ENVIRONMENTAL AND HUMAN-HEALTH CONSEQUENCES OF THE CHERNOBYL NUCLEAR DISASTER IN BELARUS

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Fall 2010

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For my family

ABSTRACT

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On April 26, 1986, Unit 4 of the Chernobyl Nuclear Power Plant exploded, causing the most severe disaster ever to occur in the history of domestic nuclear-power production. That explosion spread both fission products of the normal operation of the reactor and unexpended uranium fuel across a large area. In total, ~14 EBq[5] radioisotopes were released from the reactor, some of the most harmful being 1.8 EBq of ^{131}I, 0.085 EBq of ^{137}Cs, 0.01 EBq of ^{90}Sr, and 0.003 EBq of plutonium (2003-2005 Chernobyl Forum 22). More than 200,000 km^2 of Europe received levels of ^{137}Cs in excess of 37 kBq/m^2; and ~70% of this area was in the Ukraine, Belarus, and Russia (2003-2005 Chernobyl Forum Report 22). Of these 3 most affected countries, Belarus suffered the greatest level of ^{137}Cs, absorbing ~33.5% of the total amount emitted. Although Belarus was severely affected, the consequences of this event have not been well studied and a full accounting of the human-health and environmental effects has not been released for the country. This report reviews, analyzes, and combines key literature available to date to document the current state of knowledge upon which further research and appropriate management strategies can be initiated. The investigation finds that deposition was influenced by atmospheric winds and precipitation that caused radioactive rain to enter the country. ^{137}Cs and ^{90}Sr remained within the top 15 cm of the soils and livestock accumulated large doses of radiation that was transferred to foods. Gomel and Mogilev continue to produce milk that

exceeds the Belarusian limit of 100 Bq/L, and several small farms have not been adequately remediated. 1.7 million ha of Belarusian forests and resources were contaminated, causing mutations, cytogenetic effects, and chromosomal aberrations in several organisms. But, radiation has decreased in both the Pripyat and Dnieper Rivers. ~134 emergency workers suffered from ARS; thyroid cancer and mental health have clearly increased following the accident and some studies have identified increases in non-thyroid cancer cases as-well.

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Introduction:

On April 26, 1986, Unit 4 of the Chernobyl Nuclear Power Plant exploded, causing the most severe disaster ever to occur in the history of domestic nuclear power production. The explosions damaged the Chernobyl nuclear reactor and produced fires that caused 10 days of radioactive particles to be released into the environment (Chernobyl Forum 10). According to some estimates, the radioactive plume travelled as high as 8 km because of extreme pressure gradients that had accumulated inside the core (Petryna 1). The pressure, together with atmospheric winds and precipitation patterns, caused the radioactive cloud to be mainly dispersed in Belarus, Ukraine, and the Russian Federation. Although it is known that Belarus suffered from high levels of radionuclide contamination, the environmental and human-health consequences have not been fully documented, therefore. This report focuses on reviewing the key literature that is available to date, in order to document the current state of knowledge upon which further research and appropriate management strategies can be initiated.

Reason for Selecting Topic:

This topic is especially important to me because my father's side of the family lived in the Gomel oblast, which is 120 km from Chernobyl, during the disaster. They moved to the United States in 1991, but several people had developed various cancers including, cancer of the mouth, cancer of the uterus, thyroid cancer, colon cancer, and just recently, cancer of the lung. 25 years have passed since the disaster and the people of Belarus, as-well as my family members, are still unsure of the environmental and health consequences of the Chernobyl accident. My hope is that this report will help to answer just some of their questions.

Literature Review:

In 2003, the United Nations launched an Inter-Agency initiative called the Chernobyl Forum. It was designed to review the health, environmental, and socio-economic consequences of the Chernobyl disaster in Belarus, Ukraine, and the Russian Federation. The Forum consists of 8 organizations that are part of the United Nations family including, the International Atomic Energy Association (IAEA), the World Health Organization (WHO), and the United Nations Development Program (UNDP). It also includes about 100 experts and representatives from the 3 most affected countries. The 2003-2005 Report produced by the Chernobyl Forum builds on an earlier study that was published in 2000 by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The UNSCEAR Report is one of the most comprehensive pieces of literature covering the Chernobyl disaster to date. It finds that Belarus was one of the most highly contaminated countries, experiencing radionuclide deposition in its soils, agriculture, and forests. The Report also finds that thyroid cancer incidence has increased in the country, especially amongst children.

The 2003-2005 Chernobyl Forum Report finds that Belarus was exposed to some of the highest levels of ^{137}Cs deposition in Europe. In order to determine this, airborne spectrometer surveys of various radionuclides were performed. Any land that was found to exceed 37 kBq/m^2 ($1Ci/km^2$) was considered to be contaminated. This level was chosen because it was found to exceed the level of previously deposited ^{137}Cs particles in Europe by 10 times. In addition, humans typically accumulate about 1mSv of radiation at that level, which is considered to be high (IAEA 30). The Chernobyl Forum found that 41,900 km^2 of Ukrainian land was polluted by ^{137}Cs, 46,500 km^2 of Belarusian land was contaminated by ^{137}Cs, and 57,900 km^2 of land found in the Russian Federation was affected by ^{137}Cs levels above 37 kBq/m^2 ($1 Ci/km^2$) (IAEA 23).

The Report also found that food products in the Gomel and Mogilev oblasts (areas) contain the highest levels of ^{137}Cs in all of Belarus. For example, the areas of Gomel that are contaminated with levels above 185 kBq/m^2 have a mean of 30 Bq/kg for grain, 10 Bq/kg for potatoes, 220 Bq/kg for meat, and 80 Bq/L for milk (IAEA 41). The oblast of Mogilev, with contamination levels ranging from 37-185 kBq/m^2, were found to contain mean levels of 10 Bq/kg of grain, 6 Bq/kg for potatoes, 100 Bq/kg for meat, and 30 Bq/L for milk (IAEA 41).

Belarusian forests were also affected by the radioactive plume. There, ^{137}Cs ranged from greater than 10 MBq/m^2 to between 10 and 50 kBq/m^2 (IAEA 42). While the tree canopies initially absorbed 60%-90% of the radioisotopes, contamination was rapidly reduced within weeks to months due to rainwater wash-off, and leaf needle fall (IAEA 42). By 1987, only 5% of the contamination remained in the tree canopy while the remainder migrated to the soil where it was mainly isolated in the first 15 cm layer (IAEA 43). Forest foods, such as berries and mushrooms were also discovered to readily uptake ^{137}Cs, which then transfers to forest wildlife (IAEA 43). The cycling of ^{137}Cs throughout the forest ecosystem puts the human population at risk because they often rely on forest for their food source. Natural decontamination is slowly occurring, but the net export of ^{137}Cs from forests is less than 1%/year (IAEA 42). Therefore, ^{137}Cs remains a concern and must be monitored and managed accordingly.

Existing literature has also demonstrated that the younger population of Belarus has clearly suffered from an increase of thyroid cancer incidence. Over 4000 cases have been reported since the accident to the appropriate registries of the 3 most affected countries

(WHO 23). Ukraine experienced the largest number of cases, Belarus experienced the 2nd largest, and the Russian Federation had the least number of thyroid cancer cases. Between 1986 and 2002, Ukraine had 2,344 cases, Belarus suffered from 2010 cases, and the Russian Federation from 483 (WHO 23). The majority of patients were found to be with the 0-14 year interval.

Overview of Belarus:

Belarus has a rich geography, environment, and culture. The country is bordered by Lithuania and Latvia to the North, Ukraine to the South, the Russian Federation to the East, and Poland to the West (President.gov). Its location, in the center of 5 influential countries, is strategically beneficial in terms of communications, trade, and economics. Over 1/3 of the country is covered by forests, including the Polissya Region, which borders the Ukraine, along with the Chernobyl Nuclear Power Plant. Belarus is also home to thousands of rivers and lakes, vast areas of farmland, and a moderate climate. The total area is 207.6 thousand km^2, which is larger than the countries of Austria, Greece, Poland, and Ireland (President.gov). Belarusian culture has developed over the past millennium and has been influenced its rich history and religions, including Slavic and Baltic cultures, Byzantine Christianity, Catholicism, Orthodoxy, Judaism, and Islam. Its literature often represents the rural culture of Belarus while paintings, sculptures, music, film, and theatre focus more on urban realities and issues. The capital city of Minsk is the center of Belarusian culture, while oblasts also add to the nation's richness (President.gov). The 6 oblasts are displayed in figure 1 below. They are Minsk, Vitsyebsk

(Vitebsk), Mahilyow (Mogilev), Homel (Gomel), Brest, and Hrodna (Grodno). Each oblast is further divided into smaller administrative districts called rayons (regions). They include many other cities and towns, each with their own unique characteristics.

Fig. 1 Map of Belarus. Russia-Ukraine-Travel. 2 February 2010.

www.russia-ukraine-travel.com/belarus-maps.html.

The Polissya Region:

The Polissya Region is geographically diverse. It encompasses the Northern Region of Ukraine, Southern Belarus, and small sections of Poland and Russia, thus serving as an environmental resource for many communities throughout Eastern Europe and Russia. The North-Ukrainian section is home to Chernobyl (in Ukrainian "Chornobyl"), a small ancient town located north of the large metropolitan city of Kiev (Mould 307). The region also includes the city of Pripyat, which was built to house the workers of the Chernobyl Nuclear Power Plant, and it includes Kiev as-well. In Southern Belarus, Polissya incorporates the cities of Gomel, Brest, and Pinsk. The Polissya Region's geographical richness is paralleled by its vast environmental resources.

The Polissya's landscape is composed of an abundant supply of forests and ecosystems. Perhaps that is why the region was named Polissya, where "po" translates from Russian to "on" or "in," and "lis" (pronounced in Russian as "les") meaning woodland, are combined to form Polissya, or in/on the woodland. Though not as widespread and diverse as in the 16th century and past, the 19th century Polissya Region, never the less, remains home to many great forests (Mycio 46). The vegetation mainly consists of mixed forests of Scots pine, oak, and birch on sandy hills, meadows, swamps, and bogs within river valleys (Mould 307). Located in the south-western section of the East-European lowland, the Polissya swamp ecosystem is amongst the largest and richest in Europe. Some of its benefits include a buffer zone to guard communities against flood waters, a habitat for living organisms, water filtration, groundwater recharge, pollution control, food supply, and recreation. Like the swamp areas, forests, bogs, and meadows are also used as habitats for vegetation and wildlife, while providing local populations with a source for wood, berries, mushrooms, meat, and recreation. According to Z. Medvedev, the 100,000 km^2 Polissya Region absorbed 10% of the radioactive caesium released from the damaged reactor, while also absorbing large quantities of radiostrontium (91).

From the 10th century on, the Belarusian population traditionally utilized their forests for the local brown shale, quartzite and multicolored amber. Shale was used to create spindles for weaving, sarcophaguses, decorations for women, and icons, while quartzite provided the material for constructing cornices, mosaic floors, idols, and Christian crosses (Mould 312). These valuable stones became an integral part of life in the Polissya Region, manifesting itself in various forms of culture such as clothing, jewelry, religion, and burial ceremonies. Spiritual emblems created by Polissya craft workers can be found in the church of St. Cyril and the cathedral of St. Sophia in Kiev today (Mould 312). Multicolored amber was used to create necklaces and charms for local spiritual leaders (Mould 312). They too, are still cherished today as cultural emblems of the Polissya Region.

Another long-held tradition has been the use of forested areas for bee-keeping. The tradition of bee keeping can be traced back to ancient times when forest bee nests were kept in natural hollows within tree trunks (Mould 312). By utilizing the natural wood features, local residents worked in harmony with the land, producing honey while not disrupting the ecosystem with artificial nests and materials. Like the traditions of harvesting shale, quartzite, and amber, bee keeping too has remained an integral part of the culture today. In fact, the log bee hives and instruments to obtain honey that were used during the 10^{th} and 12^{th} centuries, were found to be in use by as late as the 1980's (Mould 312). The vast time span over which bee keeping, along with other trades, was practiced suggests how dependent the local communities once were, and still are, on their forests.

Locals depended on the land and forest for virtually all aspects of their livelihood from food and medicine, to housing and personal hygiene. As Mould points out, such uses more specifically consisted of hunting, fishing in the Pripyat River, herb and insect collection, charcoal and tar production, wicker basket weaving, wood tar, charcoal, and tool production, and home construction (312-313). The many uses derived from the forests provided locals with the opportunity of self-sustenance and economic growth through trade and sales. For example, a red dye named "chervets" was often derived from an insect found only in the Polissya Region. This dye gained such popularity that even the Polish noble families, the Cossaks, and Kiev Princes

Fig. 2 Map of the Polissya Region. "File: Ukraine-Polissya.png." April 2009. Wikipedia. 20 December 2009. http://en.wikipedia.org/wiki/File:Ukraine-Polissya.png.

regularly demanded it (Mould 313). Other materials from Polissya included soap, dyes, and glass from the charcoal and iron tools such as axes, hammers, pincers, scythes, sickles, and iron ploughs. Homes in the region were also constructed of forest wood. Most natural resources were utilized to form the foundations for life, economy and culture in the Polissya.

The Pripyat River Watershed is also found in Polissya. It flows into the Dnieper River and empties into the Black Sea (fig.3). The Chernobyl Nuclear Power Plant was built near the Pripyat River, which positions it within the Dnieper River-Reservoir system, one of the largest surface water systems in Europe (Smith and Beresford 139). The Kiev Reservoir is found just downstream of the Pripyat River and serves as a major source of drinking water for the city of Kiev. The close proximity of the Chernobyl Nuclear Plant to the Pripyat River, the Dnieper River-Reservoir system, and the Kiev Reservoir, make nearby inhabitants and ecosystems especially vulnerable to contamination. However, recent studies have confirmed that contamination levels in the Pripyat and Dnieper Rivers have shown some signs of decline (Mould 205).

Fig. 3 Pripyat-Dnieper River-Reservoir System showing Chernobyl and Kiev with the Kiev Reservoir in between. Smith, Jim and Nicholas A. Beresford, eds. Chernobyl: Catastrophe and Consequences. Chichester, UK: Praxis Publishing, Ltd., 2005.

Background to Nuclear Science:

The Atom, its Structure, Behavior, and Energetic Properties:

Atoms are minute, yet amazing energy-producing structures that may be positively charged, negatively charged, or stable. Their unique qualities create energy and matter, making life on Earth possible. The atom's structure contains a nucleus with positively charged protons and neutrally charged neutrons, while its outer valences house the atom's negatively charged electrons (fig. 4). The electric charge creates electrical force when opposite charges attract and

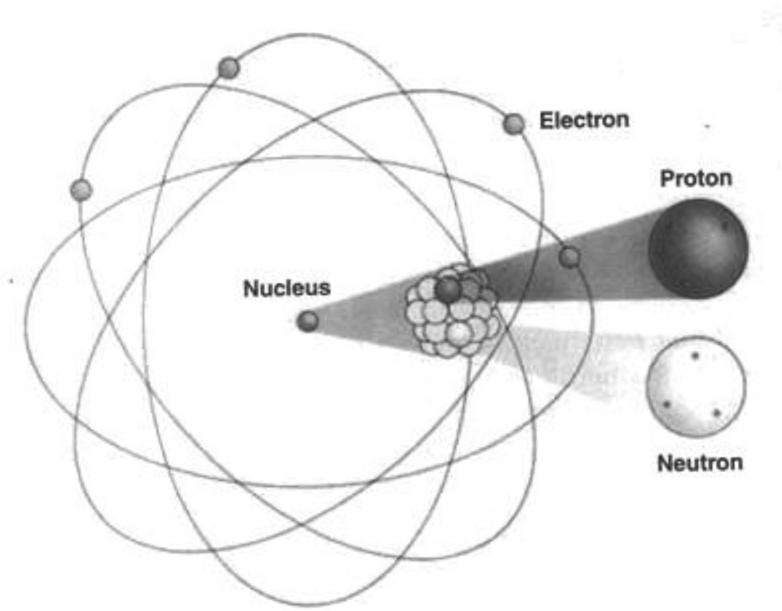


Fig. 4 Structure of an Atom. Mycio, Mary. Wormwood Forest: A Natural History of Chernobyl. Washington, DC: Joseph Henry Press, 2005.

like charges repel. The force heightens as the atoms or particles get closer and weaken as they move further apart. Thus, the close proximity of an atom's protons to its electrons creates a strong electrical force tightly binding them together as one atom. At this point, you may be asking, how does the nucleus remain intact with its many protons repelling each other and the neutrons' lack of charge? There is actually a force even stronger than the electrical force produced between the protons, which keeps the nucleus intact. This force has been named "the strong force" by physicists. It attracts protons to protons and neutrons to neutrons (Mycio 10-11). These particles are all extremely close within a nucleus and their mutual attraction is extremely intense. An atom's nucleus is so tiny because "the strong force" only works in short distances. In fact, "the strong force" even holds together much smaller particles within the nucleus called quarks. Quarks have their own energy, as-well as gluons, which are force-mediating particles. With the help of gluons, the quarks form triplets. This ultimately creates the protons and neutrons found within the nucleus of an atom (Mycio 10-11). In summary, an atom's nucleus is held together by "the strong force," while the atom's electrons remain a part of the atom by the electrical force created by the positive charges within the nucleus and negative charges within the valences.

Elements are formed by the combination of atoms. Elements contain an atomic number and an atomic weight that influence the nucleus' stability. The atomic number is determined by the quantity of protons within the nucleus. This number also determines which element will be formed by the atoms. The atomic weight is a product of the number of protons and neutrons inside the nucleus. In nuclear energy science, both the atomic weight and the atomic number of an element are important because the number of protons within a nucleus will determine the severity of its electrical repulsions. As the number of protons increases, the force trying to break the nucleus apart also increases thus, requiring a greater amount of "strong force" energy to keep it together. However, in order to keep the "strong force" energy active, the nucleus requires a certain number of quarks that are found within the neutrons (Mycio 11). Therefore, the number of neutrons relative to the number of protons within a nucleus will often times influence its stability. A preferred number of protons and neutrons are required to keep an element stable. The ratio for lighter elements appears to be equal, while heavier elements often require a greater number of neutrons than protons. If the fragile balances are off, the nuclei will become radioactive by decaying and emitting radiation in the form of gamma rays, alpha, and beta particles in order to achieve a balanced state.

What are isotopes? How do gamma rays, alpha, and beta particles work?

Isotopes occur when atoms of the same element have varied numbers of neutrons. Each nucleus with its unique number of neutrons is considered an isotope of the same element. Sometimes the atom is unstable and thus, radioactive, if an atom contains too many or too few neutrons. In such cases, the atom emits radiation in the form of electromagnetic waves, such as gamma radiation or particles, like alpha or beta pieces. The "Isotopes" article from Science Trek displays an example of beta decay when the radioactive element tritium $^3H_1$ decays to helium $^3He_2$. The number on the left is the atomic mass (protons + neutrons) while the number on the right is the atomic weight (protons). In this particular example, tritium has taken one of its excess neutrons and converted it to a proton, creating helium, and becoming stable. However, the extra proton taken from tritium must be balanced out by an extra electron being emitted. The nuclear reaction looks like this: $^3H_1 => {}^3He_2 + {}^0e_{-1}$. Since both sides have the same nuclear mass number, it is considered a nuclear reaction.

