. Discussions regarding the prevention of accidents and the reduction of their repercussions were held extensively, with an emphasis on improving codes and standards ranging from stress analysis to in-service inspection. Reactivity transients and fuel failure mechanisms were the subject of thorough investigations by many research facilities. These facilities included USA, France, Japan, and other several reactor types. (Tanguy 1988, 53–54.)

The emphasis on safety of construction, precisely design safety, happened from 1967 to 1979. Quality assurance was the key aspect introduced at this time. David Okrent, in his book *The Technology of Nuclear Reactor Safety*, noted the following in 1964:

> “Since many reactor projects have experienced difficulty due to inadequate workmanship, faulty materials, and other construction problems, the

> importance of this phase (the construction stage) cannot be overemphasised. The execution of a reactor design, if not properly carried out, can nullify the safety features. Very little can be said in the way of guidance except that it is essential to maintain the highest standards of construction and installation."

Quality assurance became a well-accepted concept, even if its implementation raised problems. Another concept that went through a considerable evolution was safety design. Full extension was taken by independent regulatory bodies during this period. This period also held a lot of changes to different countries' responsibilities and organisations, and many design safety issues were raised.

A programme of safety guides in the USA was originally initiated by the AEC in 1970 to carry out the design safety criteria, which was then given to the Nuclear Regulatory Commission (NRC), established by the Energy Reorganization Act, in 1974. In France, Service Central de Sûreté des Installations Nucléaires (SCSIN) took over the safety responsibility from CEA in 1973. The NII was formed in the Health and Safety Executive in Great Britain in 1975. (Tanguy 1988, 53–54.)

By 1979, severe accidents were not ignored. The nuclear community was so confident in the expected significant mitigation effects from the containment that they believed nuclear power plants were designed to be overly safe, resulting in a very slim chance of severe radiological impacts to both the public and the environment. It was initially incorrect to assume that nuclear power plants had not advanced over the years, as their power capacity had increased, resulting in higher levels of decay heat. The designs of the plants had become much more complicated, even if new safety features were added to minimize the probability of accidents. Various safety features now included important relationships between possible failures, and insufficient attention was allocated to safety procedures and the potential for human error. Though from 1979 on, after the Three Mile Island accident in the US, operational safety did eventually get the importance and attention it deserved. (Tanguy 1988, 54–55.)

5.2.1 International safety

As the number of nuclear power plant projects increased, the harmonisation of varying national standards and regulatory mandates was instrumental for the expansion of international trade in nuclear power plant services and equipment in the 1970s. The development of an extensive body of safety standards for nuclear power plants began by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA/OECD). Sixty documents were published in the Agency’s Nuclear Safety Standards (NUSS) programme, which dealt with safety aspects and measures mentioned earlier.

After the accident at TMI, new nuclear power plants experienced a fall in the number of orders. The Agency revised its Basic Safety Standards in 1982, considering the recommendations of International Commission on Radiological Protection (ICRP) on dose optimization. A plethora of technical guidance documents focused on emergency planning and preparedness, as well as occupational and public requirements within the realm of radiation protection, were also issued by the Agency. (Tanguy 1988, 56.)

To address the growing needs of Member States, in 1972, the Agency provided missions for Integrated Safety Assessment of Research Reactors (INSARR), many of which were located in developing countries. Then, in 1973, the Agency implemented the Operational Safety Review Teams (OSART) to offer nuclear power plant operators’ valuable guidance and a platform for exchanging ideas on increasing safety at the operational level. Later in 1973, to enable benefit from “lessons learned” to operators from all participating countries, an International Incident Reporting System (IRS) was established. To evaluate its actions in nuclear safety efforts and make recommendations regarding its future operations, the Agency founded the International Nuclear Safety Advisory Group (INSAG) in 1985. The assessment of data and analysis of results from the Post-Accident Review Meeting in Vienna in 1986 following the Chernobyl accident, was conducted by it. The Agency additionally provided assist to non-nuclear power States in enhancing their radiation protection capabilities through Radiation Protection Advisory Team (RAPAT). (Tanguy 1988, 56–57.)

Conclusions

The Windscale accident serves as an important milestone in nuclear history, with profound implications for safety regulations, public perception, and policy development. The incident, which occurred due to a combination of design flaws, operational challenges, and political pressures, highlighted the necessity for strong safety precautions and comprehensive investigations within the nuclear sector. The aftermath of the incident underscored the importance of clear communication, effective regulatory frameworks, and international collaboration in order to guarantee the safe and responsible use of nuclear technology.

