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Simulation of Spread of Radionuclides in Result of an Accident in A Nuclear Facility

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ABSTRACT

Accidents at nuclear facilities (nuclear power plants, radioactive waste management facilities, nuclear fuel factories, etc.) could cause critical impacts on health of the employees, local population, and environment. Apparently, a radiological crisis set off by human error, a demonstration of war, damage or a cataclysmic event could be the most intricate emergency to deal with. The accident at the Windscale nuclear facility (plutonium production plant, i.e., military reactor) in UK in 1957 resulted in releasing huge amount of radioactivity in the south-eastern direction, which negatively affected the public health and environment.Thiswork aims to simulate the Windscale accident using HOTSPOT Health Physics Code, and meteorological data and released activity data of radionuclides to the atmosphere. With this simulation, TEDE (total effective dose equivalent) is determined, next compared with the field result data.This work could be a base for future research on the aerial scattering of radionuclides after the Windscale, or other accidents. The diverse technique could be implemented to improve the outcomes.

Keywords: nuclear accident, radionuclides, absorbed dose, HOTSPOT Health Physics Code, released radioactivity

1. INTRODUCTION

In today's era of instrument and technology, there has been the use of nuclear fuel (e.g., U-235), to produce nuclear weapons (e.g., Pu-239) as well as radioisotopes (e.g., Tc-99) utilized in nuclear medicines procedures, which are augmented in our routine life. Even though radiation accidents happen intermittently, the world's rising dependence on nuclear power and the industrial utilization of radioisotopes increase the prospect that such events will occur in the future. Nuclear power plants must have been operated within the utmost secure way by following all safety and security measures and standards at domestic, territorial, and global levels. When these safety and security measures are avoided or not accurately followed by nuclear plant operators, then the accident can result in serious consequences to public health and the environment. Because of this reason, assessment of the nuclear operations should be conducted regularly by the government and the owner of the nuclear power plants. The point of this evaluation is to check whether a satisfactory level of safety goals and criteria as indicated by the plant designer, the operating organization, and the regulatory body have been achieved. Safety estimation should be a precise procedure that has to be considered through the life span of the atomic power plant, to distinguish radiation danger that emerges on the people, and the environment amid the activity of the nuclear power plant. The point of the security appraisal is to decide whether satisfactory measures have been taken by the governments and nuclear power plant engineers to control radiation dangers to an adequate level, with an account of both the anticipation of irregular occasions and the relief of their consequences.

In case of a nuclear accident, in the first hour's local emergency personnel will have to provide support to the victims specifically if the victims have sustained physical wounds. All the while in the early phase of the response, trained staff members must also attempt to curb further radiation disclosure to all individuals in the affected area while tackling to predict the negative effects of the release to nearby people. During the following period of the reaction, local personnel must contact the master advisors and ask the fundamental assets to absolutely oversee the casualties and the circumstances.

Few nuclear accidents happened since the 1950's listed below table with INES scale and released radioactivity:

Table 1. Radioactivity released to the atmosphere by INES 4–7 nuclear accidents (in PBq). [1]

Location	Country	INES	Date
Fukushima	Japan	7	11 March 2011
Chernobyl	USSR	7	26 April 1986
Mayak	USSR	6	29 September 1957
Chalk River	Canada	5	12 December 1952
Windscale	UK	5	10 October 1957
Simi Valley	USA	5–6	26 July 1959
Belojarsk	USSR	5	1977
Three Mile Island	USA	5	28 March 1979
Chernobyl	USSR	5	1 September 1982
Idaho Falls	USA	4	29 November 1955
Idaho Falls	USA	4	3 January 1961
Monroe	USA	4	5 October 1966
Lucens	Switzerland	4–5	21 January 1969
Windscale	UK	4	1973
Leningrad	USSR	4–5	6 February 1974
Leningrad	USSR	4–5	October 1974
Jaslovske´ Bohunice	CSSR	4	22 February 1977
Saint-Laurent	France	4	13 March 1980
Buenos Aires	Argentina	4	23 September 1983
Tokaimura	Japan	4	30 September 1999

INES 0–3 events are indicated as inconsistency, irregularity, and incidents.
INES 4 is an accident with local consequences.
INES 5 is an accident with wider consequences.
INES 6 is a serious accident.
INES 7 is a major accident (major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures).

n.d.a. no data available; [a] Substantial emission of ^{85}Kr, ^{133}Xe assumed though n.d.a.; [b] Substantial ^{131}I emissions assumed, though n.d.a.; [c] Mainly ^{85}Kr emitted; [d] No strong source of radioactivity to the atmosphere; [e] Release of radioactive sludge from filter powder to the environment.

From these accidents, I have chosen to analyze the Windscale accident in 1957, UK.

2. WINDSCALE PILES

The UK was in a run to construct Pu for its nuclear weapon program in the nuclear arms race during the Cold War. So that, two air-cooled piles to produce weapon-grade plutonium were built and operated at the Windscale, now called Sellafield, a site at the northwest coast of the UK. [3]

2.1 Construction

During the time frame 1950-51 to 1957, two air-cooled, graphite-moderated, open-circuit nuclear reactors known Windscale piles were worked at Windscale-works, Sellafield, on the Cambrian shoreline of northwest England, to produce materials, essentially plutonium, for the UK nuclear weapons program, and they stopped the production after the fire accident in Pile no.1 in October 1957 [2]. The reactor was fueled with cartridges, which generally contained natural uranium metal in an aluminum cladding, situated in horizontal channels inside a graphite-moderated reactor core. There was an air blower to cool down the reactor core which pumped the cooling air from the atmosphere through the reactor core and released from the chimney stack height at more than 100m.

Amid routine fuel releasing tasks, cartridges from specific zones inside the reactor got stopped in the cooling air outlet ducts at the base of the pile chimney stacks, cartridges likewise got stopped on the release face of the reactor or entangled within the scanner gear situated on the release face. Some cartridges ruptured on impact, so the irradiated uranium fuel was subject to go through slow oxidation in a warmed air stream and release particles of uranium oxide, a small portion of which was conveyed through the chimney stacks. Despite having a huge bank of filters had been introduced at the top of the stacks, there had been trouble in keeping up proficient filtration, bringing about irradiated uranium oxide particles being released to the atmosphere.

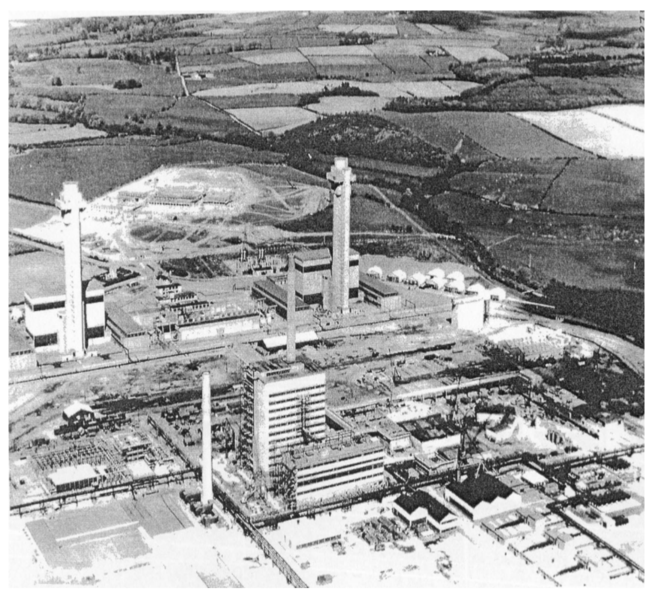

Fig 1. An early aerial photograph of the Windscale works taken in 1951 looking northeast, showing the two Windscale piles in the background. [2]

2.2 Operation

The Windscale two nuclear reactors are also known as Windscale piles. The Windscale piles were built of concrete as a structure and biological protecting material from radiation. Each pile had 2000 tons of graphite core with 3440 horizontal channels in each one of which was put a line of 21 fuel components of, in common, natural uranium metal covered with aluminum canisters. At the point when completely charged, each pile contained more than 70,000 fuel elements. With the controlled evacuation of neutron-absorbing control rods, the course of action of the fuel components inside the graphite moderator was with the end goal that the neutron flux expanded to the level required for the self-sustaining nuclear chain reaction to happen and the reactor achieves the criticality. The fuel rods were regularly changed as an idea creation of plutonium was accomplished, and the discharged rods were transported to another part of Windscale works for compound disintegration and division of the plutonium from the unused uranium and the waste fission products [2].