Two other forms of radioactive decay are alpha particles and gamma rays. Some heavy isotopes decay by giving off alpha particles, composed of two protons and two neutrons: $^{238}U_{92} \Rightarrow {}^{234}Th_{90} + {}^{4}He_{2}$ (“Isotopes” Science Trek). Helium $^{4}He_{2}$ is emitted because the protons and neutrons found in this element are in an exceptionally tight bind. At this point, one may be thinking, why neutrons can all of sudden escape from a nucleus when in the example with tritium, they could not. The reason why the neutrons do escape in an alpha decay is because “the strong force” is sometimes overpowered by the electric force given off by the protons. This occurs when the nucleus changes shape, disrupting the balance between “the strong force” and the electric force provided by the protons, and pushing the particles out of the nucleus. Alpha decay is a minor case of this, while fission is a more dramatic case, in which the nucleus may break in approximately half due to the electric force pushing the particles out of the nuclei (“Isotopes,” Science Trek). Following an alpha or beta decay, the nucleus is often left in an excited state with excess energy. In order to rid itself of this extra energy, the atom emits a gamma ray.

^{235}U is a natural element that can support a nuclear chain reaction to be used in electric power plants. According to Z. Medvedev, it is the only atom found in nature that can support a nuclear chain reaction and it forms 0.7% of the ^{238}U (4). A nuclear chain reaction begins with the fission process: A free floating neutron collides with the nuclei of ^{235}U, splitting it in half, briefly creating an unstable isotope called ^{236}U, which then splits into 2 fission fragments, additional neutrons, and often gamma rays as-well. The newly created elements are called radionuclides because they are often unstable and radioactive. The newly emitted neutrons produced during fission have the capability of splitting another ^{235}U atom, if it is close by.

The next ^{235}U particle splits, and again, creates two more radionuclides, additional neutrons, and gamma rays. Thus, the self-sustaining chain reaction continues. According to Z. Medvedev, if the process is taking place near a major piece of ^{235}U, it can be so fast that it actually produces an explosion (4). This is what occurred during Hiroshima in 1945. If the ^{235}U particles are separated, however, and the neutron speed is slowed down by a moderator, the fission reactions can be controlled so that the energy produced may be managed and used to form electricity. Most of the nuclear reactors in the world are water-moderated, but the Chernobyl Nuclear Power Plant was moderated by graphite. This proved to be a major design flaw.

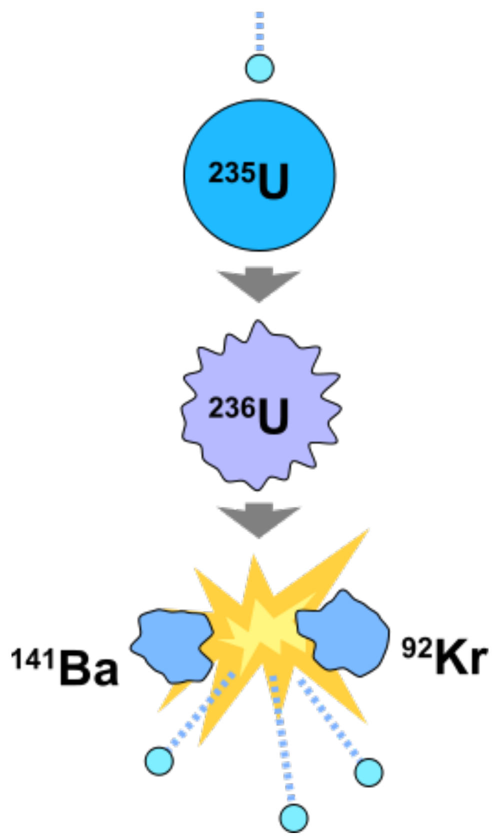


Fig. 5 Nuclear Fission. "File: Nuclear fission.svg." 22 November 2009. Wikipedia. 4 January 2010. http://en.wikipedia.org/wiki/File:Nuclear_fission.svg.

Although the percentage of ^{235}U relative to the amount of ^{238}U is small, it still is quite capable of producing a lot of energy, provided that the ^{238}U is enriched and composed of 2-3% ^{235}U. For example, only 1 pound of ^{235}U can produce the equivalent of 15 tons of coal in heat energy (Medvedev Z. 5). Despite its efficiency in producing energy when compared to coal, Z. Medvedev warns that, "very large amounts of highly radiotoxic and often very volatile fission radionuclides are produced at the same time, making the use of uranium very dangerous (5). Nearly 100 highly radioactive and hot substances accumulate in the fuel rods during fission. With time, this nuclear waste becomes increasingly hazardous as radioactive fission products are accumulated. So, old nuclear fuel, like the kind present in Unit 4 of Chernobyl during the accident, is more dangerous than fresh fuel.

Units of Radioactivity and Terminology:

Ionizing radiation is measured using 5 concepts: exposure, absorbed dose, equivalent dose, effective dose, and activity. Exposure is measured in roentgens (R) and is a term used to describe the amount of radioactivity present in the environment. The absorbed dose is measured in gray units (Gy) or the rad, and signifies one joule of energy absorbed per kilogram of tissue. While the absorbed dose provides the amount of radiation absorbed per unit of tissue, the equivalent dose goes one step further by incorporating coefficients that account for the individual capacity of each radionuclide to harm biological tissue (Savchenko 4). For example, gamma emitting elements such as radiocaesium are considered to be more harmful than alpha and beta emitters, due to their penetrating power. The equivalent dose not only shows the amount of energy absorbed per unit of tissue, but it also takes into account what kind of radiation is absorbed and its relative power. The term effective dose was also created because many organs and tissues were exposed to ionizing radiation following Chernobyl and the term captures the overall health risk to a living being due to any combination of radiation (2003-2005 Chernobyl Forum 12). The term effective dose incorporates both concepts stated above, while building upon them by taking into account the susceptibility to harm of various biological tissues (Savchenko 4). For example, if the lungs receive 2 mSv with a weighing factor of 0.12 and the thyroid receives 1 mSv with a weighing factor of 0.05, the calculation for the effective dose would be: $(2\times0.12) + (1\times0.05) = 0.29$ mSv for the entire body. This number combines internal, external, uniform, and non-uniform radiation and shows at what point a severe radiation-induced cancer or genetic defect may develop.

Table 1

Units of Radioactivity

What is being measured?	New Name/Symbol	Old Name/Symbol	Conversion
Exposure		Roentgen (R)	
Absorbed Dose	Gray (Gy)	Rad	1 Gy = 100 Rad
Equivalent Dose	Sievert (Sv)	Rem	1 Sv = 100 Rem
Activity	Becquerel (Bq)	Curie (Ci)	1 Ci = $3.7 * 10^{10}$ Bq

*List of Prefixes: kilo (k) = 10^3, mega (M) = 10^6, giga (G) = 10^9, exa (E) = 10^{18}
milli (m) = 10^{-3}, micro (μ) = 10^{-6}, nano (η) = 10^{-9}.

Source: Medvedev, Zhores A. The Legacy of Chernobyl: 1st American Edition. New York: W.W. Norton, 1990.

Nuclear Energy Development:

The beginning of radiation science dates back to 1895 and 1896. It started with Dr. Wilhelm Conrad Röntgen, a German physicist who in 1895 discovered ionizing radiation while passing an electric current through an empty glass tube, creating x-rays ("Outline History of Nuclear Energy" WNA). In honor of his accomplishment, the unit of radiation exposure was named the Roentgen (R). The next important figure in the history of atomic radiation is Dr. Antoine Henri Becquerel. In 1896, the French physicist discovered the phenomenon of alpha and beta radiation while witnessing a substance called pitchblende (an ore containing radium and uranium) darkening a photographic plate ("Outline History of Nuclear Energy" WNA). As a result, the term Becquerel (Bq) is now commonly used to measure radioactivity in the environment. Later, French physicist Dr. Paul Villard was credited with discovering the presence of gamma rays and their distinct characteristic of being able to penetrate deeper into substances than x-rays. Finally in 1896, Dr. Pierre Curie and Dr. Marie Curie, originally from France and Poland, gave the term "radioactivity" to the various forms of radiation discovered. In honor of Drs. Pierre and Marie Curie, an alternate unit of radiation activity was named, the Curie (Ci). The scientists mentioned above, together with many other pioneers of atomic science, such as Ernest Rutherford, Frederick Soddy, and James Chadwick, all paved the way to further research into nuclear fission.

The technology to produce nuclear power for electricity began with the native Italian scientist, Dr. Enrico Fermi. His work led him to the realization that an atomic nucleus can be split by a neutron, producing various new radionuclides, some heavier and some lighter ("Outline History of Nuclear Energy" WNA). If the lighter radionuclides were proven to be roughly half of the atomic mass of uranium, the element that he initiated the experiment with, then the atom was split into roughly two equal parts, and nuclear fission could be confirmed to have occurred. In 1938, researchers Otto Hahn and Fritz Stassman proved just that, and atomic fission was officially born. Later, Lise Meitner and Otto Frisch, under the guidance of Niels Bohr, found that the nucleus split due to the absorption of a neutron, causing vibrations within the nucleus, and ultimately leading to the nucleus splitting into two, more or less, equal parts ("Outline History of Nuclear Energy" WNA). Research continued with the discovery of additional neutron releases during the fission reaction and the ability to produce a self-sustaining nuclear chain reaction with the use of slow moving electrons given a moderator. The newly acquired knowledge about the nature of the atom had both positive and negative effects. Its peaceful uses include human healthcare technologies, energy development, electronic devices, and more, while the negative impact has been the creation of the atomic bomb.

The first nuclear chain reaction took place as a result of the Manhattan Project. On August 2, 1939 Albert Einstein wrote his famous letter to President Franklin D. Roosevelt warning him that Germany may be able to produce an atomic bomb by using nuclear fission. According to Z. Medvedev, Einstein felt obligated to warn the U.S. President after his conversation with profound nuclear physicist Niels Bohr's, who suggested that a fission bomb was feasible (Medvedev Z. 226). Due to Niels Bohr's pioneering role in nuclear fission research, Einstein took this physicist's comment quite seriously. The result was the creation of the U.S. office of Scientific Research and Development in June of 1941, and the Manhattan Project a year later (Medvedev Z. 226). The following year, the first self-sustaining nuclear chain reaction was achieved at Chicago Pile-1, the world's first artificial nuclear reactor. The reactor was designed at the University of Chicago and was built as a part of the Manhattan Project. A new day in energy production had come and countries would soon begin utilizing this groundbreaking technology.

<u>The Chernobyl Nuclear Power Plant:</u>

Location, Engineering, and Technology:

The Chernobyl Power Complex was built in the Former Soviet Union in the now independent country of Ukraine, in the eastern section of the Polissya Region. It is located 20 km south of Belarus, a country with a population of 10 million, including 2.3 million children. Belarus is located 130 km north of Ukraine. Ukraine has a population of 60 million, including 10.8 million children (Mould 16). Its close proximity to the capital cities of Minsk and Kiev was of concern in the aftermath of the accident. Minsk, the capital city of Belarus is located 320 km from the power plant and Kiev is 146 km from the facility (Mould 16). Minsk has a population of 1.3 million and Kiev has 2.5 million people (Mould 16). It was feared, that both cities would have to be evacuated, but especially Kiev, since the plant's cooling pond was located right next to the Kiev Reservoir, a major drinking source for the city. According to the World Nuclear Association (WNA), the population living within a 30 km radius was between 115,000 and 135,000. The closest city, the city of Pripyat was 3 km away and contained 49,000 inhabitants, while the closest town, Chernobyl, had 12,500 inhabitants and was located 15 km southeast of the plant (WNA). The location of the reactor was most likely chosen for economic reasons, so that the energy would not have to travel far distances before reaching consumers, this however, did not come without an increased health risk.

The entire complex consisted of 4 RBMK-1000 Nuclear Power Units. RBMK-1000 is a Russian acronym for "reactor high-power boiling channel type" (Medvedev Z. 318). The RBMK was designed in the Soviet Union and its name is derived from the 1000 megawatts (MWe) of electricity it produces and its channel-type pressure tubes that house the uranium fuel. All 4 Units were constructed using the RBMK design. Units 1 and 2 were constructed between 1970 and 1977, while Units 3 and 4 were completed in 1983 (WNA).

Figure 6 displays the inside workings of an RBMK-1000 nuclear reactor. Nuclear reactors are used to produce electricity. The production process begins inside the reactor core where nuclear fission of ^{235}U produces heat while sustaining a nuclear chain reaction. The heat produced then turns the cooling water found within each individual pressure tube into steam. The steam power rotates the turbo generators, which then generate electricity that is sent to the grid. The fuel is composed of a mixture of slightly enriched ^{235}U (2%) and ^{238}U atoms (WNA). The ^{235}U is enriched because when uranium is mined, it only constitutes 0.7% of ^{235}U, while 99.3% of the uranium is the ^{238}U, the isotope incapable of producing a nuclear chain reaction. Thus, enriched ^{235}U can create more electricity by supporting a more intense nuclear chain reaction. A refueling machine is used to allow fuel bundles to be changed without shutting down the reactor (WNA). Water is used as a coolant and to produce the steam. It is pumped through the bottom of the fuel channels. It then boils as it makes its way up the fuel containing pressure tubes where it then escapes from in the form of steam (WNA). The steam separator then separates any remaining water droplets from the steam. The steam is then transferred to the two 500 MWe turbines (WNA).

Other important components of an RBMK-1000 reactor are graphite moderators, control rods, and the biological shield. The graphite blocks are used to moderate the fast neutrons that are produced during fission and during the chain reaction, because slower neutrons have a better chance of colliding with another ^{235}U atom, than super-fast uncontrollable neutrons do (Medvedev Z. 5). The graphite columns are found on either side of the fuel bundles in close proximity to the fission reactions and neutrons produced. The 2,488 graphite columns separate about 1,660 pressure tubes, each about 10 m long (Medvedev Z. 5). Control rods can be found in between the graphite columns. The 211 control rods absorb neutrons while preventing the generation of new neutrons (Medvedev Z. 5). So, while the graphite columns are working to slow down the neutrons, creating a better environment for fission to occur, control rods are used to activate and deactivate the nuclear chain reaction. When the control rods are withdrawn from the core, the neutrons are present and the nuclear reaction is activated; when they are inserted into the core, the neutrons become absorbed, their production is ceased, and the chain reaction is inhibited (Medvedev Z. 6). A nuclear reactor must have a containment structure shielding the environment from the radiation found inside. The containment structure located at the Three Mile Island Power Plant Reactor was made of reinforced concrete. It was successful in that, after the explosion, it kept the radioactivity inside and away from the environment (Medevedev Z. 4). Unfortunately, the biological shield at Chernobyl was not so effective. According to Mould, the upper biological shield, composed of steel and serpentinite rock, was blown out of position following the accident (14). It was not designed to withhold the intense pressure caused by the explosion.

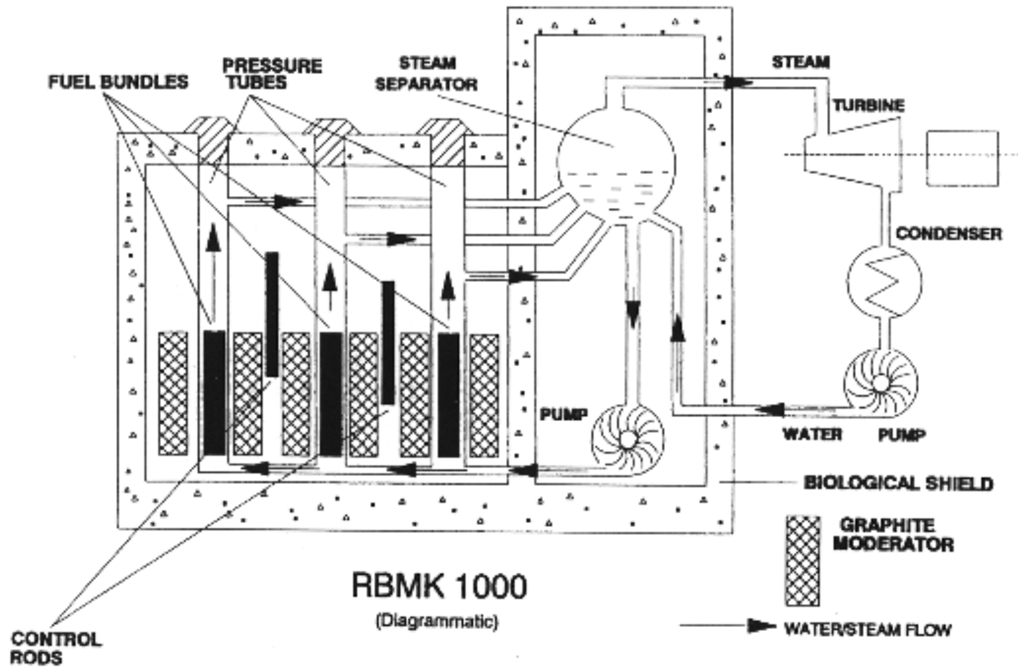


Fig. 6 The Chernobyl Plant. "Chernobyl Accident." World Nuclear Association (WNA). 22 December 2009. http://www.world-nuclear.org/info/chernobyl/inf07.html.

Design Problem of the Chernobyl Nuclear Reactor:

Unit 4 at the Chernobyl Power Plant Complex contained unsafe graphite moderators and control rods. The sudden loss of water in an RBMK-1000 reactor is a potentially great danger because, unlike the Pressurized Water Reactors (PWR), the water running through the circulation pipes is only designed to cool the reactor core, not moderate and cool. Therefore, if cooling water is removed from a PWR reactor core, the nuclear chain reaction is simultaneously aborted, due to the absence of the water moderator. Thus, the water-moderated design provides a built-in safety mechanism (Medvedev Z. 10). In an RBMK-1000, when water is lost, the graphite moderator continues to uphold the nuclear chain reaction. When this is combined with the loss of cooling water, overheating occurs and the possibility of a core meltdown becomes more real (Medvedev Z. 10). Control rods are another important safety feature present in both RBMK and PWR reactors. They are used to absorb neutrons, and lower or stop a chain reaction from occurring when needed. In an RBMK-1000, it takes 20 seconds for the control rods to reach the core from their highest position, but in the more modern CANDU reactors used in Canada, and PWRs used in USA and Japan, this operation takes 1 second (Medvedev Z. 6). The relatively slow RBMK-1000 control rods were possibly the ultimate contributors to the final catastrophe.

Chernobyl RBMK-1000 reactors contain backup diesel generators as a safety feature, but require too much time to reach their full capacity. According to Z. Medvedev, they require 15 seconds to start up, but they take 60-75 seconds to reach their full capacity of 5,500 kW (11). Since the water pumps, necessary for cooling the reactor, require 5,500 kW of power to operate, this posed a problem. During the ~75 seconds that it would take to start up the backup diesel generators, the nuclear chain reaction would continue un-cooled, possibly leading to overheating and great damage to the core. Soviet authorities felt that this gap was unacceptable and their quest to find a solution for this problem was at the heart of the fatal test performed on April 25-26, 1986. The experiment was designed to test whether the residual mechanical energy of the rotating turbine was enough to fill the ~75 second gap between the time the electricity failed and the time it took for the backup diesel generator to reach its fullest capacity (Medvedev Z. 11). It was hoped that the power generated from the winding down turbo generator would be enough to power the emergency water pumps until the diesel generators commenced.

April 25-26, 1986 Disaster:

The Chernobyl accident took place as result of the design flaws mentioned above and operator error during the April 25-26, 1986 test. The test began on April 25, 1986 with an initial power reduction to 1600 MW thermal power, which was 50% of the maximum thermal power that can be generated by the reactor. The test also began with the shutdown of turbine generator number 7 from the electricity grid (Mould 34). Reactor number 4 contained 2 turbine generators, numbers 7 and 8. In addition, 4 main circulating water pumps were transferred to generator number 8 (Mould 34). Next, the reactor's emergency core cooling system was disconnected (Mould 34). This was done in order to test whether during a power failure, the main water supply would be capable of sufficiently cooling the reactor core, solely through the power of inertia from the turbo generator. The reactor power was then kept within the 700 MW (thermal) -1000 MW (thermal) range in order to avoid xenon poising and to be able to repeat the test, if necessary.