Through the literature review of the Windscale accident, it becomes evident that the incident had a transformative impact on reactor design, emergency response protocols, and risk mitigation strategies. The valuable insights gained from the lessons learned at Windscale instigated significant challenges in the UK Atomic Authority and prompted widespread re-evaluation of safety standards and regulatory practices on a global scale. However, due to the extensive classification of information surrounding the Windscale accident, its immediate impact on the nuclear industry remained largely undisclosed. The classification and limited availability of comprehensive details limited the ability to fully grasp the consequences of the incident and impeded the prompt integration of necessary improvements in nuclear safety practices. It was not until the late 1960s and early 1970s that significant strides were made in stablishing safety criteria and regulatory practices. Only with the declassification of the Windscale documents in 1988 did a more complete picture of the accident and its implications begin to emerge, shedding light on the delayed understanding of Windscale’s impact on the nuclear industry. The release of the Penney Report further underscored the significance of transparency and knowledge dissemination, providing valuable understanding of the accident and emphasizing the importance of proactive information sharing within the nuclear field.

Furthermore, the Windscale accident serves as a stark reminder of the intricate nature and inherent risks associated with nuclear energy. It underscores a pressing need for policymakers, regulators, and stakeholders to place utmost importance to safety, public awareness, and continuous advancement within the nuclear industry. By understanding the events leading up to the accident, the accident itself, and its aftermath, invaluable lessons can be acquired to guide future decision-making processes, strengthen nuclear safety practices, and promote the responsible and sustainable utilization of nuclear technology.

The literature review of the Windscale accident and its implications for the nuclear industry opens up avenues for further research. While this publication sheds light on the historical context, events, and aftermath of the accident, there are several areas that warrant further investigation, such as a comparative analysis of the regulatory frameworks and safety practices across different countries in response to the accident, and a study of the socio-political dynamics and decision-making processes leading up to and following the incident.

In conclusion, the Windscale accident continues to hold relevance as a case study in nuclear history, emphasizing the importance of continuous vigilance, rigorous safety measures, and international co-operation to ensure the safe and sustainable use of nuclear energy for the benefit of society.

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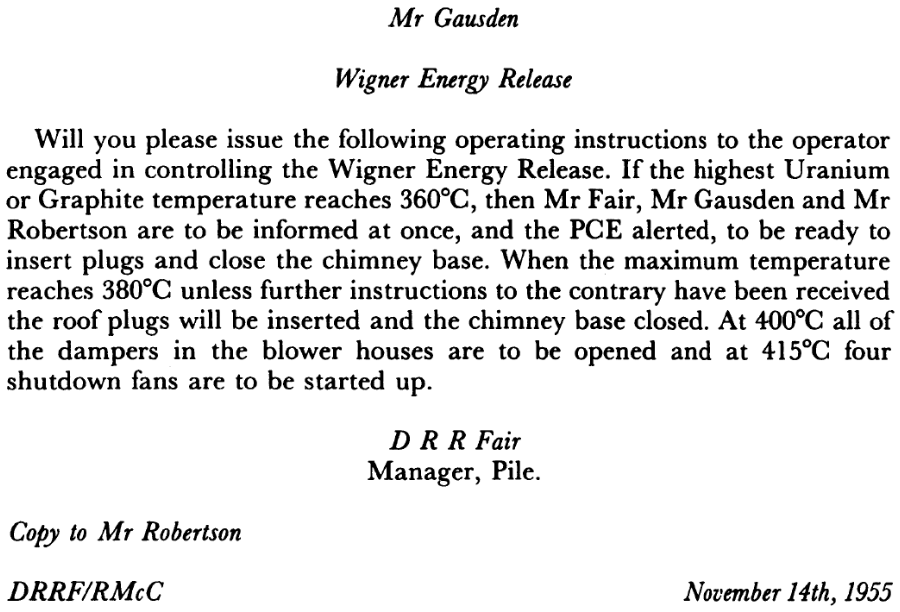
Appendix 1. Memorandum on Wigner Releases on November 14, 1955



Mr Gausden

Wigner Energy Release

Will you please issue the following operating instructions to the operator engaged in controlling the Wigner Energy Release. If the highest Uranium or Graphite temperature reaches 360°C, then Mr Fair, Mr Gausden and Mr Robertson are to be informed at once, and the PCE alerted, to be ready to insert plugs and close the chimney base. When the maximum temperature reaches 380°C unless further instructions to the contrary have been received the roof plugs will be inserted and the chimney base closed. At 400°C all of the dampers in the blower houses are to be opened and at 415°C four shutdown fans are to be started up.

D R R Fair
Manager, Pile.

Copy to Mr Robertson

DRRF/RMcC *November 14th, 1955*