The heat produced because of the fission reaction inside the reactor is usually used to produce electricity through a steam turbine. However, in the case of these piles, this was not done, and the reactors were cooled by atmospheric air, huge volumes being transferred through the core. In each pile, the heated exhaust air was released through concrete chimney, close to the highest point of which was built a filter gallery to eliminate particulate material from the emissions.

A schematic layout of the Windscale pile no. 1 is shown in Fig. 3, to assist in understanding the above depiction of the operations.

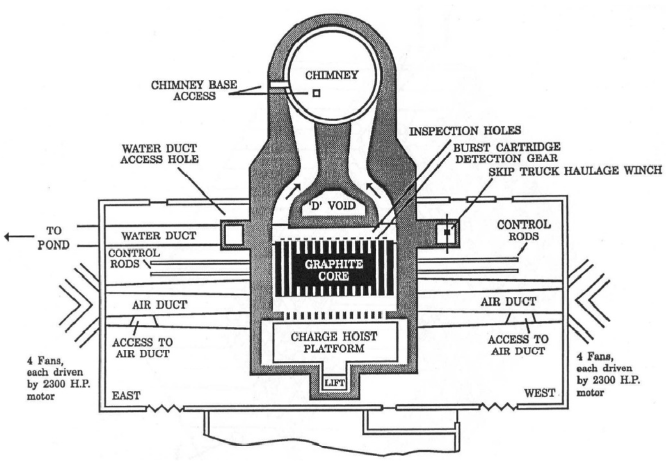

Fig 2 Plan view of one of the Windscale piles. [2]

The optimization of the fuel cartridge irradiation time inside the reactor was necessary since the plutonium production rate was moderate and demanding production targets were set for the works. Thus, careful records were kept of the fueling and de-fueling process. Furthermore, it was recognized in the design that, at the temperature of up to 400 ^{o}C, exposure of the uranium to the atmosphere would bring about consistent oxidation: hence the enclosure within aluminum containers. It was additionally perceived that if these cartridges were not appropriately sealed, oxidation would occur at any rate. Hence, a mechanical assembly was developed on the release face to identify burst cartridges. This was, basically, a system that could detect the short-lived high-energy gamma-emitting radionuclides released if the aluminum containers were compromised. The scanning gear was built with the end goal that a burst cartridge inside an individual channel could be distinguished. When this happened, the channel was cleared and re-fueled before oxidation could occur, since this would lead to contamination of the whole channel, adequately 'blinding' the detection gear to further bursts.

Because of the plan of the piles, with huge volumes of cooling air being pumped through the reactor core, it was perceived in the beginning phases of the plant that cartridges could be blown out of the channels. Hence, the cartridges in each channel were placed in an arrangement of 'boats', which were retained by aluminum wire. In the starting phases, it was discovered that the airflows were more prominent than anticipated, leading to the linkage wire breaking and fuel cartridges being blown out of channels.

WIGNER ENERGY

One of the piles was shut down on October 7,1957 for the normal maintenance operation of releasing the stored Wigner energy typical in graphite-moderated reactors. The neutron irradiation would lose atoms from their locations, generating radiation damage in the form of vacancies and interstitials [3].

Once commissioned and settled into operations, Pile 2 experienced a weird increment in core temperature. Not at all like the Americans and the Soviets, the British had a little encounter with the attitude of graphite when exposed to neutrons. Hungarian-American physicist Eugene Wigner had invented that graphite, when bombarded by neutrons, endures dislocations in its crystalline structure, causing a build-up of potential energy. This energy, if allowed to assemble, might depart in real-time in a very powerful rush of heat.

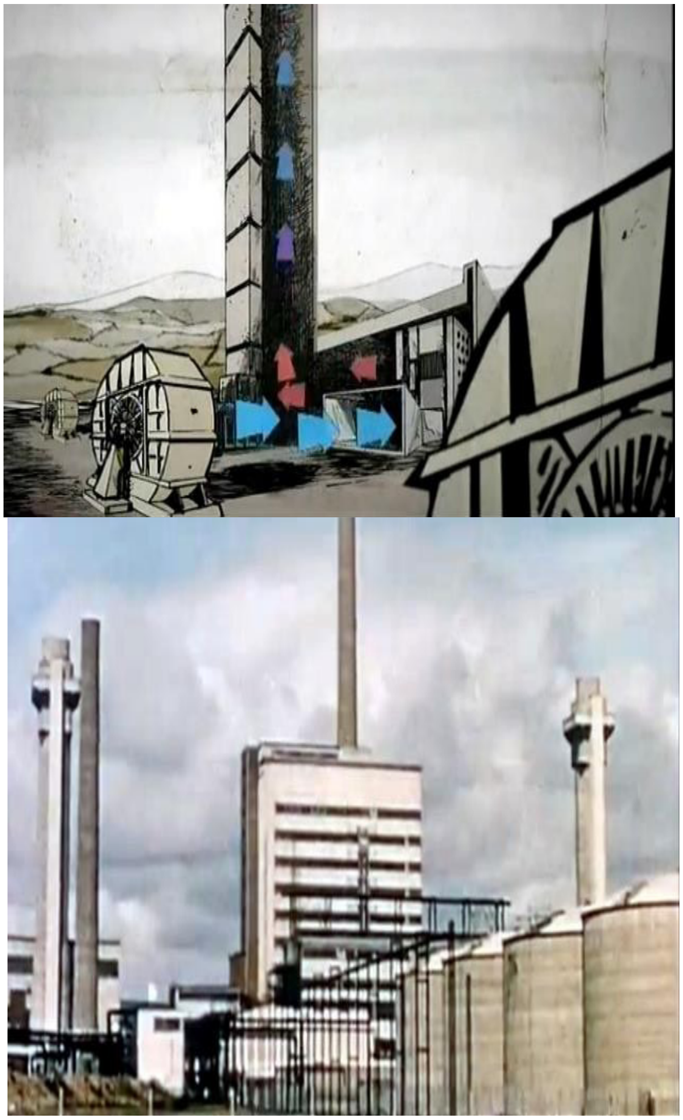

Fig 3 Air circulators and ventilation stacks with filters atop them at the Windscale reactors. [3]

The sudden bursts of energy worried the operators, who turned to the only viable solution, heating the reactor core in a method known as annealing. When graphite is heated above 250 °C it becomes plastic, and the Wigner dislocations will relax into their natural state. This method was gradual and caused a homogenous discharge that spread throughout the core.

The situation wherein the displaced atoms are held are of higher energy than the original graphite, and this potential energy is known as Wigner energy. The carbon atoms concerned can relocate to shape defect clusters, and the Wigner energy can be released from these groupings if adequate activation energy is provided.

2.3 Accident

The fire at the windscale nuclear reactor on 10th October 1957 was the most exceedingly terrible nuclear accident in Great Britain's set of experiences, positioned in seriousness at level 5 out of7 on the International Nuclear Event Scale.