Xenon poisoning of a reactor occurs when the reactor is shut down and the chain reaction is inhibited. The lower power produces fewer neutrons for ^{135}Xe, a by-product of nuclear fission, to turn into ^{136}Xe. ^{135}Xe that is not changed into ^{136}Xe is unstable and has a half-life of only 9.2 hours before it transforms into ^{135}Cs (Medvedev Z. 27). However, ^{135}I, an alternate product of fission, has a 6.7 hour half-life before it is transformed into ^{135}Xe (Medvedev Z. 27). Xenon poisoning occurs when there is an over accumulation of ^{135}Xe, when ^{135}I is transformed into ^{135}Xe faster than the latter decays. Also, with fewer neutrons available during a shutdown, ^{135}Xe does not turn into ^{136}Xe (Medvedev Z. 27). As a result, xenon begins to accumulate inside the reactor core and since it absorbs neutrons, it may take about 3 days for the ^{135}I and ^{135}I to decay to the point where the reactor may be restarted. Thus, by not fully shutting down the reactor during the test, the operators and managers hoped to avoid xenon poisoning while making it possible to repeat the test, if necessary.

The events that occurred on April 26, 1986 paved the path to the final catastrophe. At 00:28 the reactor power fell to 30 MW (thermal), a much lower level than the required 700 MW (thermal) – 1000 MW (thermal) power level guideline requirement (Mould 35). This resulted in almost a complete reactor shutdown. Some investigations suggest that the extreme power reduction was due to the control rods not working properly, but other sources have noted that the operators lowered too many rods into the core (Mould 35). The power level dramatically fell and operators managed to stabilize the power at 200 MW (thermal) by removing an alternate set of control rods (Mould 35). However, the test should not have proceeded at that point since the power level was well below the minimum power safety guidelines set forth by the government, while the reactor was in danger of xenon poisoning. However, the test proceeded and the level of steam was sharply reduced because of the low, 200 MW (thermal) power and the very high coolant flow rate continuing through the core, due to all 4 water pumps functioning simultaneously to cool generator 8 (Mould 36). At this point, the reactor should have been shut down automatically, but the operators had over-ridden the emergency system. At that point, the water levels inside the reactor core were too high, causing a decrease in steam production, while the power level was already below the necessary test guidelines, causing xenon poisoning. Again, the test should have been aborted, as a computer printout later confirmed. The operators began to raise the rods to increase output, but the power still remained at 7%, so an additional set of rods were taken out of the core, increasing the power to 12%. At that point only 6 rods remained inside the reactor core, representing less than ½ the total amount of rods (15) required for safety standards to be met (Mould 37). The operators continued with the test, however, unaware of a hotspot that was building up at the base of the reactor. The automatic emergency turbine shut down was also aborted in fear that if triggered, it would stop the test (Discovery Channel).

At 1:23 the reactor power began increasing from 200 MW (thermal) when the additional set of control rods were withdrawn and the cool water flow was reduced. This caused an increase in heat and steam generation with an increase in reactor power (Mould 37-38). A prompt critical excursion, or power surge, caused the shift foreman to order an emergency shutdown. This was supposed to automatically lower the control rods into the core (Mould 38). However, the order came too late and the rods could not travel down fast enough into the reactor core in order to lower the power in time (Mould 38). In an RBMK-1000, it takes 20 seconds for the control rods to reach the core from their highest position, but in the more modern CANDU reactors used in Canada, and PWRs used in USA and Japan, this operation takes 1 second (Medvedev Z. 6). As mentioned earlier, the relatively slow RBMK-1000 control rods were possibly the ultimate contributors to the final catastrophe. The core reached 120 times its full power in a few seconds, resulting in a steam explosion, triggered by a burning graphite moderator. The top reactor shield blew off and a second explosion followed, resulting from the mixture of hydrogen with air. That explosion spread both fission products of the normal operation of the reactor and unexpended uranium fuel across a large area.

Eyewitness Accounts:

A local watchman named, Daniil Terentyevich Miruzhenko was on duty at the hydroelectric assembly office, just 1000 feet away from the Chernobyl reactor (Medvedev G. 83). He witnessed the disaster and felt intense trembling while watching the explosions that destroyed the plant and his office, located 1000 feet away. During an interview conducted by nuclear engineer Grigorii Medvedev, Miruzhenko shared his observations on that ill-fated morning. Miruzhenko confirmed hearing the first explosion just before the final, most terrible blast. He recalled the wind carrying "the great swirling black fireball" higher into the night sky (Medvedev G. 83). As it ascended, tiny radioactive particles filled the atmosphere. With it came, "a thunderclap as loud as the sonic boom of a jet fighter, and a flash of light which cast a glow into the office," where the watchman stood in astonishment (Medvedev G. 83). According to G. Medvedev, the explosion occurred because the concentration of hydrogen in the explosive nuclear mixture reached the stage of detonation (77). The intense energy of the blast sent vibrations throughout the area nearby. Miruzhenko distinctly recalls the walls in his office shaking, the window panes shattering, while the ground quaked beneath his feet (Medvedev G. 83). Flames, sparks, and chunks of burning material went flying into the air above the reactor. The watchman saw a pillar of flame, sparks, and red-hot fragments shot up into the night sky (Medvedev G. 83). It was later learned, that the reactor core and its pieces of hot graphite constituted the major part of the burning material that flew through the air. Additional materials included bits of concrete and metal structures that could be seen tumbling above the flames (Medvedev G. 83). The pieces and debris landed around the reactor site, contaminating the surrounding environment and creating highly radioactive hot-spots.

Immediately after the 2nd more powerful explosion, Miruzhenko noticed that a fire broke out on the roof of the turbine hall and the de-aerator (Medvedev G. 83). This fire may possibly have been prevented had the roof not been constructed using a bituminous finish (Medvedev G. 83). Molten tar could be seen falling from the roof, he recalled, and the whole place was on fire (Medvedev G. 83). 250 firemen arrived at the scene and managed to put out the largest fires on the roof by 2:30, however. The intense graphite fires continued for about 10 days, causing the major part of the radioactive emissions for that time. When they were finally extinguished on the 10th day, the radioactive emission level from the reactor finally decreased substantially.

Fires at Unit 4 were also seen by other witnesses nearby. Other witnesses included the many fishermen who could often be seen trying to catch small fry at the point where the waters emerged from the power plant water circuit and into the cooling pond. After hearing the explosions, the fishermen remembered seeing, "a blinding flash of flame and a firework display consisting of fragments of red hot fuel and graphite" (Medvedev G. 86). Many observers were completely unaware of the dangers associated with what they were observing. In fact, several residents rushed toward the reactor to get a better view, while others stayed in Pripyat and drank vodka because of the commonly held belief that it would decontaminate their bodies. Unfortunately, this lack of knowledge exposed many residents to unnecessary doses of radiation.

Figure 7 is an aerial view of the damaged reactor, taken 5 months after the accident. The picture displays the cooling pond, which was connected to the Kiev Reservoir (Mould 17). The cooling pond was 22 km^2 and was situated near the Pripyat River, a tributary of the Dneiper. Its function was to provide cooling waters to Unit 4. Although the average annual concentrations of ^{137}Cs (1000 Bq/L) and ^{90}Sr (20 Bq/L) in the cooling pond were extremely high in 1986, the levels had declined substantially to 4 Bq/L of ^{137}Cs and 2 Bq/L of ^{90}Sr in 1994 (Mould 206). But, despite these decreases the area is still considered to be unsafe. The tall chimney in the picture is the ventilation stack, which was entirely contaminated from top to bottom (Mould 17). The damaged reactor core can also be seen. The long white building in front of it houses the turbine hall where the damaged roof is evident (Mould 17). The hole in the roof shows a glimpse of the yellow turbines. In addition, all of the forests in this photograph were contaminated and destroyed (Mould 17). The forests were part of the Ukrainian-Belarusian Woodlands, the Polissya, and were once a valuable environmental resource to surrounding residents.

Fig. 7 Damaged Unit 4 Reactor Mould, R.F. Chernobyl Record: The Definitive History of the Chernobyl Catastrophe. London: Institute of Physics Publishing, 2000.

Rescue Work Following the Disaster:

Firemen were marshaled in from various sections of the Former Soviet Union to fight the brutal fires that had erupted. The reactor core was severely damaged, the graphite moderator had caught on fire, and radioactivity levels were soaring (Medvedev Z. 43). But, the fire crews were completely unaware of the danger associated with their mission. They successfully extinguished the rooftop and other fires at the reactor site, but were unaware that many of the remaining fires could not be extinguished using conventional methods because it was the graphite that was on fire. So, they attempted to extinguish the graphite fires with water, but were unsuccessful because the temperatures were much higher than in regular fires and water could not adequately cool the molten mass (Medvedev Z. 43). In their quest to put out the blistering inferno, the fire crew had needlessly exposed themselves to extreme levels of radiation.
They heroically fought to extinguish the fires, but unfortunately were unequipped for the task. The firemen were untrained in radiation protection and had no dosimeters (Smith and Beresford 5). Furthermore, their clothing did not protect them from radioactive particles, nor did they have respirators (Medvedev Z. 43). Many were completely uninformed about the dangers associated with nuclear radiation as a result of inadequate training, lack of reliable information, and the absence of a safety culture. Grigorii Khmel, the driver of one of the fire trucks provides a good example of the inadequate training described. In an interview, Khmel recalls one instance when he and the fire crew were onsite, and one fireman named Misha, asked "what is graphite?" Then, another fireman picked up the graphite, with his bare hands (Medvedev Z. 44). Thus, immediately exposing himself to a lethal amount of radiation! Khmel admitted that they didn't know much about radiation and "even those who worked there had no idea"

(Medvedev Z. 44). Several firemen suffered from severe radioactive skin burns and internal radiation poisoning by inhaling radioactive particles. 134 emergency workers were found to have suffered from acute radiation sickness (ARS); 28 of them died shortly after in the Moscow Radiation Clinic (Smith and Beresford 5).

Emergency measures could have also been improved for local populations. Although stable iodine was made available to power plant workers within ½ hour of the accident, it was not, however, distributed to the residents of Pripyat, the nearest town, located approximately 3 km from the plant (Smith and Beresford 6). The population was also exposed to radiation through inhalation due to the unavailability of face masks (Smith and Beresford 6). Immediately following the disaster, the local population was not warned to stay indoors. Adults and children carried on with regular everyday activities. Children went to school and spent time at the playground, while adults could be seen gardening, sun bathing, going to work, and doing other everyday activities (Smith and Beresford 6). By the end of the day, many people developed radiation sickness and complained of nausea and unusually dark tans, often called nuclear tans.

<u>Environmental Contamination:</u>

Characteristics of Key Radionuclides:

Radioiodine-

^{131}I, ^{133}I, and ^{129}I all formed part of the total radioactive inventory that was found in the Chernobyl fallout. Out of the 3 radioactive forms of iodine, ^{131}I contributed the largest amount of radiation to the population (Smith and Beresford 66). The table below shows that the half-life for ^{131}I is only 8.04 days. During decay, it emits both beta particles (electrons) and gamma rays, which are ionizing forms of radiation. As discussed earlier, that means that the particles and energy emitted by them are capable of breaking chemical bonds that keep molecules together. This can cause cell damage, ceased reproduction, mutations, and death in living organisms. ^{131}I radionuclides usually enter the human body by travelling through the food chain. According to Smith and Beresford, iodine that is found in soils is believed to be strongly absorbed by organic matter, plant litter, humic matter, and colloidal organic molecules (66). This makes plant and animal uptake more likely to occur, causing food contamination. Particles can also travel through and contaminate the water supply. Following the explosion, for example, the Kiev Reservoir was of particular concern because of its function as a drinking water source in the region, and its connection to the Pripyat River, located only 3 km from the plant. The presence of unstable isotopes in the water is also a problem because of their ability to evaporate into the atmosphere, causing inhalation of radioactive particles. Contaminated water can also be used for crop irrigation. It is then absorbed by plants through their root systems and transferred to foodstuffs. Crops become even more dangerous when internal uptake is combined with external deposition. Livestock that ingest the contaminated crops may transfer it to humans through milk and meat products (Smith and Beresford 66).

Table 2

Characteristics of ^{131}I and ^{129}I

2.4.1 Radioiodine

Isotope data

Isotope	Half-life	Emission energy* MeV (intensity)
I-131	**8.04 d**	
Principal radioactive emissions	β-	0.069 (2%)
	β-	0.097 (7%)
	β-	0.192 (90%)
	γ	0.284 (6%)
	γ	0.365 (82%)
	γ	0.637 (7%)
	e-(I)	0.046 (4%)
	e-(I)	0.330 (2%)
Decays to	*Xe-131*	
I-129	**1.6×10^7 y**	
Principal radioactive emissions	β-	0.041 (100%)
	γ	0.040 (7.5%)
Decays to	*Xe-129*	

(I) internal conversion electron.
* For beta-particles, mean emission energy of beta-groups is given.

Source: Smith, Jim and Nicholas A. Beresford, eds. Chernobyl: Catastrophe and Consequences. Chichester, UK: Praxis Publishing, Ltd., 2005.

Radiostrontium-

Similar to iodine, the element strontium also has unstable isotopes. ^{89}Sr and ^{90}Sr can also travel through the environment, negatively impacting living organisms. Table 2 shows that the half-life for ^{89}Sr is 50.5 days and ^{90}Sr is 28.8 years. The former and especially the latter, therefore are more persistent than ^{131}I. Both decay through the emission of beta particles (electrons) until they finally reach their stable states. Like radioiodine, ^{89}Sr and ^{90}Sr also travel through the food chain, bio accumulating as higher levels are attained. As they make their way through the web, from soil to plant, plant to animal, and animal to human, their concentration increases. Once in the human or animal body, ^{90}Sr mimics calcium by lodging itself in teeth and bones (Smith and Beresford 66). Children, who are still in the development stage, therefore, receive the highest doses. In fact, following the Chernobyl fallout, Germany recorded a 10-fold increase in the amount of ^{90}Sr in baby teeth (Mycio 125). According to Table 3, this radionuclide will not leave their bodies until the age of 57.6.

Table 3

Characteristics of ^{89}Sr and ^{90}Sr

2.4.2 Radiostrontium

Isotope data

Isotope	Half-life	Emission energy* MeV (intensity)
Sr-89	**50.5 d**	
Principal radioactive emissions	*β-*	0.585 (100%)
Decays to	*Y-89*	
Sr-90	**28.8 y**	
Principal radioactive emissions	*β-*	0.196 (100%) (Sr-90 → Y-90)
	β-	0.934 (100%) (Y-90 → Zr-90)
Decays to	*Y-90 then Zr-90*	

* For beta-particles, mean emission energy of beta-groups is given.

Source: Smith, Jim and Nicholas A. Beresford, eds. Chernobyl: Catastrophe and Consequences. Chichester, UK: Praxis Publishing, Ltd., 2005.

Radiocaesium-

Radioactive caesium can also be found in the environment and in living organisms. It is released during nuclear weapons testing, through discharges from nuclear facilities, and from nuclear accidents (Smith and Beresford 69). According to table 4, ^{134}Cs has a half-life of 2.065 years, while ^{137}Cs has a significantly longer half-life of 30.17 years. Both decay through beta and gamma radiation. Like radiostrontium, radiocesium too follows the pathways of a much needed element called potassium. Like the other radionuclides discussed, radiocaesium too may enter the body through various pathways including contaminated food and water. According to Smith and Beresford, it is absorbed by soils and sediments (70). Plants lacking potassium then absorb it due to their similar chemical structures (70). Livestock will then eat the contaminated crops and again through bioaccumulation, humans and animals that eat the contaminated plants and livestock will experience the highest doses.

Table 4

Characteristics of ^{134}Cs and ^{137}Cs

2.4.3 Radiocaesium

Isotope data

Isotope	Half-life	Emission energy* MeV (intensity)
Cs-134	**2.065 y**	
Principal radioactive emissions	β-	0.210 (70%)
	β-	0.023 (27%)
	β-	0.123 (2.5%)
	γ	0.605 (97.6%)
	γ	0.796 (85.5%)
	γ	1.365 (3.0%)
Decays to	*Ba-134*	
Cs-137	**30.17 y**	
Principal radioactive emissions	β-	0.174 (94.4%)
	β-	0.416 (5.6%)
	γ	0.662 (85.1%)
	e-(I)	0.624 (8%) 0.656 (1%)
Decays to	*Ba-137m then Ba-137*	

(I) internal conversion electron.
* For beta-particles, mean emission energy of beta-groups is given.

Source: Smith, Jim and Nicholas A. Beresford, eds. Chernobyl: Catastrophe and Consequences. Chichester, UK: Praxis Publishing, Ltd., 2005.

Plutonium and Americium-

Plutonium and americium radionuclides are found in spent nuclear fuel, nuclear explosions, and other nuclear accidents. Table 5 below shows that ^{241}Am is formed through the decay of ^{241}Pu. ^{241}Am has a half-life of 432.2 years and it decays through gamma and alpha radiation. Notice that ^{239}Pu has a half-life of 24,100 years and ^{240}Pu contains a half-life of 6,540 years. Like other forms of ionizing radiation, they too travel through ecosystems, making their way into human and animal tissues. According to Smith and Beresford, plutonium and americium, too have a high affinity for soils and sediments, especially where organic matter is high (72). This characteristic is both positive and negative. It is positive because contaminated soils can be more easily identified and collected. Organic soils can also be used for bioremediation. On the other hand, their high affinity for organic soils negatively impacts rural farmers whom could not remediate their own plots. According to Smith and Beresford, Plutonium and Americium are primarily passed into the body through ingestion or inhalation; once absorbed, they often become deposited in bone and liver tissues (72-73).

Table 5

Characteristics of Plutonium and Americium

2.4.4 Plutonium and americium

Isotope data

Isotope	Half-life	Emission energy* MeV (intensity)
Pu-238	**87.7 y**	
Principal radioactive emissions	α	5.456 (28.98%)
	α	5.499 (70.91%)
Decays to	*U-234*	
Pu-239**	**2.41×10^4 y**	
Principal radioactive emissions	α	5.157 (73.3%)
	α	5.144 (15.1%)
	α	5.106 (11.5%)
Decays to	*U-235*	
Pu-240**	**6.54×10^3 y**	
Principal radioactive emissions	α	5.168 (72.8%)
	α	5.124 (27.1%)
Decays to	*U-236*	
Pu-241	**14.4 y**	
Principal radioactive emissions	β-	0.0052 (100%)
Decays to	*Am-241*	
Am-241	**432.2 y**	
Principal radioactive emissions	γ	0.0595 (35.9%)
	α	5.486 (84.5%)
	α	5.442 (13.0%)
	α	5.388 (1.6%)
Decays to	*Np-237*	

* For beta-particles, mean emission energy of beta-groups is given.
** Activity concentrations of these isotopes are often measured and quoted as '$^{239+240}$Pu' since their alpha emission energies are almost identical.

Source: Smith, Jim and Nicholas A. Beresford, eds. Chernobyl: Catastrophe and Consequences. Chichester, UK: Praxis Publishing, Ltd., 2005.

Releases into the Environment:

Most radionuclides were dispersed within the first 10 days of the accident. However, the rate of release varied according to heat level. An example can be found in the figure from Z.