During a routine operation to release Wigner energy, the fire has begun in the reactor [4]. Wigner energy released at the Windscale piles was happened first time in September 1952. As a result of this accident, a procedure was founded for controlling the release of Wigner energy. This type of event took place eight timestill the end of 1956 after the first incident. The basic technique has been to shut down the pile, to organize the proper instrumentation, and afterward make the pile diverge with no coolant airflow, so that there is increment in the temperatures of graphite and uranium. By this implies, the graphite temperature is raised at which Wigner energy discharge is started. Unfortunately, this has not always succeeded in tempering all the graphite in the pile, for example in 1956, one effort (in April) was fruitless, and two others were mostly effective [5].

Initially, the methodology was to complete Wigner discharges after 20,000 cumulative megawatt days. Later this figure was expanded to 30 000 megawatt days. The Windscale Works Technical Committee, in September 1957, considered a paper (reference IGRTN/ W.586) that prescribed an increment to 50,000 cumulative megawatt days in perspective on the expanding challenges of getting an effective release. Until additional experience had been gotten, it was concluded that the following release should be at 40,000 megawatt days. A Wigner discharge along these lines got due in October 1957. A note on the loading of the pile is related at this stage. The Pile consists of a design of graphite blocks pierced by horizontal channels on an 8¼″ square lattice pitch. Each channel contains a series of uranium fuel elements. For the function of charge and discharge, the channels are organized in groups of four, access to each group being by way of a charge hole in the front shield. In the middle of each of the groups is a channel of modest diameter ordinarily utilized for the irradiation of isotope cartridges.

The pile had natural uranium, slightly enriched (1.28Co) uranium in the fuel cartridges and a considerable variety of isotope cartridges present at the material time. There are vertical channels in the pile utilized for tests associated with the common reactor program. At the time of the mishap, each one of these channels was vacant besides from one, which contained a small magnet under test.

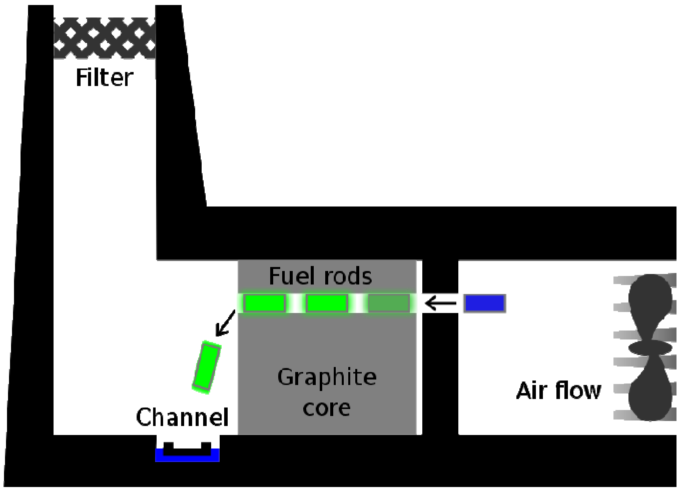

Fig 4 The design of Windscale Pile No. 1, with one of the many fuel channels illustrated.[4]

2.3.1 Cause of the Accident

At the midnight of the 7th October, the essential blowers were turned off and the pile was shut down to release of the Wigner Energy. All the essential precautions were taken to confirm that the reactor was shut down. The shutdown fans were turned off and the entrance in the base of chimney stack and back examination holes on the pile rooftop was opened to minimize coolant airflow through the pile. The thermocouples were checked and those which were not working properly were replaced to make sure the release of Wigner Energy. In the evening, the was made to deflect to produce nuclear heat for setting off the Energy. The method for Wigner energy discharge is to settle as much flux, and thus so much heat as possible, in the front lower region of the Pile by reasonable control of the lower coarse control rods, the upper control rods having been detached when completely in. At 19:25 the pile started to create nuclear heat and the power level was step by step expanded so that, by approximately 01:00 on 8th October, 1.8 MW was registering on the pile power meter.

There was a limit of the maximum cartridge temperature at 250°C, which had been laid down and should not be reached in the first instance during a Wigner release. This temperature was noted in two channels at midnight on 7th October; respectively control rods were run in again and the pile was shut down at 04:00. Most of the graphite temperature increased in the manner of normal Wigner releases. Even though at about 09:00 on 8th October the overall propensity was for the graphite temperatures to be dropping rather than raising, and it appeared to be likely that except if more nuclear heat were applied then the release would stop. The bottom rods were removed, and the pile was made dissimilar at 11.05 with the question of raising the most extreme uranium temperature, which was around 300°C to 350°C. The uranium thermocouple readings show a sharp temperature increment when the pile is separated for the subsequent time. The most elevated uranium temperature recorded was in channel 25/27; the thermocouple perusing for this channel rose by 80°C to 380°C in a matter of 15 minutes, with the greatest pace of ascent of around 30°C a minute. The thermocouple reading was decreased to 334°C within 10 minutes by the change of the control rods. Nuclear heating was kept up at a lower level until 17.00, and during this period the most elevated uranium thermocouple readings rose to around 345°C. At 17.00 the nuclear heating was ended.

On 9th October, the uranium temperatures as recorded show a greatest of 360°C, while at 22.00 the most elevated worth recorded was 340°C. The graphite temperatures indicated impressive variety, yet the overall propensity was for the temperatures to build following the second nuclear heating. One graphite temperature specifically, in channel 20/53, which had indicated a perusing of around 255°C at that point when the second nuclear heating was applied, kept on rising consistently, until by 22.00 it had arrived at a temperature of 405°C. The pile Physicist recorded the high temperature in channel 20/53 at 21.00, to close the chimney base and the examination holes to permit the chimney drought to induce some flow of air from the Pile and hence cool it. The impacts were not thought of sufficiently large and at 22.15 the fan dampers were opened to give a positive airflow through the reactor. The dampers were open for 15 minutes at this event. They have opened again for 10 minutes at 00.01 on 10th October, for 13 minutes at 02.15 and 30 minutes at 05.10. This had a cooling impact on all graphite temperatures except from 20/53, where the temperature rise was only captured.

The records from the pile stack action meter show no exceptional highlights during the early phases of the activity. There was an insignificant rise in the activity before and during the time of the initial three damper openings. At 05:40, toward the finish of the fourth damper opening, there was a sharp increment of six curies. This was noted by the Physicist; however, no unique move was made regarded as the typical outcome of the initial development of air through the pile and up the stack. This increment was trailed by a consistent drop in the bend for around more than two hours after which time stack movement rose consistently to a figure of 30 curies at 16:30 on 10th October. The outlet air duct temperature lasted the same at around 40°C until 07:00 on 9th October, however rose consistently from that point. With peaks occasioned by the progressive damper openings, it had arrived at 85 °C by 08.00 on 10th October.

The graphite temperature in channel 20/53 kept on ascending after temporary decreases during the times of damper opening, until at 12:00 on 10th October a temperature of 428 °C was recorded. The dampers were again opened for 15 minutes at 12:10 and 5 minutes at 13:40. During these openings, the second and extremely huge expansion in stack activity, which has just been mentioned, was noted. At about a similar time, a high activity reading on the Meteorological Station rooftop was recorded.

Turning on the shutdown fans at 13:45 had the impact of quickly expanding the pace of burning in the affected channels. By around 15:00, a serious fire was raging in the 20/53 gathering of channels.

2.3.2 The measures are taken to deal with the accident.

The quickly gleaming metal was found in the 21/53 gathering of channels, an endeavor was made to release the fuel cartridges, however, they were stuck quick and could not be moved. It was examined that the wrong decision was taken to switch on the main blowers to diminish the temperature, considering the high stack activity, this would likely have caused a serious neighborhood hazard. The shutdown fans must be kept on, however, to keep up a mediocre working condition on the charge lift. The workshops were mentioned, in this manner, to make graphite connects requests to clear off the over-heated channels. Nonetheless, it was quickly afterward found that in addition to the 21/53 gathering of channels distinguished by thermocouple reading, there was a rectangular area of exactly 40 gatherings of channels around 150 channels in all demonstrating red heat. The endeavor to make graphite plugs was abandoned, as it was presently certain that the extremely huge number required could not have been made as expected.