Medvedev's book, "The Legacy of Chernobyl." Z. Medvedev's findings confirm the data located in R F Mould's book, "Chernobyl Record." Both authors conclude that on day 1, the radioactive release was 45×10^{16} Bq/day (Mould 51 and Medvedev Z. 79). This high level was caused by the heat emitted by the initial explosions. On day 2, that number dropped to 15×10^{16} Bq/day, and remained at that level or lower until day 7. This cool down period is attributable to the emergency measures taken by the Soviet authorities. In order to extinguish the fire, Soviet authorities decided that it would be best to use helicopters to drop roughly 5000 tons of sand, clay, lead, and dolomite into the reactor core (Medvedev Z. 79). It was believed that these materials could put out the graphite fires and stop the nuclear fallout from continuing. Although the materials did cool down the reactor for some days, the materials actually worsened the situation. On day 7, both Mould and the Z. Medvedev show an increase in radioactive releases (52 and 79). This occurred because the materials caused an increase in pressure and heat. The temperature of the core rose to 2,500 Degrees Celsius, causing a renewed burst of radioactive gases, vapors, and aerosols (Medvedev Z. 79). On the 8th day, the release rate increased to 20×10^{16} Bq/day (Mould 51 and Medvedev Z. 79). The 2nd heat up phase reached its highest point on day 10, when 30×10^{16} Bq/day were released. But, the following day brought an extremely sharp decrease to 0.2-0.6 $\times10^{16}$ Bq/day (Mould 51 and Medvedev Z. 79). This drop was probably a result of self-extinguished fires and a decrease in nuclear activity within the core.

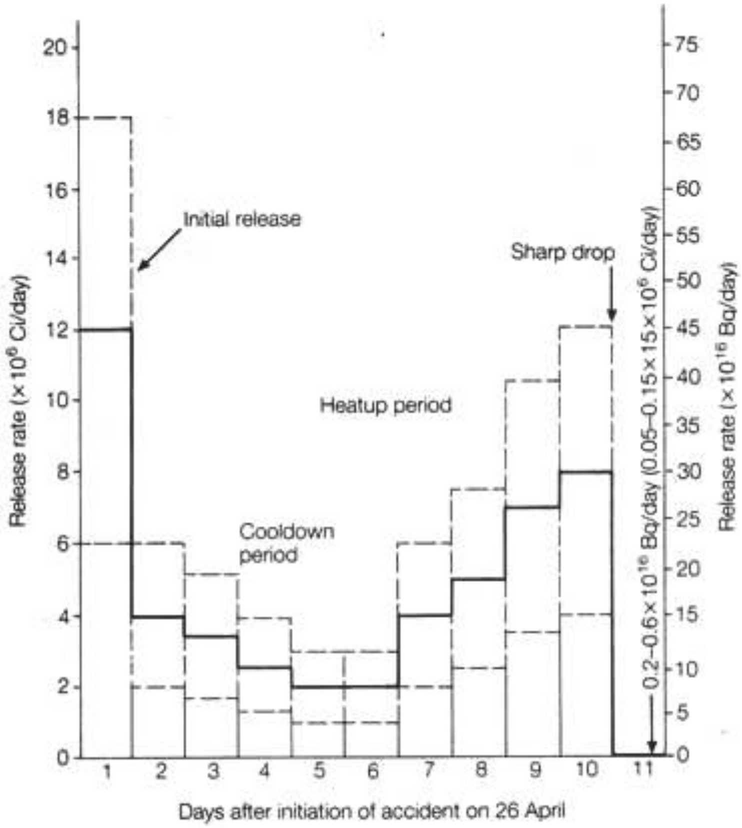


Fig. 8 Daily Release of Radioactive Substances to the Atmosphere.

Medvedev Z. The Legacy of Chernobyl: 1st American Edition. New York: W.W. Norton, 1990.

Tiny radioactive particles were suspended into the surrounding environment. According to G. Medvedev, head Engineer of the Ministry of Energy for the Former Soviet Union, pieces of "radioactive objects such as the fuel and graphite fragments lay strewn all around the damaged reactor unit as a result of the explosion" (Medvedev G. 202). According to the 2003-2005 Chernobyl Forum Report, the total release of radioactive substances was approximately 14 EBq[5], with 1.8 EBq of ^{131}I, 0.085 EBq of ^{137}Cs, 0.01 EBq of ^{90}Sr, and 0.003 EBq of plutonium radionuclides (22). More than 200,000 km^2 of Europe received levels of over 37 kBq/m^2 of ^{137}Cs and ~70% of the particles fell on the 3 most contaminated countries: Belarus, Russia, and the Ukraine (The Chernobyl Forum, 22).

Studies show that Belarus suffered from the highest levels of ^{137}Cs contamination in all of Europe. According to Mould, Belarus suffered a total of ~33.5% of the total amount of contamination across the European continent (213). Russia was exposed to 23.9% and Ukraine experienced 20% of the total fallout that fell on the European continent (213). When combined, the 3 countries together absorbed 77.4% of the total European contamination. This number is similar to the final number put forth by the 2003-2005 Chernobyl Forum, which concluded that over ~70% of Cs^{137} fallout landed on Belarus, Russia, and the Ukraine (22).

The 2003-2005 Chernobyl Forum Report and the 1996 United Nations Educational Scientific and Cultural Organization (UNESCO) Report produced similar findings on radionuclide releases. According to the 2003-2005 Chernobyl Forum Report, the total release of ^{131}I was 1.8 EBq, 0.085 EBq of ^{137}Cs were emitted, 0.01 EBq of ^{90}Sr, and 0.003 EBq of plutonium radionuclides (22). The 1996 UNESCO Report found that 47,567,567.57 Ci of ^{131}I were emitted (Petryna 116). When converting 1.8 EBq to Ci, one finds that 48,648,648.65 Ci of ^{131}I was emitted in the 2003 study, resulting in a difference of 1,081,081.08 Ci. This difference may be attributable to the uncertainties involved in measuring radioactive fallout, while it may also be due to the time difference between both Reports. When comparing ^{137}Cs levels found in the 1996 UNESCO Report and the 2003-2005 Chernobyl Forum Report, the numbers show the same level of contamination: In 1996, there was 2,297,297.30 Ci, while the later report found 2,297,297.30 Ci (Petryna 116). The 2003 Report finds that 0.01 EBq of ^{90}Sr were released.

This converts to 270,270.27 Ci, which is the same as the 1996 Report.

Levels of deposition were affected by winds patterns. The atmospheric winds were found 1000 m above ground. They were especially dangerous because they contained extremely high amounts of radiation, due to the smokestack effect produced by the graphite fires (Mycio 76). The latest IAEA Report states that the wind carried the radioactive plume through Europe in 6 distinct directions (22). On April 26, it traveled north-west toward Belarus, Lithuania, the Kaliningrad Region of the Russian Federation, Sweden, and Finland. The next day, it changed direction to the south-west, making its way toward the Polissya Region, Poland, and south-west. According to the IAEA Report, the change in wind direction was a result of an anticyclone with high atmospheric pressure air masses moving at 5-10 miles per second (21). Over the next 2 days the plume travelled towards Gomel, Bryansk in the Russian Federation, and to the east on April 29th. The following day, it blew over to the Sumy Region in Ukraine and Romania, and on May 1st to May 3rd the plume changed direction for the 5th time, heading toward the Ukraine, across the Black Sea, and to Turkey. Finally, the cloud ended its deadly journey in Western Ukraine, Romania, and Moldavia.

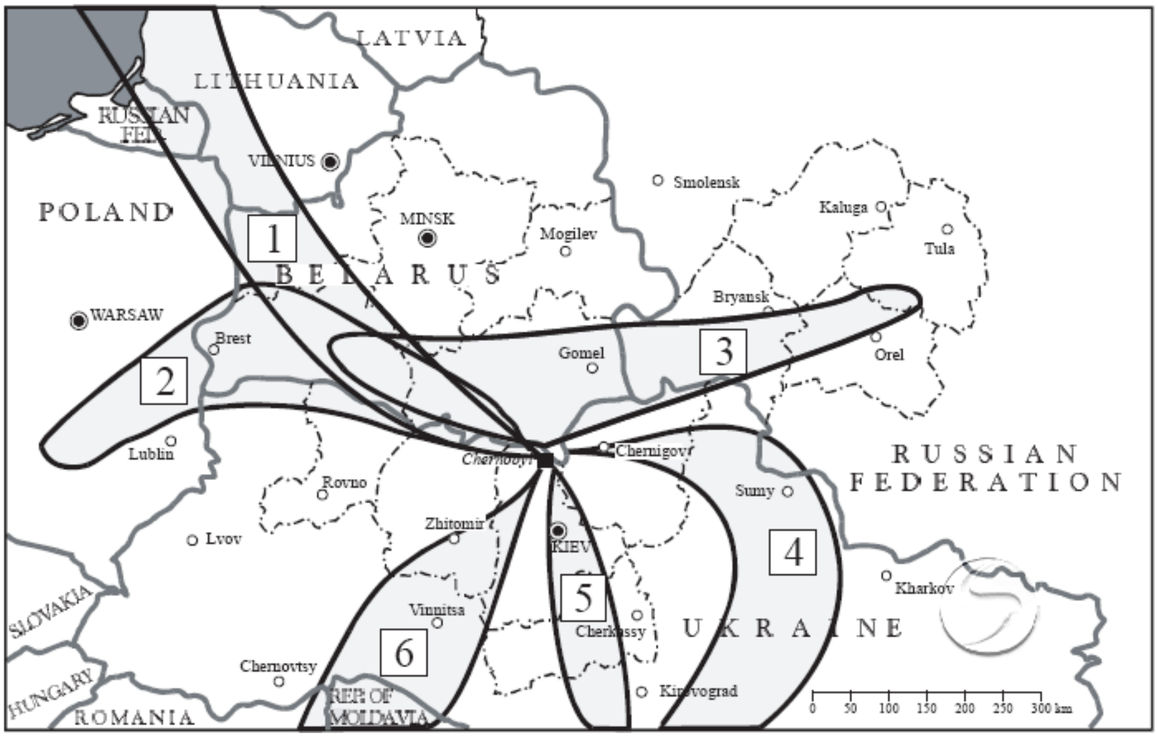


Fig. 9 Directions of Radioactive Plume. "Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience: Report of the Chernobyl Forum Expert Group "'Environment.'" Radiological Assessment Report Series. 2006. 20 September 2009. International Atomic Energy Association, Vienna Austria. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1239_web.pdf.

Precipitation patterns also determined the extent of contamination in Belarus. According to Mycio, many Soviet newspapers reported that Belarus received heavy doses of radionuclide deposition due to heavy rainfall on April 28 (76). The precipitation passed through the massive plume and formed radioactive rain that fell on Belarus. A map of the average precipitation intensity in (mm/h) for Belarus was produced by the IAEA Chernobyl Report (22). Figure 10 shows that on April 29, the precipitation in Gomel averaged 0.2-0.5 mm/h. According to the previous map, the radioactive plume was still over the city during that time. Thus, Gomel received radioactive rain on that day. Figure 10 also shows that the capital city of Minsk experienced rains of greater than 5 mm/h and to the west, the cities of Pinsk and Lida average 1-5 mm/h of rain. Although the contaminated air mass had passed Pinsk, Lida, and Minsk by April 29th, remnants of the initial north-west drift on April 26, may have brought radioactive rain to these areas also.

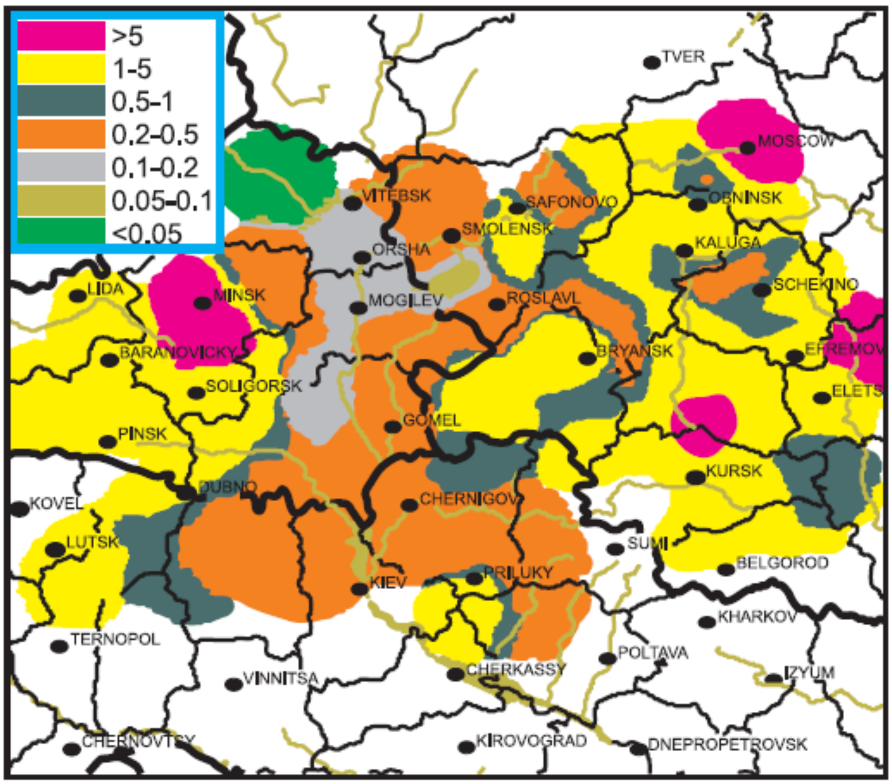


Fig. 10 Average Precipitation mm/h on April 29, 1986. "Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience: Report of the Chernobyl Forum Expert Group "'Environment.'" Radiological Assessment Report Series. 2006. 20 September 2009. International Atomic Energy Association, Vienna Austria. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1239_web.pdf.

Contamination of Land and Evacuation:

After the disaster, the government of Belarus adopted a set of relocation and management guidelines for the populations living in contaminated regions. The guidelines are provided by V.K. Savchenko's, "The Ecology of the Chernobyl Catastrophe" and are described below:

Living Zone- No change in living or labor conditions if irradiation consists of a level less than 0.1 rem (1mSv) per year.

Living Zone with Periodic Control-Territories with soil contamination by ^{137}Cs from 37 to 185 kBq/m^2 or from 1 to 5 Ci/km^2. The equivalent dose level for humans should not exceed 1mSv/year or 0.1 rem/year.

Voluntary Relocation Zone- Territories with soil contamination by ^{137}Cs from 185 to 555 kBq/m^2 (1-15 Ci/km^2), by ^{90}Sr from 18.5 to 74 kBq/m^2, and by ^{238}Pu, ^{239}Pu, and ^{240}Pu from 0.37 to 1.85 kBq/m^2. The radiation may exceed 1mSv or 0.1 rem/year.

Relocation Zone- Soil contamination with ^{137}Cs from 555 to 1,480 kBq/m^2, ^{90}Sr from 74 to111 kBq/m^2, and by ^{238}Pu, ^{239}Pu, and ^{240}Pu from 1.85 to 3.7 kBq/m^2. Human irradiation on land contaminated with 15-40 Ci/km^2 may exceed 0.5 rem or 5 mSv/year.

Compulsory Relocation Zone- ^{137}Cs must be greater than 1,480 kBq/m^2 and the additional human irradiation on lands with contamination more than 40 Ci/km^2 exceeds all permissible levels.

Exclusive Zone- 30 km zone surrounding the reactor from where the population was evacuated within the first weeks after the disaster. Access to this area is prohibited for ordinary people.

Following the Chernobyl accident, many areas of Belarus were contaminated. According to figure 11 below, the areas of Brest, Gomel, Mogilev, and Minsk were contaminated with levels between 1-15 Ci/km^2 and more than 15 Ci/km^2. The ^{90}Sr contamination was found mostly within the 30 km exclusion zone, however, certain populated areas outside of this zone have been discovered with ^{90}Sr (Savchnko 11). ^{239}Pu, ^{240}Pu, and ^{241}Pu were also mostly found within 30 km of the plant, however, areas with radioactive plutonium at the level 0.1 Ci/km^2 or more have also been found at greater distances (Savchenko 11).

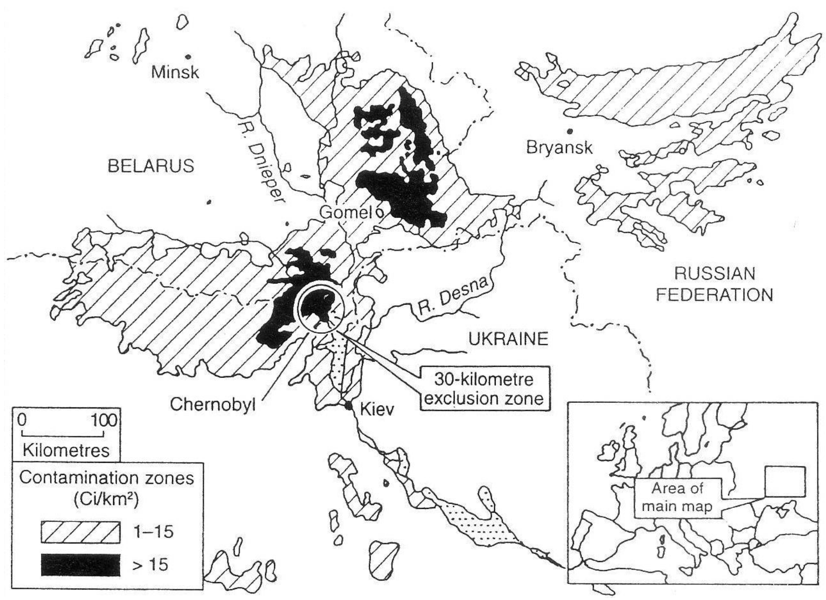


Fig. 11 Spread of Radioactive Caesium from Chernobyl over Land Inhabited by People.

Savchenko, V.K. <u>The Ecology of the Chernobyl Catastrophe: Scientific Outlines of an International Programme of Collaborative Research.</u> Paris, France: UNESCO and the Parthenon Publishing Group, 1995.

The latest IAEA Report on the environmental consequences of Chernobyl found that Belarus experienced roughly the same degree and extent of contamination as table 6 displays below, however. It also notes that 29, 900 km^2 of Belarusian land was contaminated with levels of ^{137}Cs between 37 and 185 kBq/m^2 (23).

Table 6

The Extent and Degree of Radioactive Contamination by ^{137}Cs in Belarus

	Contamination Level (Ci/km^2 (kBq/m^2))			
Ci/km^2 (kBq/m^2)	5-15 (185-555)	15-40 (555-1480)	>40 (>1480)	**Total**
km^2	10,250	4,120	2,150	16,520

Source: Savchenko, V.K. The Ecology of the Chernobyl Catastrophe: Scientific Outlines of an International Programme of Collaborative Research. Paris, France: UNESCO and the Parthenon Publishing Group, 1995.

Areas in Ukraine, Russia, and Belarus were evacuated following the explosions. On Sunday April 27 at 2 pm, the 44,000 inhabitants of Pripyat were evacuated on 1,200 buses and by May 6 the authorities decided to evacuate all people and cattle from an area of approximately 30 km in radius (Smith and Beresford 6). During the spring and summer of 1986, a total of 116,000 people were evacuated from the 30 km zone and from other highly contaminated areas (Savchenko 143). The decision was based on the level of radioactive caesium found in the 30 km exclusion zone, which was greater than 15 Ci/km^2 in about 75% of the exclusion zone in many parts of Belarus (Savchenko 11). People were told to take very few items, because they would be returning shortly, while house pets were forced to stay. What they weren't told was that they would not be allowed to return for an indefinite period of time and that from that point on, their lives would begin anew. Their once welcoming homes and personal belongings were now considered hazards and their pets, radioactive mutants, who would soon be shot and buried in mass graves. Gardens, farms, schools, playgrounds, amusement parks, and in short, life as was once known, had been destroyed.