From this time at about 17.00 on 10th October two prominent solutions were tried. Endeavors proceeded for the duration of the night to release channels from the hot region. Early in the morning of 11th October, it was important to bring platform posts from the Calder building site as the supply of steel pushrods was giving out. Some of the hot channels were taken out by this implies. Furthermore, at about 17:00 on 10th October it was chosen to make a fire break by releasing a total ring of channels around the hot area. This was effectively completed. Afterward, the second line of channels was released above and at each side of the hot region; even later, as the fire kept on taking steps to spread upwards, a third line was released over the hot zone. The release must be suspended at one point while skips were moved, to stay away from a criticality danger in the water duct. Two auxiliary measures endeavored with no achievement. The utilization of argon was thought of, yet it was discovered that deficient quantities were available underway. Besides, a big hauler of CO2 was brought over from Calder Hall, and game plans were made for CO2 to be provided to the hot channels. CO2 was fed into channel 20/56 at 04.30, but with no considerable impact.

In the meantime, inspection from the highest point of the pile through the east internal assessment hole, uncovered an obvious glow on the pile back face at 18:45; at 19:30 the flares were a lot brighter, at 20:00 they were yellow, and at 20:30 they were blue. At about this time the utilization of water was first thought of. Two dangers must be examined: first the risk of a hydrogen-oxygen blast which would blow out the filters, second a potential criticality danger because of the substitution of air by water. The executives were informed to be that as it may, of the threat of delivering high-temperature Wigner energy if the graphite temperatures were to ascend a lot higher than 1200°C. It was imagined that this may well ignite the entire pile. By about midnight, it had been decided that if the other efforts failed to secure a decline in temperature, water should be utilized. This was the major decision taken. At 01:38 the graphite in channel 20/53, close to the highest point of the 'hot' region, indicated a temperature of 1000°C, and a fuel component temperature of 1300°C was recorded by an optical pyrometer. Throughout the following two hours, 'brute force' endeavors were fruitful in releasing practically all the top line of consuming components, yet the fire proceeded with unabated somewhere else.

By 03:44, the water hoses were fit to be coupled at 15 minutes notice. Visual review at 04:00 through two of the pile rooftop examination holes demonstrated blue blazes: the graphite appeared to be burning. After the fruitless utilization of CO2, temperatures kept on rising and endeavors to release the burning cartridges continued, however by 07:00 the fire was not being checked. At 07:00, it was concluded that water ought to be utilized, but before that it was turned on all plant work ought to be undercover. Some delay was consequently important while the shift changed over at 08:00. Water was, at last, turned on at 08:55 and poured through two channels over the greatest height of the fire. From an underlying pace of 300 gallons/ minute, the stream was expanded to 800 gallons/minute. No drastic change came about; at 09:56 blazes were all the while feathering out of the back of the pile. At 10:10, hence, the closure fans were shut off to decrease airflow through the pile. The fire promptly started to die down. At 12:00, two additional hoses were introduced, and the water flow was expanded to 1000 gallons/minute. The flow proceeded considering the current rate until 06:45 on 12th October and then it was steadily decreased until at 15:10 it had halted. At this point the pile was cold.

2.4 Task to be analyzed the Windscale accident.

There was a fire at Windscale on 10th October 1957 as described above. As a result of that fire there had been emission of radionuclides into the atmosphere, soil, and water was taken place. From that here I would like to analyze the radionuclides, which were escaped at the Windscale pile from the chimney stack at the height of 120m into the atmosphere. In this task, I needed the meteorological data and released activity data to calculate the absorbed dose to the human being in the neighborhood area. Also, I will calculate ground deposition data and air concentration data. For this calculation here I will use the HOTSPOT health physics code which is created and provided to me by Lawrence Livermore National Laboratory (LLNL).

Using this software, I will calculate TEDE (total effective dose equivalent) and then I will compare it with the data from the literature to analyze the scenario and how this accident was affected people's organs and causes a cancer risk.

2.5 HOTSPOT health physics code

HOTSPOT is a free license code created by Livermore National Laboratory (LLNL) that gives Health Physics personnel, emergency response personnel,a quick strategy, field- portable calculation tool to assess the radiation impacts related to the atmospheric release of radioactive materials [6]. The atmospheric models utilized by the HOTSPOT code is the first- order approximation that estimates short-range (less than 10 km) and short-term (less than few hours) predictions downwind radiological impact following the release of the radioactive materials. Indeed, they are planned for near-surface releases, short-range scattering, and short-term emission in unhampered territories and straightforward meteorological conditions. HOTSPOT evaluates the dispersal of radioactive material utilizing the Gaussian model since the ampleness of this model for providing beginning dispersion measures or worst-case safety analyses has been tried and confirmed for a long time.

HOTSPOT code is sensibly exact for an opportune beginning estimation. More significantly, Hotspot software produces a steady yield for similar info presumptions and minimizes the likelihood of mistakes related to reading a diagram inaccurately. This acute mode can be utilized for assessing the quick radiological effect related to high intense radiation doses. The principal focal point of GPM is short calculation time, broad approval, and overall acknowledgment.

The value of utilizing this code in this exploration work is that the code is fit for assessing detailed accident conditions, transport of radionuclides, and dose calculation after the mishap using physical models. The aftereffects of the Gaussian plume models are trustworthy inside a factor of 2-4, for the short distances from the released radionuclide's location. The HOTSPOT code does not dive into direct concern related to assessed results and is deterministic. At the point when similar info boundaries are used for different simulation scenarios, a similar answer is gained each time.

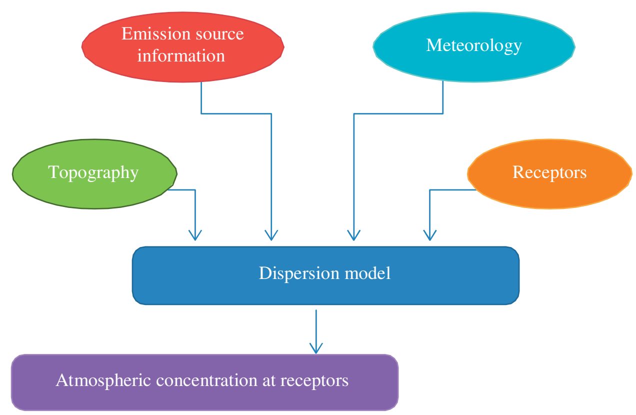

Fig.5 Flow chart of the simulation process of the Hotspot code [6].

3. THEORATICAL BASE

A fire in a nuclear reactor (the 'Windscale Number 1 Pile') at Sellafield, located on the coast of the present-day province of Cumbria in north-west England, on 10–11th October 1957 (the 'Windscale Fire') delivered considerable amounts of radionuclides to environment throughout 20 hours. The releases included 1800 TBq of iodine-131 (radioactive half-life, 8 d), and deposition in the neighborhood area of Sellafield delivered groupings of iodine-131 in cow's milk that were adequately high for a nearby milk distribution ban to be set up. The plume of radioactive material at first went toward the north-east before a north-westerly wind conveyed the emissions toward the south-east, over southern Cumbria and the adjoining district of Lancashire (figure 9), the remainder of England and European territory. Dosages assessed to have been gotten by everyone because of the Windscale mishap have been introduced [7].

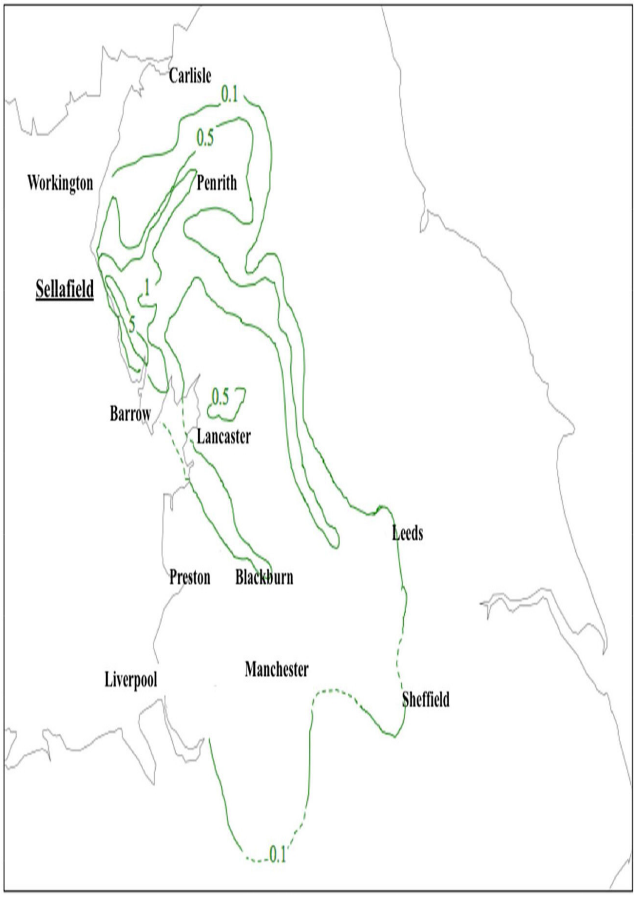

Fig 6 Map of northern England, showing iodine-131 deposition in the counties of Cumbria and Lancashire following the Windscale nuclear reactor accident at Sellafield in October 1957. Contours of iodine-131 deposition are labelled in units of μCi · m^{-2} (37 kBq · m^{-2}) [7].

3.1 Exposure of Radiation

At the point when it was understood that there was a significant release of activity to the environment from the reactor stack there were three potential risks that required quick assessment. These were: (1) the external radiation risk; (2) the inhalation of activity; and (3) the ingestion of activity from contaminated food and water. It is important to evaluate these three components and to give rapidly the essential data whereupon precaution might be started. A particularly environmental overview can be comprehensively part into two classes: (1) Physical review including direct radiation estimations and air examining; (2) Biological observing including the examining and investigation of biological materials.

The physical study can be done moderately rapidly while biological study requires an assortment of the requisite samples and radiochemical test by research center strategies, the two of which require considerable association and time to work easily when managing huge quantities of samples.

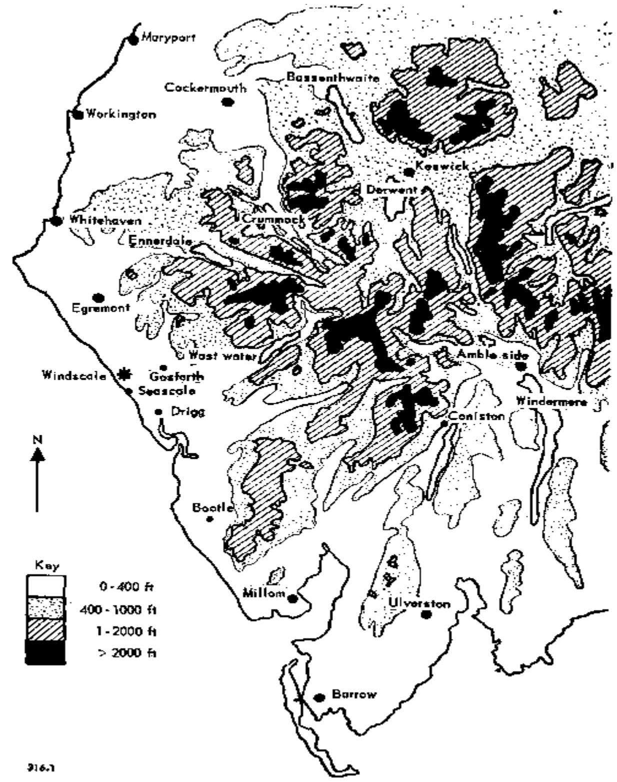

Fig 7 Contour map of West Cumberland and Furness [8].

In a release of these radionuclides from a reactor accident, the external radiation exposure to an individual can be brought about by (1) direct radiation from the passing plume of activity; and (2) radiation because of ground deposition of activity.The primary necessity was to decide gamma radiation levels in the area around the processing plant.

Before the mishap, routine gamma-radiation studies in west Cumberland made with ionization chambers fixed in overview vehicles had shown that the normal gamma foundation fluctuated by position over a scope of 4-10 micro roentgens per hour, with a mean estimation of 7 micro roentgens per hour. Most of the study work following the event was done with sparkle counters initially intended for geographical prospecting. These were promptly convenient and more sensitive for gamma radiation from the stored iodine than the regular ionization chambers, even though they were not energy-free [10].

Review vehicles were conveyed from the plant into the downwind territory to measure these levels. One of the study vehicles had the option to get under the plume at a point roughly 1 mile (1.6 km) down-grid on the coast. The most noteworthy radiation level estimated was 4 milliroentgens per hr. The ordinary regular background radiation level in the region is about 0.01 milliroentgens per hr, so this measured value was around multiple times the normal level. The wind direction was variable, and surveys made at areas temporarily out of the way of the plume uncovered that the radiation because of deposited activity was for the most part about 0.15 to 0.20 milliroentgen per hr in the territory 2 to 3 miles (3.2—4.8 km) south of the power plant, and much lower in different a direction. These estimations proceeded all through the time of release and it was evident that the accident had not caused any significant external radiation exposure to people living in the neighborhood. It was at the first time assessed that the integrated radiation exposure because of ground gamma radiation for an individual excess in the open in the district of maximum deposition during the week following the mishap would be around 10-20 milliroentgens, to be compared with maximum reasonable exposure, for the overall population, of 500 milliroentgens in a year. In practice, there is a considerable protecting variable to be applied when individuals are in block or stone houses. As more definite outcomes became available and the decay rate of the activity was discovered, it got conceivable to make a more precise prediction of the total dose to people in the heaviest deposition. The estimation of this assessment was 30-50 milliroentgens. It is seen that from this accident the external exposure brought by the public living in the area was negligible.

3.2 Emitted Fission products quantity

The environmental evaluation showed that ^{131}I as well as ^{137}Cs overwhelmed the radioactivity released. Both were all around recorded in environmental evaluation and ^{131}I has drawn in most attention, albeit an exhaustive re-appraisal showed that the health effects of ^{210}Po was similar as for ^{131}I. The releases of other radionuclides have been assessed utilizing proportions to ^{131}I or ^{137}Cs in biological and other examples [9].

Air concentration data for sampling stations within 30 km of the line from Liverpool to Flamborough Head was taken for 48 h starting at 09:00 in the morning of 10th October. The average ^{131}I concentration was noted down as 250 pCi m^{-3}. The width of the plume crossing the line was captured to be 120 km, and the wind segment perpendicular to the line, 5ms^{-1}. The air was somewhat unstable up to a height of 1500 m, yet the plume might not have been mixed all through this layer.

The measure of radioactivity delivered during the mishap is not known accurately, however approximate evaluations were produced using the estimations of the radioactive iodine kept on the ground in this country, and from estimations on air filters acquired both in the United Kingdom and in Europe. (A portion of the filters analyzed were being run regarding investigations of ordinary air contamination in various towns in the U.K.) [10].