Additional areas of contamination were later discovered and according to the IAEA 2006 Chernobyl Report, the total area with levels above 0.6 MBq/m^2 (15 Ci/km^2) of ^{137}Cs was 10,300 km^2, including 6,400 km^2 in Belarus, 2,400 km^2 in the Russian Federation, and 1,500 km^2 in the Ukraine (24). This coincides with the measurements found by Savchenko in table 6 above. According to the laws on social protection in the 3 most affected countries, any level of land contamination above 37 kBq/m^2 (1 Ci/km^2) of ^{137}Cs, was considered to be contaminated and in 1995, 1880 people were found to still be living in areas of ^{137}Cs contamination above that level (IAEA, 25). While contamination amounts varied across Belarus, the Gomel and Mogilev oblasts were found to be the most heavily exposed (Mahoney et. al. 2). In the end, approximately 330,000 people were evacuated from the most heavily-affected areas in Europe.

Contamination of Soil:

Studies performed using soil samples from Gomel, Veprin, Lake Svyatoe, and a random selection from Belarus have shown that ^{137}Cs and ^{90}Sr do not migrate into soil horizons found below 15 cm. Figure 12 displays an example that shows the migration of ^{137}Cs and ^{90}Sr in soils found in Gomel, Belarus. Notice that more than 90% of both radionuclides have stayed in the top 0-15 cm layer (Beresford and Smith 42). Figures 13 and 14 below also show that more than 90% of the ^{137}Cs content stayed in the top 0-15 cm later of the soils (Beresford and Smith 42). Moisture helps radionuclides absorb into the top soil horizons where they often get trapped in the soil matrix without further vertical penetration into lower soil horizons (Beresford and Smith 41). This low vertical mobility can be both positive and negative. When radionuclides are trapped in the upper soil levels, the ground water is better protected. Also, remediation may be easier to perform due to their containment in the upper soil horizons. Low vertical mobility, however, also puts the population in greater risk due to agriculture contamination, runoff into nearby drinking water supplies, and through personal contact. Also, when runoff reaches aquatic systems it often gets trapped in bottom sediments. For example, in the year 2000 ^{137}Cs was found in the sediment of Lake Svyatoe in Belarus. From there, radionuclides may be transferred to plants, fish, and organisms, until finally reaching local populations whom rely on fishing as a food source.

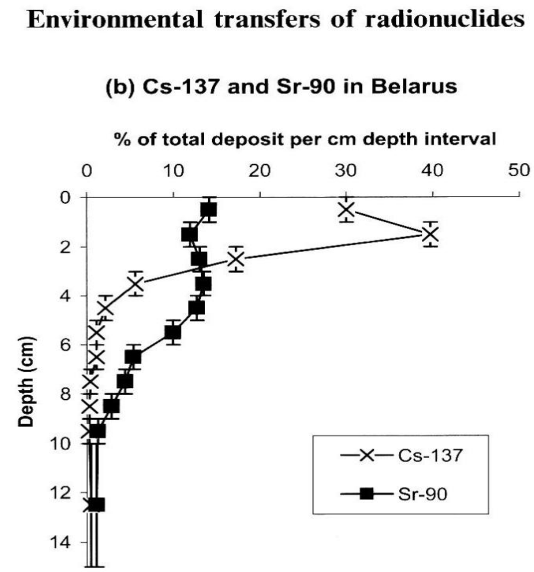
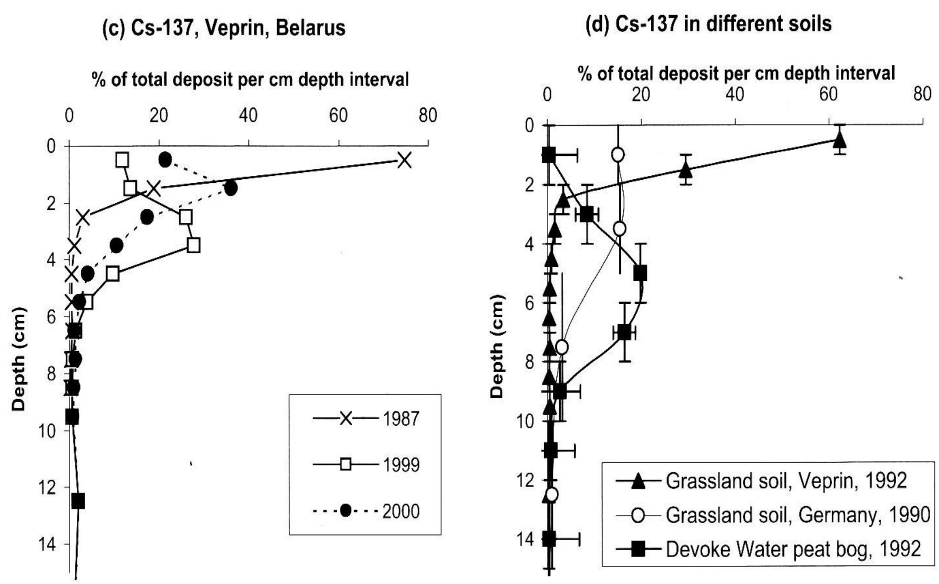


Fig. 12 ^{137}Cs and ^{90}Sr in Soils of Belarus. Smith, Jim and Nicholas A. Beresford, eds.

Chernobyl: Catastrophe and Consequences. Chichester, UK: Praxis Publishing, Ltd., 2005.



Figs. 13 and 14 ^{137}Cs in Soils of Veprin, Belarus. Smith, Jim and Nicholas A. Beresford, eds.

Chernobyl: Catastrophe and Consequences. Chichester, UK: Praxis Publishing, Ltd., 2005.

A study of ^{90}Sr and ^{137}Cs availability within different types of soils showed that 60-100% of ^{90}Sr radionuclides were available for uptake by plants, while 30-73% of ^{137}Cs were found in the fixed state (Savchenko 45). Fixed radionuclides form strong chemical bonds with the soil particles, preventing further migration. The sandy types of soils were found to contain a larger number of radionuclides in exchangeable form, but clay and loam soils had higher proportions of radionuclides in the fixed state (Savchenko 45). This suggests that the ^{90}Sr and ^{137}Cs particles seen in the more sandy soils of figure 12 were in exchangeable forms, allowing for plant uptake, while the sandy-loam soils present in figures 13 and 14 could have contained a mixture of both, exchangeable, and fixed forms.

Contamination of Agriculture:

Subsistence Farmers-

Agricultural contamination created problems for small-scale subsistence farmers. Many villagers in Belarus rely on their small private farm plots for survival (Mould 180). Yet, their older traditions and technologies, poorer economic conditions, and lack of government support for remediation made it difficult to adequately decontaminate their farms in the aftermath of Chernobyl. For example, remediation instructions for milk were only provided to managers and local authorities of government-owned large-scale farms and not to the private farming system of the rural population (Fesenko et. al. 6). Thus, private farmers either continued producing contaminated milk or abandoned their farms completely. According to the guidelines set forth by Soviet authorities, land containing ^{137}Cs levels at or above 37 kBq/m^2 was considered to be contaminated. Between 1986 and 1990, 256,700 ha (2567 km^2) of agricultural land was withdrawn from production due to contamination levels of more than 1480 kBq/m^2 (Savchenko 53). For farmers whom rely solely on this land for survival, this proved to be detrimental because their family-owned plots and livelihoods had now vanished. Other farmers were permitted to keep their plots, but according to Fesenko et. al., a 1987 study found that a total of 1,434,300 ha of Belarusian land that remained in agricultural use was also considered to be contaminated, while 800,800 ha of that land was found in the Gomel area (3). While large-scale collectivized farms were often remediated by the government, small private farmers, on the other hand, usually lacked the means to properly manage their plots. Their farms were often either taken out of production or left in the contaminated state.

Livestock within the 30 km Zone-

Livestock that remained within the 30 km Exclusion Zone from April 26 to May 3 suffered from radiation poisoning. Ruminant animals such as cattle, sheep, and goats typically accumulate large quantities of radionuclides in their bodies (IAEA 131). This is due to their physiology, which requires that they digest plant-based foods for survival. A single cow, for example, can consume 30% of the grass from a 150 m^2 plot of land (IAEA 131). This will result in high levels of internal radiation, since plants are typically known to accumulate radionuclides. Table 7 shows ^{131}I and ^{133}I doses received by cattle that stayed within 30 km of the Chernobyl plant for the 4 day period from April 26 to May 3. According to the IAEA Report, an absorbed dose of 50 Gy is sufficient enough to cause 69% of reduction in function of the thyroid gland and 280 Gy would cause an 82% decrease in thyroid function (132). Based on the results below, the cattle of Belarus, which were further away from the plant, in the 14-35 km range, still suffered extremely high doses at 260 Gy and 90 Gy that were large enough to cause the maladies listed above. In addition to the thyroid problems found in adult cattle, calves born to cows with irradiated thyroid glands, experienced irregular hormonal levels.

Table 7

Doses of ^{131}I to Cattle that Stayed in the 30 km Exclusion Zone from 26 April to 3 May

Distance from the Chernobyl nuclear power plant (km)	Surface activity (10^8 Bq/m^2)	Absorbed dose (Gy)		
		Thyroid	Gastrointestinal tract	Whole body internal
3	8.4	300	2.5	1.4
10	6.1	230	1.8	1.0
14	3.5	260	1.0	0.6
12	2.4	180	0.7	0.4
35	1.2	90	0.4	0.2

Source: "Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience: Report of the Chernobyl Forum Expert Group "'Environment.'" Radiological Assessment Report Series. 2006. 20 September 2009. International Atomic Energy Association, Vienna Austria. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1239_web.pdf.

Permissible Levels of Contamination-

In 1986, the USSR Ministry of Health introduced radiation limits for the period between 1986 and 1991. The limits were set relatively high and they may have caused unnecessary health ailments in the affected populations. The temporary whole body dose limit was set at 173 mSv but, according to the World Nuclear Association, an international nuclear industry forum, the lowest level at which any increase in cancer clearly becomes evident is 100 mSv/year. Therefore, under the USSR Ministry of Health standards, the population may have accumulated dangerously high levels of radiation during that time frame.

The maximum allowable contamination levels for foodstuffs were also developed. They are listed in table 8. The table shows that ^{131}I and all beta-emitters were of primary concern in the early period of 1986. Later, in 1987 ^{134}Cs and ^{137}Cs combined were more of a focus, and in 1991 ^{90}Sr maximum threshold levels were also established. The reason, these particular radionuclides were chosen was due to many factors. As discussed earlier, ^{131}I is taken up by the thyroid gland, caesium radionuclides follow the pathways of potassium and are delivered to soft tissues such as muscle, and ^{90}Sr is deposited in hard bone tissue, following the path of calcium in the body. Temporary maximum permissible levels of ^{90}Sr, ^{137}Cs, and ^{131}I were also set relatively high.

The 1986 radioiodine limitations in milk developed by Soviet authorities greatly exceeded the World Health Organization (WHO) limitations. The WHO recommends a limit of 2000 Bq/L of milk for adults and 1000 Bq/L of milk for children for radioiodine contamination during emergency situations (Medvedev Z. 111). These levels are only permissible for short-term periods and may not be exceeded without putting the population at much greater risk. The Soviet authorities, however, set the maximum permissible level of radioiodine in milk at no more than 3,700 Bq/L, a significantly higher amount than the WHO recommendation. Perhaps the increase of thyroid cancer incidence was a result of this higher threshold. Z. Medvedev also believes that the total daily radionuclide intake levels were set too high. They were 7,400 Bq for ^{131}I, 370,000 Bq for ^{137}Cs, and ^{90}Sr (Medvedev Z. 112). Perhaps, the Soviet authorities felt that they would rather expose the population to higher levels of contamination than risk the occurrence of a possible food crisis.

Table 8

Temporary Permissible Levels (TPL, Bq/kg) of Radionuclide Concentrations in Food Products established in the USSR (1986-1991)

TPL	4104-88	129-252	TPL-88	TPL-91	
Date of adoption	06.05.1986	30.05.1986	15.12.1987	22.01.1991	
Nuclide	^{131}I	β-emitters	$^{134}Cs + ^{137}Cs$	$^{134}Cs + ^{137}Cs$	^{90}Sr
Milk	370–3700	370–3700	370	370	37
Dairy products	18,500–74,000	3700–18,500	370–1850	370–1850	37–185
Meat and meat products	–	3700	1850–3000	740	–
Fish	37,000	3700	1850	740	–
Eggs	–	37,000	1850	740	–
Vegetables, fruits, potato, root-crops	–	3700	740	600	37
Bread, flour, cereals	–	370	370	370	37

Source: Fesenko, Sergey V., et. al. "An Extended Critical Review of Twenty Years of Countermeasures used in Agriculture after the Chernobyl Accident." Science of the Total Environment 383.1-3 (2007): 1-24.

Highly contaminated foods were often reprocessed into different items. According to Medvedev Z., the levels of ^{134}Cs and ^{137}Cs were high enough in some foods found in Belarus to make them unsuitable for consumption (112). Yet, they were often reprocessed into other items that were believed to be consumed in smaller portions. The radioiodine concentrations in

Belarusian milk often exceeded even Soviet limitations. For example, according to the May 1986 Soviet IAEA Report, south-east Belarus experienced from 0.01 μCi/L for cows milk to 30 μCi/L for cows milk (Medvedev Z. 113). The north-west region of Belarus experienced from 0.055 μCi/L to 90 μCi/L (Medvedev Z. 113). But, despite these amounts, the milk was still being used to produce cheese, butter, and other dairy products. Furthermore, Soviet reports state that 10% of the meat in Minsk, 40% in Gomel, and 20% in the Mogilev and Brest oblasts were above the permissible levels for consumption (Medvedev Z. 112-113). However, the meats were still used to produce sausages, salami, and cured meats (Medvedev Z. 112). Authorities reasoned that since these foods were typically consumed in smaller portions, the populations would not be subjected to an increased risk. Unsuspecting consumers purchased the contaminated foods and rates of consumption went undocumented.

In 1991, USSR separated into different countries, creating Belarus, a separate autonomous nation state. A new policy was then adopted by Belarus allowing up to 1 mSv as an effective annual dose limit per person. The most current action levels put forth by the government of Belarus are from 1999, however. Those policies allow for 100 Bq/L for milk, 37 Bq/kg for infant food, 50-200 Bq/kg for other dairy products, 180-500 Bq/kg for meat and meat products, 150 Bq/kg for fish, 40-110 Bq/kg for fruits and vegetables, no amount is listed for eggs, and 40 Bq/kg are permitted for bread, flour, and cereals (Fesenko et. al. 7). When the new Belarusian standards for agriculture are compared to the Temporary Permissible Levels set forth by the Soviet Union from 1986-1991, the latter values listed in 1999 are much lower and safer.

Certain Belarussian oblasts continue to produce highly contaminated milk today. The next table presents the mean and range of current ^{137}Cs concentrations in agricultural products in the Gomel and Mogilev oblasts. As stated above, the national limit for contaminated milk in Belarus during non-emergency situations is 100 Bq/L (IAEA 40). Table 9 shows that Gomel contains higher ^{137}Cs concentrations in milk than the national limit. Some areas in Mogilev are also currently producing milk that is above national standards. Both areas remain a high priority and appropriate remediation efforts should be implemented. Approximately 15 years after the accident, over 200 Belarusian settlements were found to still be producing milk contaminated by ^{137}Cs above the 100 Bq/L limit (IAEA 40). Those settlements should also be managed accordingly. Furthermore, in 2001 another study concluded that 5 Belarusian settlements were still producing milk contaminated with radiocaesium levels as high as 500 Bq/L (IAEA 41). The populations found in these areas should be monitored and their land managed immediately.

Table 9

Mean and Range of Current ^{137}Cs Concentrations in Agricultural Products across Contaminated Areas of Belarus

(data are in Bq/kg fresh weight for grain, potato and meat and in Bq/L for milk)

Caesium-137 soil deposition range	Grain	Potato	Milk	Meat
Belarus				
>185 kBq/m^2 (contaminated districts of the Gomel region)	30 (8–80)	10 (6–20)	80 (40–220)	220 (80–550)
37–185 kBq/m^2 (contaminated districts of the Mogilev region)	10 (4–30)	6 (3–12)	30 (10–110)	100 (40–300)

Source: "Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience: Report of the Chernobyl Forum Expert Group "'Environment.'" Radiological Assessment Report Series. 2006. 20 September 2009. International Atomic Energy Association, Vienna Austria. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1239_web.pdf.

Water Contamination:

Pripyat River-

The figure below represents a decline of ^{90}Sr and ^{137}Cs levels in the Pripyat River from 1987-2000. The results were derived from a series of monitoring stations that measured concentrations and their total fluxes (IAEA 49). Concentration levels are measured in Becquerels per litre and ^{90}Sr has decreased from ~0.5 Bq/L in 1987 to ~0.4 Bq/L in 2000. According to the IAEA Report, most of this contaminant was found as fuel particles that entered by force following the explosion, and later through runoff from nearby soils (48). ^{137}Cs has shown a more dramatic decrease. It has fallen from ~0.8 Bq/L in 1987 to ~0.06 Bq/L in 2000. Contamination has not decreased further due to both, the continued runoff from nearby soils, and the 30.17 and 28.8 year half-lives of the isotopes. Furthermore, the ^{137}Cs and ^{90}Sr that have entered catchment soils at the bottom of the Pripyat are slowly being transferred to river water through erosion of soil particles and by desorption (IAEA, 49). This finding suggests that decontamination would require collection and relocation of contaminated catchment soils.