To provide enthusiasm for the measure of the event which happened it is critical to give examinations of both the entirety and nature of the radioactivity conveyed. These assessments are based on the study estimations made in the zone along with testing of the material found in the exhaust channels resulting in the occurrence. The key splitting item delivered was iodine- 131. More modest amounts of other parting items such as caesium-137, strontium-89 and 90, ruthenium-103 and 106, tritium, xenon-133, zirconium-95, telirium-132, and cerium-144 along with polonium-210 were also released. The table of best- estimated releases of the radionuclide along with their half-life after the accident is shown below:

Table 2. Summary of emission estimates derived in the atmosphere from literature studies (TBq) [9].

Radionuclide	Estimated released activity (TBq)	Half-life
$^{131}I^{f}$	1800	8 days
^{137}Cs	180	30.15 years
^{132}Te	1300	77 hours
^{89}Sr	26	50.5 days
^{90}Sr	0.75	29 years
^{144}Ce	13	284.893 days
^{140}Ba	69	12.8 days
^{103}Ru	72	39.26 days
^{106}Ru	3	373.59 days
^{210}Po	42	140 days
$^{3}H^{g}$	5000	12.32 years

^{95}Zr	16	65 days
^{85}Kr	45	11 years
^{133}Xe	26000	5.245 days
^{238}U	$2.5*10^{-4}$	4.5 billon years
^{239}Pu	0.02	24100 years
^{60}Co	7	9.5 days
^{14}C	0.1	5730 years
^{35}S	1.2	87.4 days
^{152}Eu	2.1	13.516 years

[f] the values given refer to elemental plus particulate ^{131}I. There may have been a smaller amount of ^{131}I in other forms (organic or HOI) that were not retained by the filter paper air samples.

[g] These values are for essential tritium gas. There may likewise have been some tritium oxide emitted; the most extreme release in both forms was about 6500 TBq, the amount available in the damaged portion of the reactor.

3.3 Radiation doses caused in human thyroid organs.

The fundamental danger to individuals emerged from the contamination of milk, and the control measures have been already described. In a couple of cases, notwithstanding, there was reason to suspect that the control of milk had not been completely effective. In these cases, people were welcome to the research facilities at Windscale, and estimations were made of the activity of iodine 131 in their thyroids. Moreover, a few individuals from the public more delegate of those in the down-wind territory were comparatively welcomed for estimation. The aftereffects of these thyroid estimations are given in Table 3. Calculations of the strategy for computation of the thyroid dosages that appeared in this table have been published (Dunster et al., 1958).

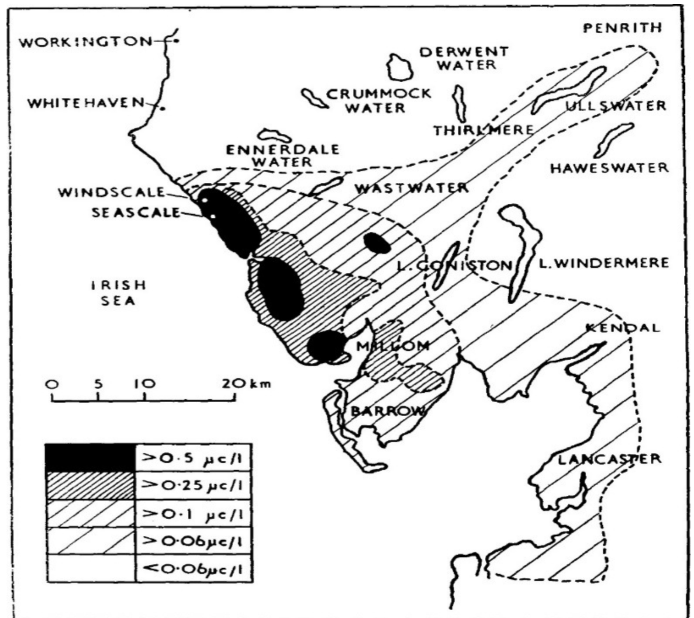

Fig 8Map of the Windscale area showing contours of radioiodine contamination in milk on the 13th of October 1957 [10].

The most noteworthy dose to a kid's thyroid was assessed as 16 rads and the relating figure for an adult's thyroid was 40 rads. Notwithstanding the estimations given in the table for people in the down-wind area, roughly 113 other thyroid estimations were made on individuals from the public living in different areas nearby. Of these, 107 showed a dose of nothing and the most noteworthy dose was 12 rads.

Place	Range (miles)	Distance (kms)	Average Dose (rads) Adults	Average Dose (rads) Children	Maximum Dose (rads) Adults	Maximum Dose (rads) Children
Seascale	2	3.21869	0.5 (18)	0.8 (9)	1.4	3.9
Drigg	4	6.437	1.4 (8)	3.9 (3)	2.8	7.3
Holmrock	4.5	7.24	1.4 (7)	-	2.7	-
Ravenglass	6	9.65	1.8 (8)	12.2 (3)	4.0	16.1
Bootle	11	17.70	1.4 (12)	6.0 (11)	3.4	9.8
Millom	19.5	31.38	0.4 (29)	-	1.8	-
Ulverston	23	37	0.5 (5)	4.4 (3)	1.4	11.4
Barrow	24	38.62	0.3 (9)	-	1.1	-

Table 3. Radiation doses in human thyroids [10].
People who lived in the down-wind sector* however who were not in the Windscale Works at the time of the event.
* At places having an orientation somewhere in the range of 130 and 160 degrees from Windscale.
The quantity of people inspected is appeared in brackets.

3.4 Meteorological Data

Following the event, detailed meteorological information was gathered concerning the Windscale area for the time frame between 10th-12th October 1957. The assessed wind velocities and direction at the Windscale site, at a height of 500 feet (152 m), are given in Table 5. The change in the wind direction happened between 03:00 and 04:00 G.M.T. on

11th October related with the entry of a frontal through moving from northwest to southeast across the territory. There showed up to be not very much considerable reversal in this frontal through. The change was from extremely light breezes to a clearer wind flow from between north and west [8].

Table 4. Estimated Wind at Altitude of 500 Feetover Windscale [11].

Date	Time (G.M.T.)	Wind at 500 ft (152m)	
		Direction, ° true	Speed, knots (km/hr)
10th October	00:01	180° (i.e., from due S)	3 (5.5)
	06:00	180° (Light Variable)	3 (5.5)
	12:00	Light Variable	
	18:00	Light Variable	
11th October	00:01	220°	7 (13)
	06:00	360°	10 (18.5)
	12:00	310°	12 (22.2)
	18:00	300°	12 (22.2)
12th October	00:01	270°	8 (14.9)
	06:00	230°	8 (14.9)
	12:00	230°	12 (22.2)

Input Data on HOTSPOT health physics Code

- Atmospheric Dispersion model = General Fire
- Release Location:
  Windscale works, Sellafield.
  (On the coast of Cumbria, northwest England—54°25.0' N 3° 30.2' W)

Coordinates in degree-minutes-seconds (dd°mm'ss") can be converted into decimal-degree format (dd.xxxx) as follows:

dd + (mm + ss/60) / 60 = dd.xxxx

(1) (54°25.0' N) = 54 + (25 + 0/60) / 60 = 54.416667 N
(2) (3° 30.2' W) = 3 + (30 + 2/60) /60 = 3.500556 W

- Radionuclide = Mixture of all radionuclides as shown in Table 2 with the released activity
- Damage ratio = 1.0
- Leak path factor = 1.0
- Release radius = pile radius = 7.5 m [9]
- Air Temp = 85°C (The outlet duct air temperature remained stationary at about 40°C until 07:00 on 9th of October, however, it hiked steadily then after, with the maximum temperature peak occasioned by the successive damper openings, it had reached 85°C by 08:00 on the morning of 10th of October [9].
- Physical height of fire = 150 m
- Wind speed = 1.5 m/s
- Wind direction = 150° (In the direction of SSE) (In this code wind is coming from 300°, so WNW)
  The release hiked about 09:00 on the 11th of October and gave a plume of deposition running SSE [4].
- Heat Emission rate = $3.95*10^4$ Cal/sec

  It is given by,

  $Q/t = б *e *A *T^4$

  Where, $б = 5.67*10^{-8}$ $J/(s*m^2*K^4)$, is the Stephan Boltzmann law of radiation
  A = Surface is of the object, m^2
  T = its absolute temperature in Kelvin(K)
  e = 1

- Hold up time = 1.5 min (assume)
- Sample time = 1200 min (20 hours)

Emission from the Windscale endured around 18 hours, from 16:00 on 10th of October to 10:00 on 11th of October 1957, at which time the fire was extinguished with water [4].

- Wind input height = 100 m
- Breathing rate = $3.4*10^{-4}$ m^3/sec
- Contours

	TEDE(Sv)	Deposition(kBq/m^2)
Inner	0.05	110.00
Middle	0.04	37.00
Outer	0.03	3.7

Fig 9. Windscale map (Google earth)

4. RESULTS AND ANALYSIS

After entering the above data in the HOTSPOT code and doing simulation, the Hotspot code estimated the radiation dose produced after the release based on the site-specific meteorological condition. i.e., TEDE, the ground deposition, and the respiratory time-integrated air concentration were calculated as a function of downwind distance as shown in Table 6. It can be seen from Figure 22 that the TEDE initially increases with increasing distance downwind, reaches the maximum value, and then decreases sharply. A similar Gaussian trend is shown in Figure 23 for the plume centerline ground deposition of radionuclides as a function of downwind distance. It can be realized from Table 6 and Figure 22 that the maximum TEDE is 1.1E-02 Sv and this occurs at the downwind distance of 4.5 km., is most extreme TEDE esteem is recorded inside the limited region., i.e. TEDE values at distances of 80 km and beyond where public occupation is probably going to be found, are far beneath the annually regulatory limits of 1 mSv from public exposure in a year even in case of most pessimistic scenario situation as set in IAEA Safety Standard No. GSR Part 3.

Source Term: Windscale 1957.mix (Mixture Scale Factor = 1,0000E+00)
Heat Emission: 3,95E+04 cal/s
Air Temperature: 85,0 deg C
Release Radius: 7,50E+00 m
Physical Height of Fire: 150 m
Effective Release Height: 156 m
Wind Speed (h=100 m): 1,50 m/s
Wind Direction: 300,0 degrees Wind from the WNW
Avg Wind Speed (h=H-eff): 1,60 m/s
Stability Class: D
Receptor Height: 1,5 m
Inversion Layer Height: None
Sample Time: 1200,000 min
Breathing Rate: 3,40E-04 m3/sec
Distance Coordinates: All distances are on the Plume Centerline.

Maximum Dose Distance: 4.5 km
Maximum TED: 0,011 Sv
Inner Contour Dose: 0,047 Sv
Middle Contour Dose: 0,038 Sv
Outer Contour Dose: 0,030 Sv
Exceeds Inner Dose Out To: Not Exceeded
Exceeds Middle Dose Out To: Not Exceeded
Exceeds Outer Dose Out To: Not Exceeded

Table 5. Downwind distance and other plume parameters at different arrivaltime intervals

DISTANCE (km)	TEDE (Sv)	RESPIRABLE TIME-INTEGRATED AIR CONCENTRATION (Bq-sec)/m^3	GROUND SURAFACE DEPOSITION (kBq/m^2)	GROUND SHINE DOSE-RATE (Sv/hr)	ARRIVAL TIME (hour:min)
1,000	1,60E-04	3,50E+08	1,00E+03	2,30E-07	0:10
2,000	4,90E-03	1,10E+10	3,30E+04	7,40E-06	0:20
3,000	9,40E-03	2,10E+10	6,20E+04	1,40E-05	0:31
4,000	1,10E-02	2,40E+10	7,20E+04	1,60E-05	0:41
4,500	1,10E-02	2,40E+10	7,30E+04	1,60E-05	0:46
8,000	9,00E-03	2,00E+10	6,00E+04	1,40E-05	1:23
10,000	7,70E-03	1,70E+10	5,10E+04	1,20E-05	1:43
15,000	5,40E-03	1,20E+10	3,60E+04	8,10E-06	2:35
20,000	4,10E-03	9,00E+09	2,70E+04	6,10E-06	3:27
30,000	2,70E-03	5,90E+09	1,80E+04	4,00E-06	5:11
40,000	1,90E-03	4,20E+09	1,30E+04	2,80E-06	6:55
60,000	1,20E-03	2,50E+09	7,60E+03	1,70E-06	10:23
80,000	8,30E-04	1,80E+09	5,30E+03	1,20E-06	13:51
100,000	6,30E-04	1,30E+09	4,00E+03	9,00E-07	17:18
110,000	5,50E-04	1,20E+09	3,50E+03	7,80E-07	19:02
120,000	4,90E-04	1,00E+09	3,10E+03	6,90E-07	20:46
130,000	4,40E-04	9,10E+08	2,70E+03	6,10E-07	22:30
150,000	3,60E-04	7,40E+08	2,20E+03	5,00E-07	>24:00
175,000	2,90E-04	5,90E+08	1,80E+03	4,00E-07	>24:00
200,000	2,40E-04	4,80E+08	1,40E+03	3,20E-07	>24:00

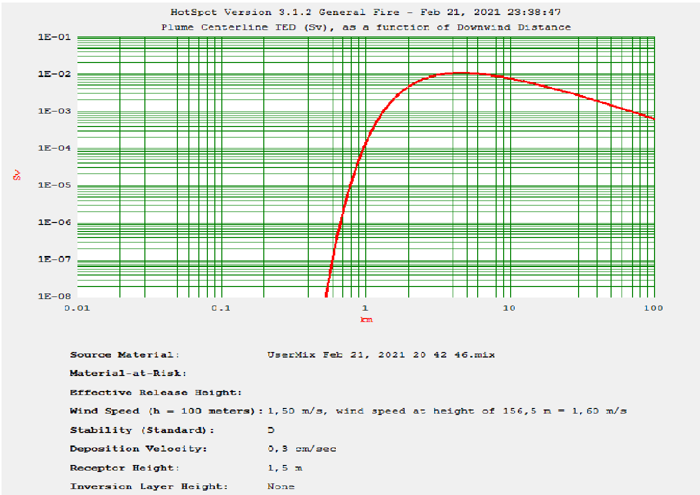

Fig 10. TEDE (Sv) as a function of downwind distance from the release point

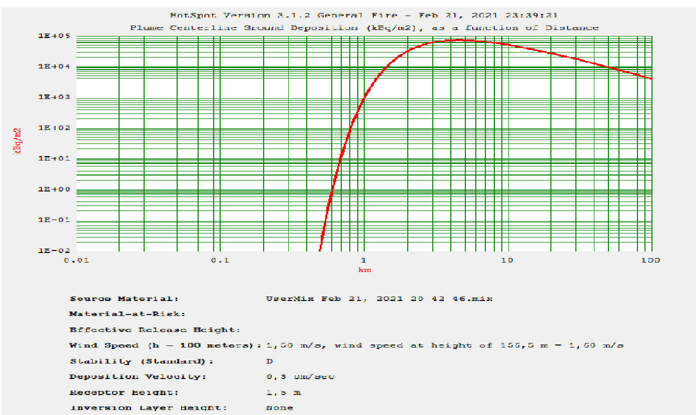

Fig 11. Plume centerline ground deposition of radionuclides as a function of downwind distance

The most extreme respiratory time-integrated air concentration as well as the ground deposition values of 2,40E+10 (Bq-sec)/m^{3}and 7,30E+04 kBq/m^2, respectively, occurred at 4.5 km at an appearance of around 46 minutes. At the around 80 km distance downwind, the respiratory time-incorporated air concentration and the ground deposition values of 1,80E+09 (Bq-sec)/m^{3}and 5,30E+03 kBq/m^2 are recorded at an appearance time of 13 hours 51 minutes.