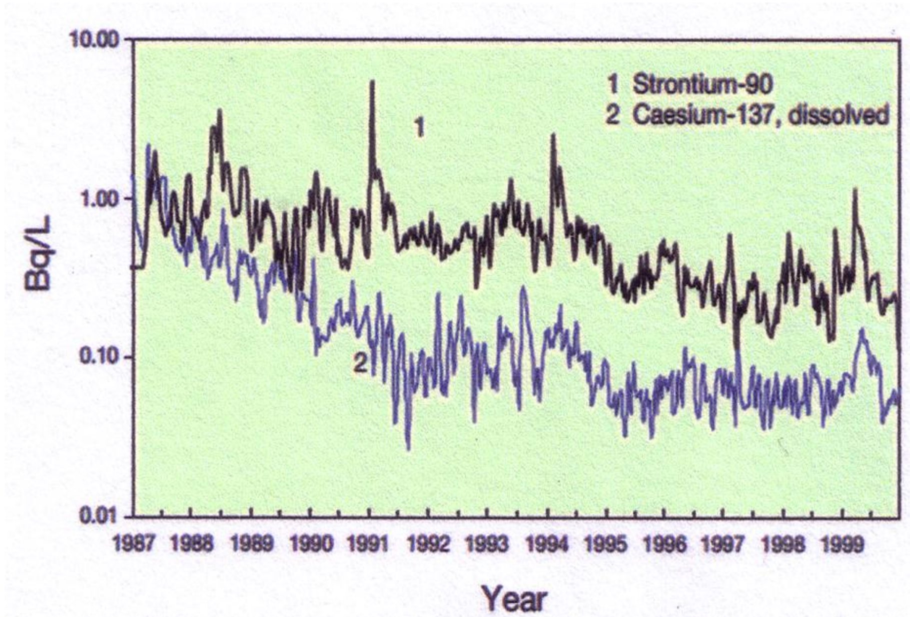
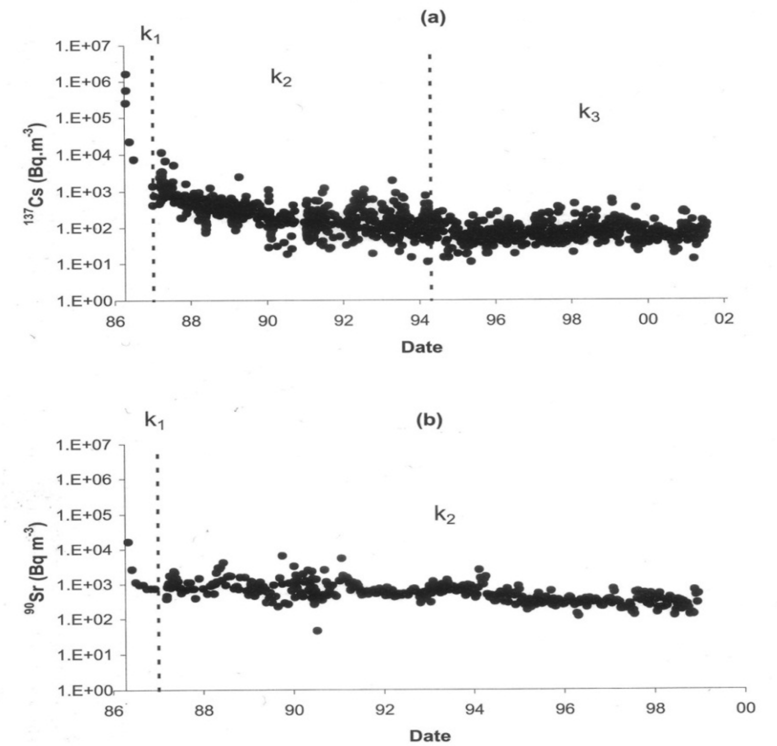


Fig. 15 Average Monthly ^{90}Sr and ^{137}Cs Concentrations in the Pripyat River.

"Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience: Report of the Chernobyl Forum Expert Group "'Environment.'" Radiological Assessment Report Series. 2006. 20 September 2009. International Atomic Energy Association, Vienna Austria. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1239_web.pdf.

The graphs below are another illustration of the declining trend of ^{137}Cs and ^{90}Sr in the Pripyat River. Graph (a) indicates that ^{137}Cs levels have fallen from ~1.E+06 (Bq.m^{-3}) in 1986 to ~1.E+01 (Bq.m^{-3}) in the later part of 2001. Graph (b) also displays a decrease in ^{90}Sr, ranging from ~1.E+04 (Bq.m^{-3}) in 1986 to ~1.E+03 (Bq.m^{-3}) in ~1999. The values presented have been derived by modeling time changes in the radionuclide contamination of the Pripyat River, which use a series of exponential functions. For ^{137}Cs and ^{90}Sr, the radionuclide concentration (Bq.m^{-3}) as a function of time is found through the use of a formula that incorporates the decay constant, radionuclide deposition to the catchment, radionuclide-specific constants, effective ecological half-lives, wash-off processes, soil fixation and redistribution, and equilibrium (Smith, et. al. 144).



Figs. 16 and 17 Changes in ^{137}Cs and ^{90}Sr Concentrations in the Pripyat River. Smith, Jim and Nicholas A. Beresford, eds. Chernobyl: Catastrophe and Consequences. Chichester, UK: Praxis Publishing, Ltd., 2005.

Both the IAEA and the Smith figures support the conclusion that the ^{137}Cs and ^{90}Sr levels have declined since 1986, but are still prevalent in the Pripyat River. Despite the different methodologies used, both studies displayed a sharper decrease in ^{137}Cs and a lower decrease of ^{90}Sr. The IAEA study found that ^{137}Cs has decreased by ~0.74 Bq/L in 13 years since the accident and the Smith study presented a decrease of ~1.E+05 (Bq.m^{-3}) in ~15 years. When these values are compared to the declines in ^{90}Sr, ~0.1 Bq/L in 13 years in the former study, and ~1.E+01 ($Bq.m^{-3}$) decline in 13 years in the latter, one can see that although both have shown signs of decline, ^{137}Cs has clearly decreased more drastically.

Dnieper and Pripyat Rivers-

Although ^{131}I contamination in the Dnieper and Pripyat Rivers appears to have been significantly elevated immediately following the disaster, the levels are showing signs of steady decrease. The table below shows ^{131}I contamination in both rivers, starting before the accident of April 1986, to May 1987. The results are displayed in 2 forms of measurement, microCuries per litre and Bequerels per litre. Taking the latter form as an example, the data displays a1109.963 Bq/L difference between the time prior to the accident and 7 days later on May 3, 1986. The IAEA Report has also discovered that the maximum concentration of ^{131}I activity in the Pripyat River was 4440 Bq/L (49). The spike totaling 1,110 Bq/L below and the IAEA results suggest that these measurements were performed during a similar time frame. The levels then drastically decline to 1106.3 Bq/L by mid-June, probably mainly due to the short 8.04 day half-life of the radioisotope. By May 1987, the values nearly return to the background level.

Table 10

^{131}I Levels in the Dnieper and Pripyat Rivers.

Date	Contamination (μCi/litre)	(Bq/litre)
Before April 1986	1×10^{-6}	0.037
Maximum on 3 May 1986	3×10^{-2}	1,110
Mid-June	1×10^{-4}	3.7
May 1987	1×10^{-5}	0.37

Source: Mould, R.F. Chernobyl Record: The Definitive History of the Chernobyl Catastrophe. London: Institute of Physics Publishing, 2000

The contamination in the Dnieper River is characterized by 2 main trends. According to Savchenko, the concentration of radionuclides increases with water flow (15). As a result, as the Dnieper flows through Belarus and Russia at its north end, the levels are decreased. But, as the river flows south, to Ukraine, through the Kanev and Kremenchug Reservoirs, and ultimately into the Black Sea, radionuclide concentrations increase. This phenomenon naturally decontaminates the river for the countries of Belarus and Russia, while putting extra strain on the countries to the south. Studies have also found that deeper waters typically contain higher levels of contamination than surface waters (Savchenko 15). This may open certain areas of the river, where contamination has settled in deep waters, for uses like, boating and fishing.

One of the main factors contributing to the sustained levels of radioactivity in the Pripyat and Dnieper Rivers is the location of radioactive waste sites. There are approximately 800 radioactive waste sites that were created immediately following the accident and placed near both rivers (Mould 205). Their locations, near 2 prime sources of water that serve many cities, are a great risk and an example of the improper engineering preparations during the post-accident phase. Other examples of insufficient planning are the disposal sites that were formed in sandy soils in '2 to 3.5m deep trenches with no isolating covers or liners (Smith, et. al. 11). The lack of protective barriers means that radiation is not adequately confined to the designated site. Radioactive leaching and contamination of the nearby environment may, therefore, easily occur. One study has found that the total water volume that has accumulated inside the radioactive waste sites along the Dnieper and Pripyat equals approximately 1 million m^3 with the total activity levels approaching 15 PBq (Mould 205). The fluid state and proximity of the contaminated sites to the major rivers heightens the chance that these water bodies will become contaminated. ^{90}Sr has been discovered in levels ranging from 100 to 1 million Bq/L and from 1000 to 100 000 Bq/L near the storage sites (Mould 205).

Groundwater-

Groundwater contamination has occurred largely due to the construction and placement of faulty waste disposal sites. The French-German initiative for the Chernobyl Forum Report has also demonstrated that certain temporary radioactive waste facilities that were initially constructed during the post-accident phase, have a significant influence on groundwater transport (157). Radioactive debris, as well as trees from the "Red Forest" near the reactor site were buried in a series of unlined, shallow trenches near aquatic systems and groundwater aquifers (Smith, et. al. 179). The heaps of waste have accumulated large quantities of water. Studies have shown that transfer of toxins into groundwater supplies occur mostly in flooded and partially flooded trenches like the examples described in the section above (IAEA 157). As a result, ^{90}Sr activity in the groundwater located in the exclusion zone, near the waste disposal sites, reached levels of 1,000 $Bq1^{-1}$ (Smith, et.al. 179). According to the nation's temporary permissible levels for ^{90}Sr in drinking water, which were 3.7 Bq/kg, the groundwater amounts in the exclusion zone are unfit for consumption. Without proper engineering features such as containment vessels and barrier walls, the waste disposal sites are especially risky and inadequate. Furthermore, the toxins have increased mobility in the presence of water, which stresses the importance of separating the waste from all aquatic sources.

Contamination of Forests:

Resources-

Belarus suffered from high levels of contamination that created a negative impact on forest resources. According to Savchenko, 1/4 of the forested area, or roughly 1.7 million ha (17, 000 km^2) was contaminated; 188,000 ha (1,880 km^2) were found to be situated in a high zone, ranging between 555 and 1,480 kBq/m^2 (37). Gamma radiation was one form of pollution and studies have shown that 80% it came from ^{137}Cs (Savchenko 37). Gamma rays are more dangerous than alpha and beta particles because they have greater penetrating power and can therefore, cause more damage to living tissue. Soil profiles located in a Scots Pine forest near Gomel, Belarus confirms the earlier findings of this report. It shows that between 1992 and 1997 the ^{137}Cs was concentrated in the top 0-15 cm layers of soil and ranged from 200-2650 Bq/kg (IAEA 43). This makes it possible for forest goods such as berries, mushrooms, trees, plants, and animals to easily uptake the ^{137}Cs. In fact, the 2003 Chernobyl Forum Report has discovered that over the past 2 decades, particularly high ^{137}Cs concentrations have occurred in mushrooms, berries, and game fond in Belarusian forests (25). Traditionally, the population of Belarus has relied on forest goods for survival, but the large quantity of ^{137}Cs found in the radioactive plume, its uptake by forest goods, and its longevity in the ecosystem, has compromised the residents' environment and health.

Wildlife-

Animals are exposed to radiation very much like humans are, by 3 different routes. First, they can inhale radiation into their lungs by breathing radioactive dust, smoke, or gaseous toxins (Moller, et. al. 202). Once inhaled, the particles settle into the lung tissue where they will remain for an indefinite period of time. This action takes place in both humans and animals, and has been associated with mostly β and α particles (Moller, et. al. 202). Many of the key contaminants that were dispersed over Belarus contained both β and α radiation. This includes the plutonium isotopes, which have an indefinite half-life, and if inhaled will continue emitting β and α radiation for the remainder of the organism's life. The second form of exposure to wildlife is ingestion by swallowing contaminated foods and other sources (Moller, et. al. 202). Again, β and α particles are the greatest concern because strontium and plutonium are easily absorbed into the digestive system and internal organs; they are also easily fixed into bones, teeth, and liver tissues (Moller, et. al. 202). Once ingested, the particles emit large amounts of energy to the entire digestive system and to surrounding tissues, causing DNA, possible mutations, and other damage to the cell tissue. Again, long-lived isotopes such as radiostrontium and plutonium are the greatest concern due to their persistence, absorption, and fixation abilities. The final mechanism for exposure to wildlife is direct or external exposure through contact with γ or β emitters (Moller, et. al. 202). Most of the key radionuclides from the post-accident phase included γ or β rays, a skin penetrating form of radiation that can generate burns, eye damage, and skin damage. Alpha radiation is not as great of a concern because of its inability to penetrate the skin, however. According to the U.S. Environmental Protection Agency, organisms with cuts or wounds are at risk for injury. Gamma and beta rays, on the other hand, are a special concern due to their ability to corrupt the outer body tissues, like the epidermis, while penetrating the skin to impair internal organs and tissues. In fact, iodine, strontium, caesium, ^{241}plutonium, and ^{241}americium, and almost every main Chernobyl radionuclide contains γ and/or β radiation. This suggests that many of Chernobyl's victims have or will suffer from direct or external radiation from γ or β particles.

Contact with ionizing radiation can negatively impact a living cell in several ways. The affected cell may experience DNA damage. This occurs when ionizing radiation causes breaks in the DNA strands (Ron, S30). This more commonly occurs with mid-to-high levels of ionizing radiation, however. Irreparable DNA damage has also been associated with low-level doses. Irreparable damage can result in transcriptional or replicable errors and may lead to viral infections, cancer, and premature aging. Other effects can be deviations in development processes, metabolic activity, and morphogenesis (Savchenko, 105). Morphogenisis is a biological process that allows an organism to develop its shape. When an organism's genetic makeup is compromised with radiation, the organism may develop abnormally. For example, an animal may develop a tumor; it may be born without a vital organ, or with an enlarged limb.

Mutations like these occur due to a change in the DNA sequence of a cell's genome. This alters the product of the gene and creates mutated organs or may prevent the gene from functioning normally.

Mutations and cytogenetic effects have shown signs of increase since the accident, in both animals and plants, living in the Polissya Region. Cytogenetics is a branch of genetics that studies the structure and function of the cell, especially in chromosomes. In their paper entitled, "Biological consequences of Chernobyl: 20 years on," Drs. Møller and Mousseau compile 33 studies that investigate mutations and cytogenetic effects on irradiated plants and animals in the Polissya Region. Plants and animals were also collected from control areas that contained little or no radiation, to be able to test the effects of the Chernobyl fallout more accurately. The results indicate that there is considerable heterogeneity in the mutations and cytogenetic abnormalities, with 25 of the studies showing an increase in these abnormalities (Møller, et. al. 202). Chromosomal aberrations occur when the normal structure or number of chromosomes in an organism is abnormal. The Møller and Mousseau compilation shows that 9 organisms suffered from various degrees of chromosomal aberration along with various genetic markers. For example, one the most negatively impacted organisms was the mouse (Mus musculus). It contained a number of reciprocal translocations in its genetic structure that increased by a factor of 15 following the accident.

9 studies were also presented, which investigated somatic mutations on certain organisms from the Polissya Region. Somatic mutations are a form of gene alteration that can be passed to the progeny of the mutated cell during cell division. Somatic mutations differ from germ line mutations because they are inherited genetic alterations that occur in germ cells such

as the sperm and egg. 7 out of the 9 organisms included in this compilation showed a significant increase in somatic mutations. One example is the bank vole (Clethrionomys glareolus), which was found to have substitutions in cytochrome b, as-well as mutations that increased by 19%. Other results, reported no significant increase probably due to small sample sizes with low statistical power (Møller, et. al. 202). The significant results should be further investigated to determine what effects the genetic consequences have on the species as a whole and how that changes the integrity and function of the ecosystem that they compose.

The destructive impact of Chernobyl radiation on Scots Pine (Pinus sylvestris) was witnessed in the study above, as-well as an additional study produced by the Academy of Sciences of Belarus, the University of Minsk, and the Division of Ecological Sciences for UNESCO. The former Report finds that Scots pine samples, collected from field populations in the Polissya Forest, had chromosomal aberrations that had increased by a factor of 3 (Møller, et. al. 205). The species was also found to contain a mutation at the enzyme loci that had been increased by a factor of 20 (Møller, et. al. 205). The latter study looked at 30 pine trees from the 30 km zone. Pine trees that had received absorbed doses ranging from 0.4 to 12 Gy could expect to undergo a mutation in the seeds endosperm for 7 allozyme loci at a rate of 10 times higher than the spontaneous mutation rate found in control groups (Savchenko, 107). The similar conclusions make a convincing case that the post-accident radiation significantly damaged the genetic structure of the Scots pine species.

The Gomel and Mogilev oblasts experienced the highest radioactive input in the entire country. Studies have found that plant species found there responded to the excess radiation through various mutations. According to Savchenko, when 7 plant species were tested in the

Gomel and Mogilev oblasts, the results showed an increase in chlorophyll mutation frequency, decrease of seed viability, mass gall formation, asymmetric morphoses of the leaf, abnormal branching, fasciations, dwarfism, tumors, and distortions of the stem (108). For example, the species Salix cinerea and Artmesia cumpestris developed unusually shorter branches with many narrow, mutant leaves that looked more like cones (Savchenko 108). The study also found that the most sensitive species to radiation, producing the greatest variation of mutations, was the Lysimachia vulgaris (Savchenko 108). By comparing the Møller and Mousseau study described earlier to the Savchenko findings, one can see how plants generally respond to excess radiation. Although the variation in the plant species sample size was small, they all however, experienced genetic damage and subsequent mutations.

The image below displays barn swallows (Hirundo rustica) with and without partial albinism living near the accident site. It is a part of the study described earlier by Møller and Mousseaux, which studies the barn swallow population before and after the accident in both contaminated and control areas. The study finds that although partial albinism is normally rare among animals, the frequency of this phenomenon has increased 5-10 fold following the disaster (Møller and Mousseaux 204). This increase is presented in the graph below, which displays the frequency of partial albinism as a percentage before and after the accident, in control and contaminated areas. The graph shows that partial albinism was non-existent before the accident, however. In 1991, the frequency of cases increased substantially to about 15%, while remaining in between the 10-17% mark until 2005. Interestingly, the control and non-effected area also seemed to have increased a small amount (2-5%). This was probably due to the dispersal of radionuclides from polluted to "clean" regions through weather and migration processes.

The findings support the conclusion that excess radiation from the accident caused mutations that in turn, produced partial albinism. How this will affect the barn swallow population in its entirety and the consequences of mating mutants with non-mutants remains to be seen.

Fig. 18 Partial Albinism caused by Mutations in Barn Swallows. Møller, Anders Pape, and Timothy A. Mousseau. "Biological Consequences of Chernobyl: 20 Years on." Trends in Ecology and Evolution 21.4 (2006): 200-207.

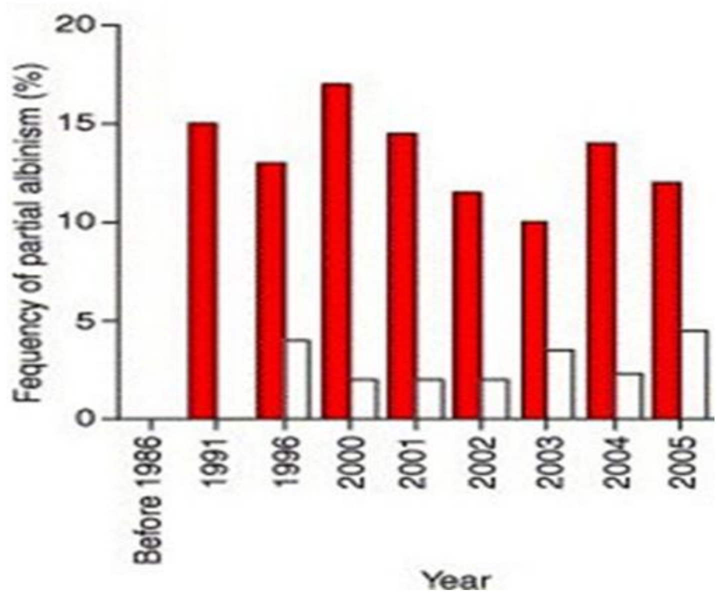


Fig. 19 Frequency of Partial Albinism in Barn Swallows from Contaminated Areas (red) vs. control areas (white) before and after the Disaster. Møller, Anders Pape, and Timothy A. Mousseau. "Biological Consequences of Chernobyl: 20 Years on." Trends in Ecology and Evolution 21.4 (2006): 200-207.