TEDE contour plot and plume contour ground deposition distribution under the plume is appeared by Figures 24 and 25, respectively, for stability class D and wind speed of 1.5 m/s. From Figure 24, it tends to be seen those three regions with the areas of 0.69, 175, and 3000 km^2 have been set apart with dose contours of 1.00E–02, 1.00E–03, and 1.00E–04 Sv. Likewise, in Figure 6, three regions have been set apart with deposition contours of 1.10E+02, 3.70E+01, and 3.70E+00 kBq/m^2., i.e., TEDE and plume contour ground deposition distribution spread away from the source of release as a function of downwind distance. i.e., red-shaded area portrays higher dose hazard for personnel and population; the green and blue zones are less hazardous compared with the red zone. Depending upon the above-mentioned results and examination, the determined TEDE in distances less than 80.0 km is underneath the most extreme public dose limit of 1.0 mSv proposed by ICRP 103.

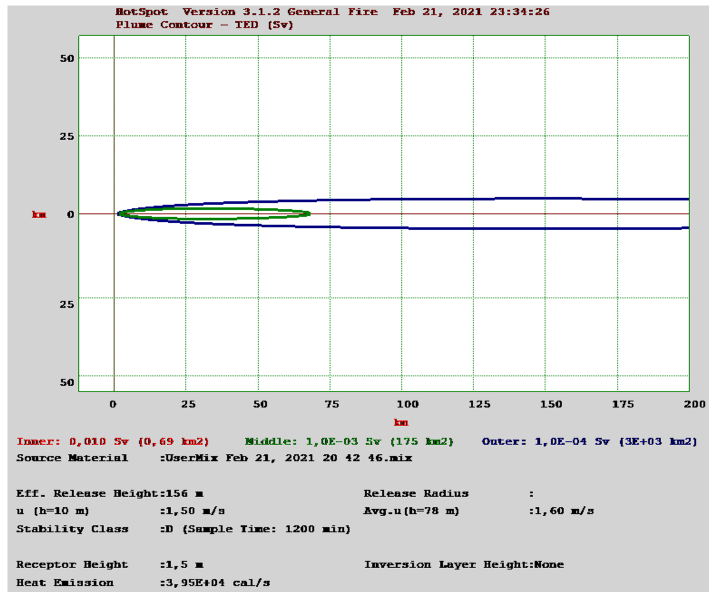

Fig 12. TEDE contour plot

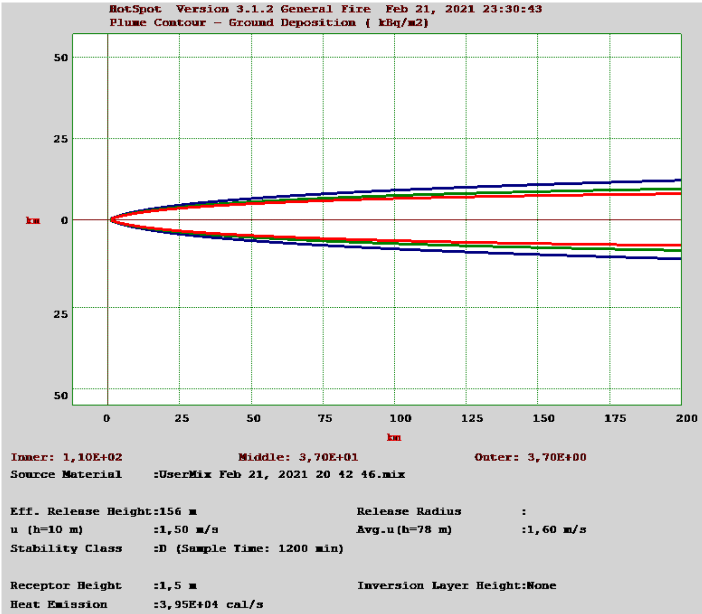

Fig 13. Plume contour ground deposition distribution

Now, here I would like to compare the data from the literature with the simulation data of the HOTSPOT code. There is data available from the literature about radiation doses in human thyroid who lived in the downwind direction of the released radionuclides as shown in Table 3. With the help of the HOTSPOT code, one can get all the radiation dose data for different organs of the human body. So, the table 7 shows the TEDE (Total effective dose equivalent) data for the thyroid gland. This data can be converted into the absorbed thyroid gland data to an equivalent dose with the following formula:

An equivalent dose is calculated for individual organs. It is based on the absorbed dose to an organ, adjusted to account for the effectiveness of the type of radiation.

Equivalent dose = absorbed Dose multiplied the appropriate radiation weighting factor.

Here, the radiation weighting factor is 1 (for gamma rays).

Now, Effective dose = sum for all organs of (equivalent dose to the organ times the appropriate tissue weighting factor)

Here, tissue weighting factor for thyroid = 0.05 (ICRP 60)

Table 6. Calculated effective dose (sievert) for thyroid gland.

Distance (km)	Effective Dose using HOTSPOT	Calculated effective Dose (sievert)
3.219	2,8E-02	2.5E-02
6.437	1,5E-02	7.0E-02
7.240	1,3E-02	7.0E-02
9.650	9,4E-03	9.0E-02
17.700	4,4E-03	7.0E-02
31.380	2,2E-03	2.0E-02
37.000	1,8E-03	2.5E-02
38.620	1,7E-03	1.5E-02

The absorbed dose from the literature is for the thyroid gland is approximated calculation. So, from the table, the effective dose for thyroid can be compared with the HOTSPOT code calculation. The effective dose is a maximum of around 4.5 km while the literature approximated absorbed dose is maximum at around 9 km.

Moreover, as described above, that Lancaster (56km from Windscale) and Preston (at 86 km) were affected by activity released around or after midnight [9]. The release of radionuclides into the atmosphere had started at 16:00 on 10th of October. So as per this simulation result which is shown in table 6 the released radionuclides reached Lancaster (56 km from Windscale in SSE direction) after 10 hours, which states that it reached at after midnight 02:00 on 11th of October. Same as for Preston (at 86 km), where released radionuclides reached at around 06:00 on 11th of October.

5. CONCLUSION

This analysis has been realized for the atmospheric release of radionuclides from the Windscale accident that happened on 10th of October 1957. There has been fire in the plutonium production graphite-moderated reactor, which was ended up after almost 18 hours, but there has been some activity released to the atmosphere throughout the accident. From this mishap, approximately 34573 TBq (including all radionuclide) activity was released. The HOTSPOT health physics code has been used to simulate this release of radionuclides to the atmosphere with the help of data given in the literature study. Past examinations have suffered from uncertainty in the release conditions and the quality of the available meteorology, which restricted the accuracy of the result produced. This study has shown the enhancement inaccuracy which can be picked up when progressed emission sources are combined with great quality of meteorological fields within the framework of a strong dispersion model.

From the simulation of the scenario, it can be concluded that the Hotspot code worked and the TEDE data at different distances, ground deposition data, as well as arrival time of the radionuclides, are generated. According to the site-specific meteorological data used, the maximum TEDE and ground deposition values are 1.1E-02 Sv and 7,30E+04 kBq/m^2 respectively at 4.5km from the Windscale works. The direction of the radionuclide emission from the release point is towards south-east. There were estimated 20 radionuclides involved in this release, but from that I-131, Cs-137, Te-132, Sr-80, Sr-90, and Xe-133 were the main contributors of the released activity. It is recommended to require defensive measures to avoid inhalation and ingestion in case of accidents since these radionuclides may negatively affect the human health and environment.

However, Hotspot code has some limitations, such as it can simulate the data only for a few-hundred-kilometer distances and few hours of the release of radionuclides to the atmosphere. So, this work could be a basis for future analysts, who can compare these results to their data, obtained using different simulation techniques.

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