Higher frequencies of bilateral asymmetry were found in several organisms that were located near the accident site. Bilateral asymmetry occurs when there are differences in length between the left and right parts of an organism. A total of 15 species were taken from the contaminated areas near the reactor site and from control areas. The species include 4 plants, 4 insects, 2 fish, 1 amphibian, 1 bird, and 3 mammals (Møller, et. al. 204). The variability of species, taken from several levels of the food web, allows researchers to make a stronger claim regarding the effects of radiation on the ecosystem as a whole. The results revealed higher frequencies of asymmetry in representatives from the polluted sites than from the "clean" areas. Asymmetrical wing length for birds could result in the inability to fly and early death; for amphibians it could create variations in foot and leg length that hinders their ability to swim and jump; and it could make fish incapable of swimming. Furthermore, each organism not only depends on itself for survival, but it also depends on the other ecosystem constituents and the integrity of the community as a whole. For example, mammals consume other animals; birds consume insects; fish eat amphibians; amphibians rely on insects; insect populations are managed by amphibians, birds, and other species; and, everyone relies on plants. The results presented above, coupled with the importance of the species to the ecosystem as a whole, suggests that the Polissya Region should be a high priority for remediation, management, and further study.

Scientists have also found a way to predict which species' DNA is most vulnerable to becoming damaged. Professors Mousseau and Møller analyzed the changes that have occurred in a DNA sequence over time, in the 30 km zone of alienation (Gill 1). This study takes the analysis one step further: Prior studies have shown the prevalence of mutations and cytogenetic effects in wildlife post-accident, while this study explains the likelihood that a particular organism will experience DNA damage and by what mechanism. The mechanism is located within the species' DNA lineage (Gill, 2). With every generation, the pattern of DNA changes, due to an individual's ability to repair DNA damage (Gill, 2). The rate of this change is called the substitution rate; it provides a tool that allows scientists to predict what species are most vulnerable to radiation (Gill, 2). This information adds to the previous study mentioned above that discovered a statistically significant increase in the number of organisms with chromosomal aberrations, somatic mutations, germ line mutations, and other effects. It sheds light on how the structure of DNA determines what species will be more sensitive to the radiation. According to Drs. Møller and Mousseau, brightly colored birds that migrate long distances, like the barn swallow, have weaker DNA repair mechanisms and were most likely to be affected (Gill, 2). The question of why certain species have the required DNA repair mechanism to survive, and others don't, remains a knowledge gap that must be examined.

Certain species have developed a natural defense mechanism in response to the post-accident radiation. According to a reporter from The New York Times, Sindya N. Bhanoo, some plants, found in contaminated areas, were actually flourishing in the soils (1). Researchers from the Environmental Science and Technology Journal and from the Slovak Academy of Sciences wanted to better understand this phenomenon. The former group discovered that this adaptation capability stemmed from alternations in the plants' protein levels (Bhanoo 1). A later study performed by the Slovak Academy of Sciences confirmed this finding. This group grew flaxseeds in contaminated soils near Chernobyl and compared them with flaxseeds grown in non-contaminated soils (Bhanoo 1). The results showed a 5% difference in flaxseeds grown on the former vs. the latter soils (Bhanoo 1). This was interpreted as a natural defense mechanism. In fact, the area near the Chernobyl site and on the border between Ukraine and Belarus has actually become a rich and diverse natural reserve, thriving with various species. In addition to the well adapted plants mentioned in the studies above, other species that seem to have been able to adapt are the Przewalski Horse, an animal believed to be the only living descendant of the wild horse (Discovery 1). According to one Animal Planet article, about 17 Przewalski Horses were introduced to the highly contaminated site in 1998; now the steeds number between 80 and 90, and the area around Chernobyl has become one of the horses' few homes throughout the world (Discovery 1). There are many other examples of thriving wildlife in the zone and the area has become a haven for some species. It is important to continue studying why some species, like the barn swallow, degenerate under these conditions, and why others thrive.

Health Consequences:

Epidemiology:

The effects of radiation on the human body are typically studied using epidemiology. Epidemiological studies have many forms such as cohort studies, case-control studies, and ecological studies. In a cohort study, a particular population that is known to be at risk of radiation exposure is followed either forward in time, or the population is studied in some time past (Ron S31). In a case-control study persons with and without a specific condition are compared, and in an ecological study, a group is evaluated based on existing group and not individual data such as a state cancer or radiation data base (Ron S31). All branches of epidemiology involve identifying a group of interest based on specific criteria that may include geography, age, food and water intake, medical history, and radiation exposure. The subject's geographical history and building of residence may determine the external radiation exposure. To estimate internal radiation a person will often be asked to indicate the type, origin, and consumption rate of their food choices (WHO 20). To check how accurate the dose estimates are, a party from the same group is sometimes provided with a personal dosimeter (WHO 20). The group dose is then compared to this person's dose to check for accuracy. A human's absorbed dose is measured in Sieverts (Sv), in honor of the Swedish radiologist, Rolf Maximilian

Sievert (1896-1966), who studied biological effects of medical radiation.

Radiation Doses and their Effects:

Studies have shown that a moderate to high level radiation dose can cause cancer, genetic mutations, and other damage to living tissue, while the effects of low-level radiation, remains uncertain. These results have been concluded largely through animal testing and by studying the health records of the surviving victims from Hiroshima and Negasaki. According to table 11, low-level radiation is considered to be ~3.1 mSv/year, moderate radiation is considered to be ~100 mSv/year, and 1000 mSv or more per year is considered to be high. The absence of conclusive data on low-level radiation is attributable to several factors including the absence of a control group, the large number of people required for an epidemiological study of this sort (millions of people), the difficulty associated with determining exactly what form of radiation caused the damage, and the complications associated with other carcinogens present in our everyday lives such as cigarette smoke, asbestos, chemicals, and ultraviolet light (IAEA). The effects of mid to low-level radiation are better known and the Chernobyl Forum study has found that a human absorbed dose of 1 Gy is sufficient enough to cause acute radiation syndrome or ARS (12).

The 1986 mean thyroid, mean external, and mean internal effective doses to the evacuated populations from Belarus were recorded. The estimated mean thyroid dose was 1 Gy, which according to the Chernobyl Forum is sufficient enough to cause acute radiation syndrome (ARS). The mean external dose was 0.03 Sv and the mean internal effective dose was 0.006 Sv

(WHO 20). Doses have also been recorded from 1986-1995 for the 6 million residents living in contaminated regions of Belarus that were not evacuated. They contained a mean internal exposure dose of 5 mSv and a mean external exposure dose of 3 mSv (WHO 20). According to the World Nuclear Association, that is roughly the level of radiation a person could expect to receive from background sources, however. One should also keep in mind that the numbers given are means, so there could have been substantially higher doses in some areas.

Table 11

Comparative Radiation Doses and their Effects

1 mSv	Total dose limit introduced by Government of Belarus in 1991
2.4 mSv/yr	Average dose to US nuclear industry employees.
3.1 mSv/yr	Average dose received from background radiation (Smith and Beresford, 28)
Up to 5 mSv/yr	Typical incremental dose for aircrew in middle latitudes.
9 mSv/yr	Exposure by airline crew flying the New York – Tokyo polar route.
20 mSv/yr	Current limit (averaged) for nuclear industry employees and uranium miners.
50 mSv/yr	Former routine limit for nuclear industry employees. It is also the dose rate which arises from natural background levels in several places in Iran, India and Europe.
100 mSv/yr	Lowest level at which any increase in cancer is clearly evident. Above this, the probability of cancer occurrence (rather than the severity) increases with dose.
173 mSv	The USSR Ministry of Health Temporary Whole-Body Dose Limit from 1986-1991
350 mSv/lifetime	Criterion for relocating people after Chernobyl accident.
1,000 mSv cumulative	Would probably cause a fatal cancer many years later in 5 of out of every 100 persons exposed to it (*i.e.* if the normal incidence of fatal cancer was 25%, this dose would increase it to 30%).
1,000 mSv single dose	Causes (temporary) radiation sickness such as nausea and decreased white blood cell count, but not death. Above this, severity of illness increases with dose.
5,000 mSv single dose	Would kill about half those receiving it within a month.
10,000 mSv single dose	Fatal within a few weeks.

Source: "Chernobyl Accident." World Nuclear Association (WNA). 22 December 2009. http://www.world-nuclear.org/info/chernobyl/inf07.html.

Exposure Pathways:

Radionuclides enter the human body through various passages. As discussed earlier, they can be ingested, inhaled, and externally deposited. According to the latest WHO Report, radioiodine was mainly received internally by consuming fresh cow's milk, dairy products, and leafy vegetables (6-7). ^{131}I also travelled into the body by inhalation, though the greatest doses were received by food ingestion (WHO 7). Fig. 20 shows that radionuclides can be inhaled from contaminated air, particles that are deposited onto the surface and later re-suspended, and from deposits onto skin and clothing. External doses were received from contaminated air, deposition onto the skin and clothing, from water bodies, and through contact with sand and sediment. The 91,000 emergency workers from Belarus served from 1986-1989 and suffered from external radiation. According to the National Registry, only 9% had their external radiation doses calculated (WHO 18). The mean for this group was 46 mGy while the median was 25 mGy (WHO 18).

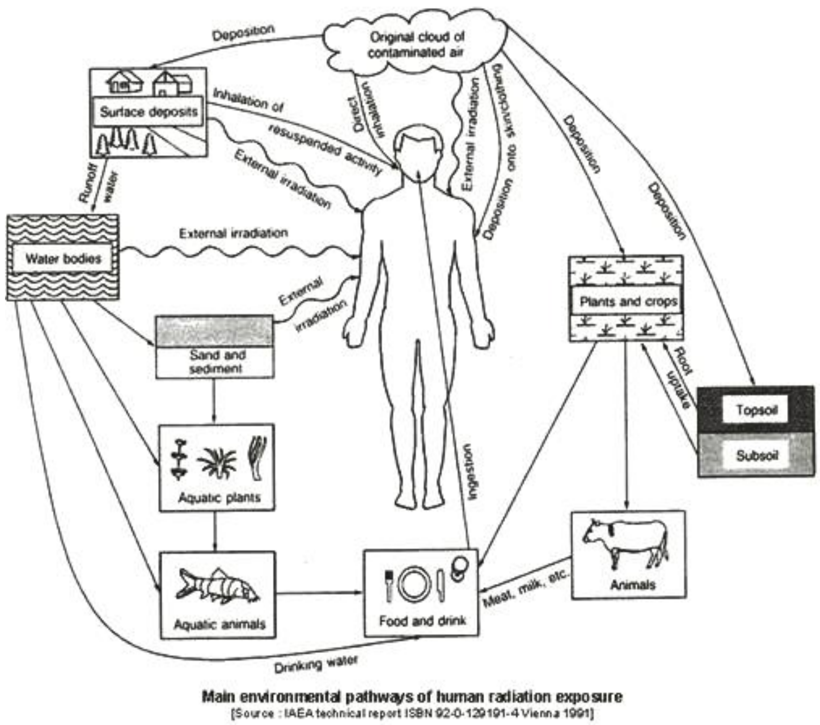


Fig. 20 Radionuclide Pathways. "Chernobyl Accident." World Nuclear Association (WNA). 22 December 2009. http://www.world-nuclear.org/info/chernobyl/inf07.html.

Background Radiation:

Chernobyl in Context-

When studying the health consequences following Chernobyl, it is important to consider the background radiation that is already present in the environment. Smith and Beresford have shown that the mean annual dose that a human receives from natural background radiation and x-ray procedures is 3.1 mSv/year (28). This annual dose was broken down as follows:

Table 12

Background Radiation Sources

Cosmic rays = 0.38 mSv/year

Cosmogenic radionuclides (mainly C^{14}) = 0.012 mSv/year

Primordial radionuclides: external dose = 0.48 mSv/year

Primordial ^{40}Potassium: internal dose = 0.165 mSv/year

Primordial uranium, thorium series: internal dose = 0.12 mSv/year

Radon 220, 222 (mainly lung irritation) = 1.2 mSv/year

X-Rays = 0.72 mSv/year

TOTAL = 3.1 mSv/year

Source: Smith, Jim and Nicholas A. Beresford, eds. Chernobyl: Catastrophe and Consequences. Chichester, UK: Praxis Publishing, Ltd., 2005.

Cosmic rays are tiny radioactive particles that originate from the sun and from outer space. They are mostly absorbed by the atmosphere, but sometimes transmitted to Earth's surface. Tiny ‘cosmogenic’ particles such as, ^{14}C, ^{7}Be, and ^{3}H are often formed and transmitted to Earth’s surface (Smith and Beresford 29). The mean annual dose that humans can expect to receive from both cosmic rays and cosmogenic radionuclides is relatively small when compared to some doses received in the aftermath of Chernobyl. Primordial radionuclides are next on the list and include potassium, thorium and uranium, which were formed when the universe was created. While thorium and uranium provide mostly external doses, potassium, on the other hand, travels inside the body through foodstuffs such as milk, beef, lamb, poultry, eggs, fish, potatoes, soya, and green vegetables (Beresford and Smith 29-30). Radon is a naturally occurring gas that is formed from the decay of uranium and thorium that is found in soils and rocks. Radon and medical x-rays were mentioned last, however, they together constitute more than half of the total background radiation that a person can expect to receive in one year.

Disease Incidence:

ARS-

ARS occurred in a small group of Chernobyl emergency workers (liquidators) and operators. According to Baverstock and Williams, about 150 people were treated for ARS; 28 died shortly after and 20 others have died since (1313). The Chernobyl Forum Study has put forth similar findings that found ARS was diagnosed in 134 emergency workers, while 28 died from the syndrome (14). As discussed earlier, ARS usually occurs when a human accumulates an absorbed dose of 1 Gy. It is characterized by 4 stages: The prodromal stage, the latent stage, the overt or manifest illness stage, and finally recovery or death (MedicineNet). During the prodromal stage, the patient usually experiences diarrhea, nausea, and vomiting from minutes to days following exposure (MedicineNet). During the latent stage, the person looks and feels healthy but, will soon experience symptoms based on his or her particular type of ARS syndrome (MedicineNet). The 3 types of syndromes are bone marrow syndrome, gastrointestinal (GI) syndrome, and cardiovascular (CV)/nervous system (CNS) syndrome (MedicineNet). Bone marrow syndrome offers the greatest chance for survival, while GI, CV, or CNS syndromes are the most severe. In the 4th and final stage, a person whom is diagnosed with ARS will either recover, which can take up to 2 years, or die within several months.

Svetlana Alexievich has composed a collection of personal interviews with the victims of Chernobyl. She begins her book with the powerful testimony of a young window whom provides a detailed look into the devastating effects of ARS. Lyudmilla Ignatenko was the wife of Vasily Ignatenko, a deceased fireman whose brigade arrived first at the reactor following the explosions. The interview graphically portrays the gradual debilitation of her husband that had been suffering from ARS. She describes how during the 3rd stage, the overt/manifest illness stage, her husband was "producing stool 25 to 30 times a day…with blood and mucous (Alexievich 15). She recalls his skin, "cracking on his arms and legs [and] he became covered with boils (Alexievich 15). Everyday he degenerated more and more and death came slowly and painfully. His hair had begun to fall out and "when he turned his head, there'd be a clump of hair left on the pillow (Alexievich 15). He laid at Moscow Clinic Number 6, the radiation specialty clinic where all ARS patients would go. Everyday there would be news that another fellow fireman from Vasily's brigade had died. His skin was disintegrating rapidly and every touch worsened the condition. She said that when she touched him there were pieces of skin on her hands that stuck to her (Alexievich 17). Lyudmilla covered Vasily with a thin sheet daily, but by evening, the sheet was covered in blood (Alexievich 17). Vasily was experiencing the extreme effects of ARS and he was deteriorating right before her eyes. All 6 of the firemen from his shift: Bashuk, Kibenok, Titenok, Pravik, Tischura, and Vasily died at Clinic Number 6.

Mental Health-

The WHO Report finds that mental health ailments have been the largest human-health consequence of the nuclear disaster to date. Mental anguish is widespread and was a result of a complex web of events and long-term difficulties such as relocation, an unstable economy, health consequences of current and most-likely future generations, and other stressors that resulted in physical and emotional imbalance (WHO 95). With respect to stress symptoms, the WHO study has witnessed increased levels of depression, anxiety, and medically unexplained physical complaints in the exposed populations when compared to controls (WHO 95). Unexplained physical complaints can arise from the anxiety and stress caused by societal, health, and general disturbances mentioned earlier. For example, when patients are under stress, they may falsely perceive themselves as being more ill than they are in reality. Other studies have reported that exposed populations expressed anxiety levels twice as high as control groups while being 3-4 times more likely to report several unexplained physical symptoms and poor health in general (WHO 93). Mental anguish could have also been exacerbated by the lack of knowledge and subsequent false rumors that circulated immediately following the accident. Also, if perhaps the language used to describe the exposed population was changed from “victim” to “survivor,” the population would have felt more positive about their situation.

Thyroid Cancer-

^{131}I was readily absorbed by the thyroid gland, causing thyroid cancer in a large number of people in Belarus. In order to function, the thyroid gland absorbs stable iodine from the bloodstream, but it is incapable of distinguishing been safe and unsafe types of iodine (WHO 23). So, when non-stable iodine became available, it too got incorporated into thyroid function. To exacerbate the problem, many Belarusians suffered from iodine deficiency and developed goiters because of it. These people were in greater risk for developing thyroid cancer, due to the large availability of ^{131}I and their body's need for it (Mould 78). Children were also at greater risk due to their thyroid glands still developing and requiring greater amounts of iodine. According to the most recent WHO Report on the health consequences of Chernobyl, the thyroid has been found to be one of the most susceptible organs to cancer induction by gamma radiation (WHO 23). This poses a problem, since unstable iodine is known to produce gamma radiation. The study below looks at the cases of thyroid cancer that have been reported to the National Thyroid Cancer Registry of Belarus and finds that there has been an increase in cases per year from 1986 to 1999. The birth cohort is composed of 2.7 million people that are born from 1 January 1968 to 31 December 1985, or ages 17 and under. The number of cases per year is graphed against the time of operation from 1 January 1986 to 31 December 1999. According to figure 21, by 1999 there were a total of 1292 thyroid cancer cases in all of Belarus and 569 in Gomel. The number in Gomel constitutes nearly half of the cases reported in the entire country of Belarus shows that it is a highly contaminated oblast. In Belarus, the annual cases per year increased from about 10 cases per year between 1986 and 1988, to over 100 cases in 1992, and 185 cases in 1999 (Jacob Peter et. al 216). The increase with time shows that cancer does not occur immediately following exposure and does possess a latency period, taking time to develop. According to recent estimates of the exposure-independent baseline incidence, about 2/3rds of the cases in Belarus were due to the Chernobyl accident (Jacob Peter et. al 216).

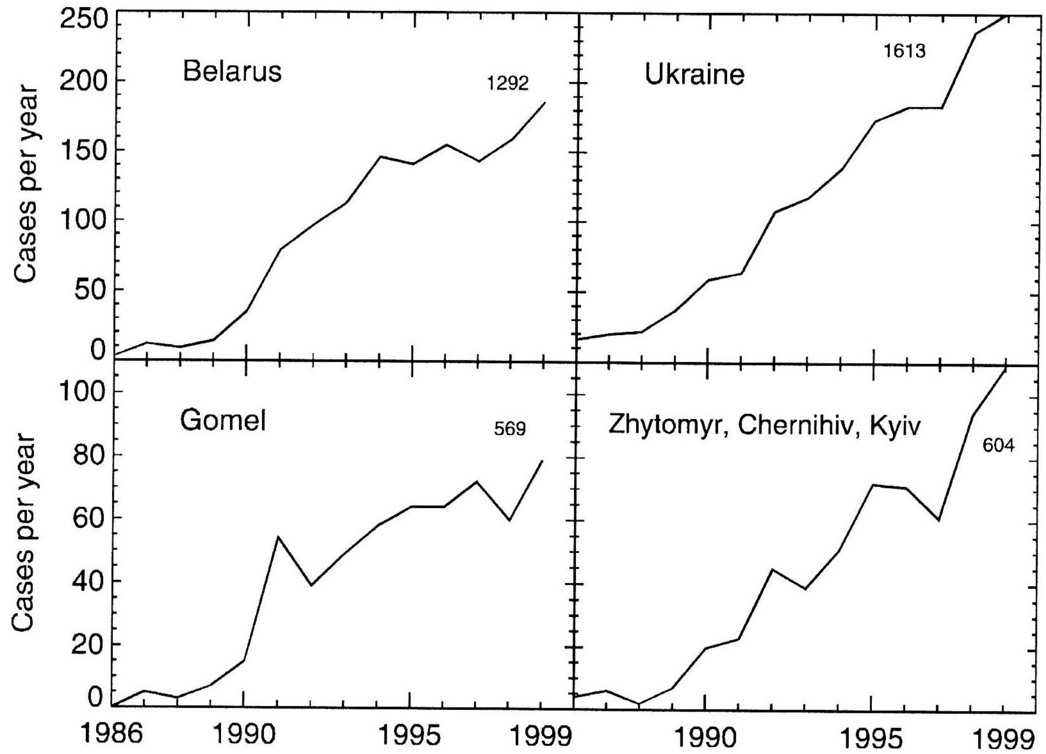


Fig. 21 Thyroid Cancer Cases that have been reported to the National Thyroid Cancer Registries for the Birth Cohort 1 January 1968 to 31 December 1985 and for the time interval of Operation from 1 January 1986 to 31 December 1999 for Cases Witnessed. The numbers in the figure give the cumulated number of cases. Jacob, Peter, et. al. "Comparison of Thyroid Cancer Incidence after the Chernobyl Accident in Belarus and in Ukraine." International Congress Series 1234 (2002): 215-219.

Figure 22 located below displays the female and male cancer cases reported for the period 1986-1999 to the Gomel oblast Registry, for the birth cohort 1968-1985, which amounts to 0.24 million males and 0.23 million females. The figure shows that the female annual cases were about 2 times greater than male cases (Jacob Peter et. al 218).

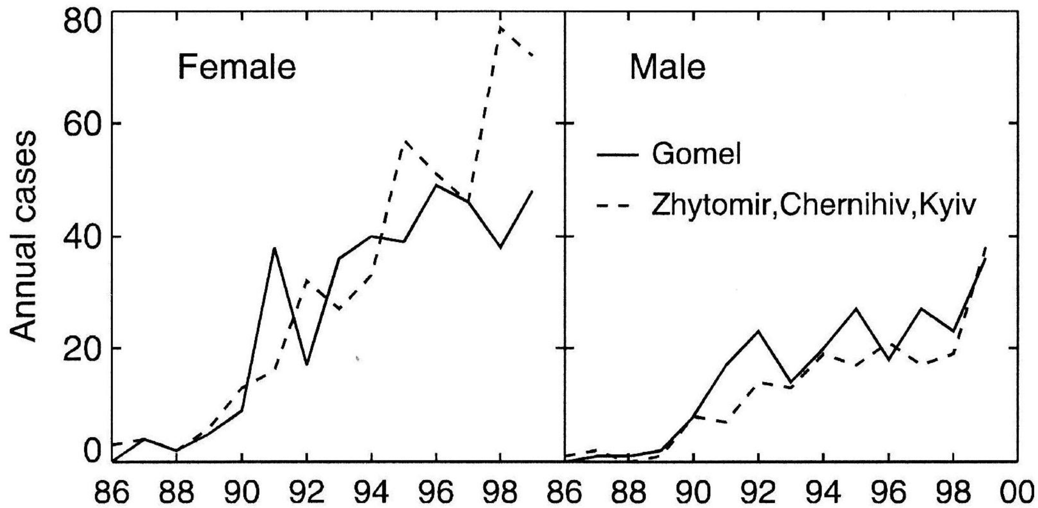


Fig. 22 Number of Female and Male Thyroid Cancer Cases reported for the period 1986-1999 to the Registries for Birth Cohort 1968-1985 of Gomel (0.24 million males and 0.23 million females), Zhytomyr, Chernihivv, and Kyiv including Kyiv city (0.95 million males and 0.92 million females) in the Ukraine. Jacob, Peter, et. al. "Comparison of Thyroid Cancer Incidence after the Chernobyl Accident in Belarus and in Ukraine." International Congress Series 1234 (2002): 215-219.

The birth cohort registry for years 1968-1985 in the Gomel oblast was also used in the study below to assess the number of thyroid cases during various operation ages. The thyroid cancer incidence in Gomel was highest for the age at operation of 10 years in the period 1992-

1995, and 14 years in the period 1996-1999 (Jacob Peter et. al 218). Since ages 0-30 were used in this particular study, it provides an opportunity to compare thyroid cancer incidence in young children and young adults. The amount of children is much higher than young adults. This is probably due to their thyroid glands still developing and requiring greater amounts of iodine. Also children probably consume higher levels of fresh milk that typically harbors large quantities of ^{131}I. The iodine is absorbed from the bloodstream to produce hormones that regulate metabolism and energy.

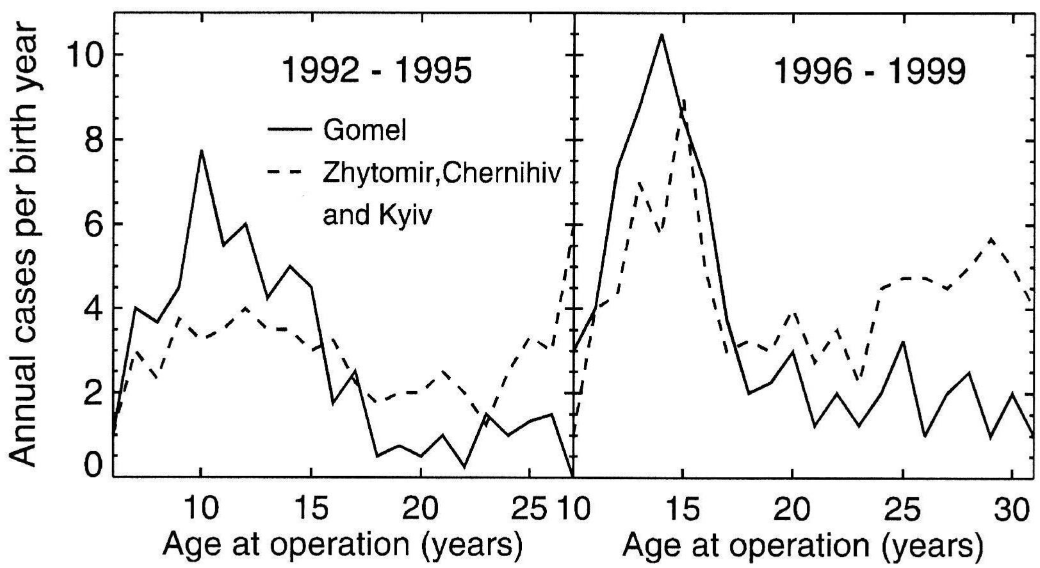


Fig. 23 Number of Thyroid Cancer Cases as a function of Age-at-Operation (years), as reported for the periods 1992-1995 and 1996-1999, to the Registries for the Birth Cohort 1968-1985 of Gomel, Zhytomir, Chernihivm and Kyiv including Kyiv city in the Ukraine.

Jacob, Peter, et. al. "Comparison of Thyroid Cancer Incidence after the Chernobyl Accident in Belarus and in Ukraine." International Congress Series 1234 (2002): 215-219.

The study found below looks at the cohort born from 1 January 1968 to 26 April 1986 that developed thyroid cancer from 1986-2000. The data was taken from the medical history of patients who underwent treatment for thyroid cancer in the Republican Scientific-Practical Center of Thyroid Oncopathology in Belarus; it also uses data from the Belarusian Cancer Registry (Kenigsberg et. al 294). The total of 1495 cases in the year 2000 is very similar to the study above that found that by the year 1999, when considering the same birth year cohort, the number of cases was 1292. Although there is a difference of 203 cases, if one considers the extra year accounted for (2000) in the study below, it could be concluded that the 2 studies support each other. Furthermore, the report mentioned earlier found that 569 cases of thyroid cancer had been reported by 1999. When taking the year 2000 into account, one can conclude that the study below on Gomel also supports the earlier, by reporting 687 with a difference of 118.

Table 13

Number of Thyroid Cancer Cases after the Chernobyl Accident by Year and Region of Residence at the Time of the Accident

Year	Region						Total
	Brest	Vitebsk	Gomel	Grodno	Minsk	Mogilev	
1986	0	1	0	1	1	0	3
1987	0	1	6	2	2	1	12
1988	1	0	3	1	4	0	9
1989	0	1	7	2	3	1	14
1990	9	2	18	0	7	2	38
1991	3	2	54	6	7	5	77
1992	21	10	45	11	9	4	100
1993	31	3	52	3	19	6	114
1994	32	5	60	10	25	14	146
1995	32	5	68	6	18	8	137
1996	42	5	67	8	25	9	156
1997	20	7	75	9	28	11	150
1998	40	5	60	8	36	16	165
1999	35	9	91	5	30	33	203
2000	34	5	81	6	22	23	171
Total	300	61	687	78	236	133	1495

Source: Kenigsberg, Jacov E., et. al. "Thyroid Cancer among Children and Adolescents of Belarus Exposed Due to the Chernobyl Accident: Dose and Risk Assessment." International Congress Series 1234 (2002): 293-300.

The next study was performed by the 2003-2005 Chernobyl Forum. It also looks at the same birth cohort as the previous studies (1968-1986), and uses data obtained by the Cancer Registry of Belarus, but looks at the thyroid cancer incidences until 2002, which is 2 additional years than the previous study (WHO 23). When compared to the 2 studies above, one can see that the amount reported from 1986-2002 is higher by 515 cases. Again, this is probably due to the 2 extra years accounted for here. The WHO Report also shows that almost the entire amount of thyroid cancer cases (1711) was seen in younger children from ages 0-14, which is consistent with the Gomel study mentioned above.

Table 14

Number of Thyroid Cancer Cases Diagnosed between 1986 and 2002 by Country and Age at Exposure

Age at exposure (yr)	No of Cases			
	Belarus[1]	Russian Federation[2]	Ukraine[3]	Total
0-14	1 711	349	1 762	3 822
15-17	299	134	582	1015
Total	2 010	483	2 344	4 837

[1] Cancer Registry of Belarus, 2006
[2] Cancer subregistry of the Russian National Medical and Dosimetric Registry, 2006 (for the 4 most contaminated regions)
[3] Cancer Registry of Ukraine, 2006

Source: Bennet, Burton, et al., eds. "Health Effects of the Chernobyl Accident and Special Health Care Programmes: Report of the UN Chernobyl Forum Expert Group "Health" Geneva: 2006." World Health Organization. 2006. 5 October 2009 WHO Press. http://whqlibdoc.who.int/publications/2006/9241594179_eng.pdf.

Non-Thyroid Cancer Cases-

The 2006 WHO Report builds upon the earlier 2000 UNSCEAR Report on Chernobyl. It finds that regarding non-thyroid cancer cases, there is, apart from pre-menopausal breast cancer and leukemia in liquidators, a lack of statistically significant evidence to show a clear increase that can be related to the Chernobyl fallout (66). This finding is consistent with the earlier 2000 UNSCEAR Report. The WHO does indicate that its conclusion may be the result of the minimum latency period required for solid cancers other than cancer of the breast and thyroid to develop. The WHO states that most solid cancers have a minimum latency period of over 10 years (66). Leukemia, on the other hand, has a latency period that is below 10 years, and breast cancer develops in roughly 5 years (WHO, 66). Since only 24 years have passed since the accident, it is unfortunately likely that with time, more non-thyroid cancer cases will surface.

One 2002 study, conducted by a team of scientists from the Belarusian Center for Medical Technologies, Informatics, Health Care Administration and Management, has discovered a moderate increase of the cancer incidence rate for thyroid and other types of cancers. The team collected the number of reported cases for various cancers from 1980-1990 to the Belarusian Cancer Registry, as-well as the mean resident population of Belarus for that period from the Belarusian State Statistical Department (Polyakov, et. al. 254). The average crude rate (CR) was then calculated. The CR measures the overall frequency of cancer incidence, which in this case is between 2 decades: 1980-1989 and 1990-1999. The 2 time periods were chosen in order to compare the cancer incidence prior to, and immediately following the disaster, as well as 3-13 years following the fallout. The short time frame (3-13 years) of the post-accident study period suggests that many non-leukemia and non-breast cancers will not have had sufficient time to develop. Thus, the results are in no way conclusive because future cases are to be expected. The results should also be interpreted, keeping several uncertainties in mind. For example, the CR was not adjusted for significant factors that could influence the rate. These include confounding factors such as smoking, an unhealthy lifestyle, improvements in reporting practices, increased awareness and screening activities, assessments of health histories, population health prior to the accident, and other environmental contamination in the environment. In order to eliminate the population change uncertainty, the study group considers the changes between the former and latter periods. The 35-74 year old population age increased slightly when compared to the former study period: 42.9% vs. 37.5% for males and 46.6% vs. 43% for females (Polyakov, et. al. 254). The 5.4% difference for males and 3.6% difference for females should be considered when assessing the final results.

The figures below display one set of results from the study mentioned above. The changes in age-specific rates for most common cancers for males between the periods 1980-1989 and 1990-1999 are presented. The dark grey line represents the former period and the light grey line, the latter. All cancers appear to increase at age 35, except for prostate cancer, which develops 10 years later at age 45 (Polyakov, et. al. 257). Likewise, all cancers appear to reach their peak incidence rate at approximately 70-75 years, besides lung, which peaks at about 65-70 years. (Polyakov, et. al. 257). These 2 observations support the finding mentioned earlier, that assigns a minimum latency period of over 10 years for most cancers to develop. The paper also seems to contradict the WHO 2006 Report and the UNSCEAR 2000 Report. The UN paper finds that regarding non-thyroid cancer cases, there is, apart from pre-menopausal breast cancer and leukemia in liquidators, a lack of statistically significant evidence to show a clear increase that can be related to the Chernobyl fallout (66). The Polyakov et. al. study, on the other hand, displays a clear increase in non-thyroid cancer incidence in most cancers that were considered. The data on incidence cases registered in the Belarusian Cancer Registry for males for the latter decade clearly shows an increase in cases over the previous decade. For example, the colon, rectum, lung, prostate, bladder, kidney, and all cancer categories display an elevated level when compared to the earlier decade (Polyakov, et. al. 257). However, stomach cancer showed a decreased incidence rate, which reveals the need for further study to explain this phenomenon.

As mentioned earlier, the population rate did increase 5.4% for this period. This may have affected the results slightly, but not to such a significant degree where the differences between the 2 periods more than double in some cases (kidney), nearly double in others (colon, lung, prostate), and increase by about 1.5 times of the earlier time frame (all cancers, bladder, rectum).

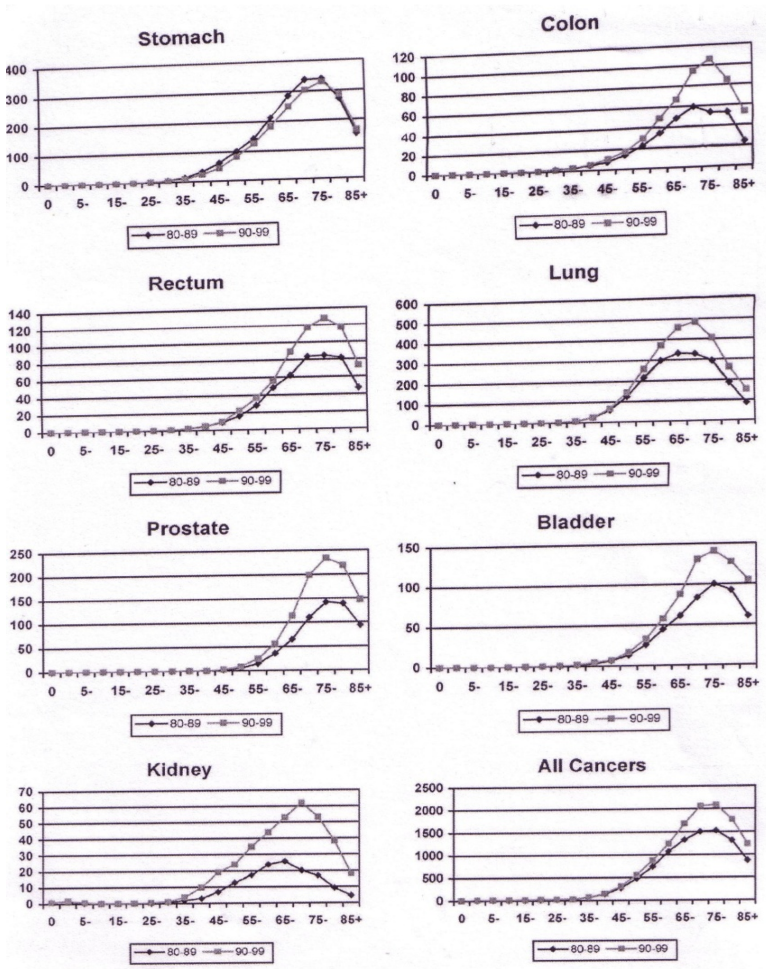


Fig. 24 Changes in Age-specific Rates of most common Cancers in Belarus for the periods 1980-1989 and 1990-1999: Males. Polyakov, et. al., Cancer incidence in Belarus after the Chernobyl accident. Elsevier Science, 2002.

The figure below represents the age-specific cancer rates for the most common cancers in Belarus for the periods 1980-1989 and 1990-1999 in females. Similar to the male findings, female cancer rates appear to have increased during the second decade for all female cancer types under study, except for one, cervix uteri. However, unlike their male counterparts, females developed certain cancers at an earlier age. For example, leukemia, kidney, breast, thyroid, and the all cancer category showed development at between ~2 and ~20 years of age (Polyakov et. al. 258). The ~3 year old age at onset observed in thyroid cancer patients was discussed earlier and is due to a developing thyroid gland in children. Leukemia and breast cancer onset was ~2 and ~20 years of age, which could be due to the less than 10 year latency period characteristic of these 2 cancers (WHO, 66). The all cancer category showed an approximately 10 year difference in age between males and females at the earliest witnessed age, with ~25 for females and ~35 for males. This should be further analyzed to discover the reasons for the earlier onset for females. Another observation to be further analyzed is the difference in onset for kidney cancers, with ~2 years of age for females and ~35 years of age for males. The increases in breast and leukemia cases found in this study are in some areas, inconsistent with the WHO Report. The Polyakov et. al. study, shows that breast cancer cases ranged from ~25 years to ~85 years of age, an age bracket that spans from pre-menopausal to post-menopausal periods. Another ambiguity was the difference between leukemia cases: The WHO study found an increase only in liquidators, but the Polyakov et. al. paper found that leukemia cases were registered at ~2 to ~85 years of age.

Similar to the male results, the 3.6% increase in population between the 1980-1989 and 1990-

1999 periods should not have a significant impact on the overall outcome. However, the population increase should certainly be analyzed to uncover where the migration originated from (contaminated vs. uncontaminated regions) and whether the emigrants were diagnosed with cancer. The results should also be considered in light of the uncertainties mentioned earlier as-well as statistical strength.

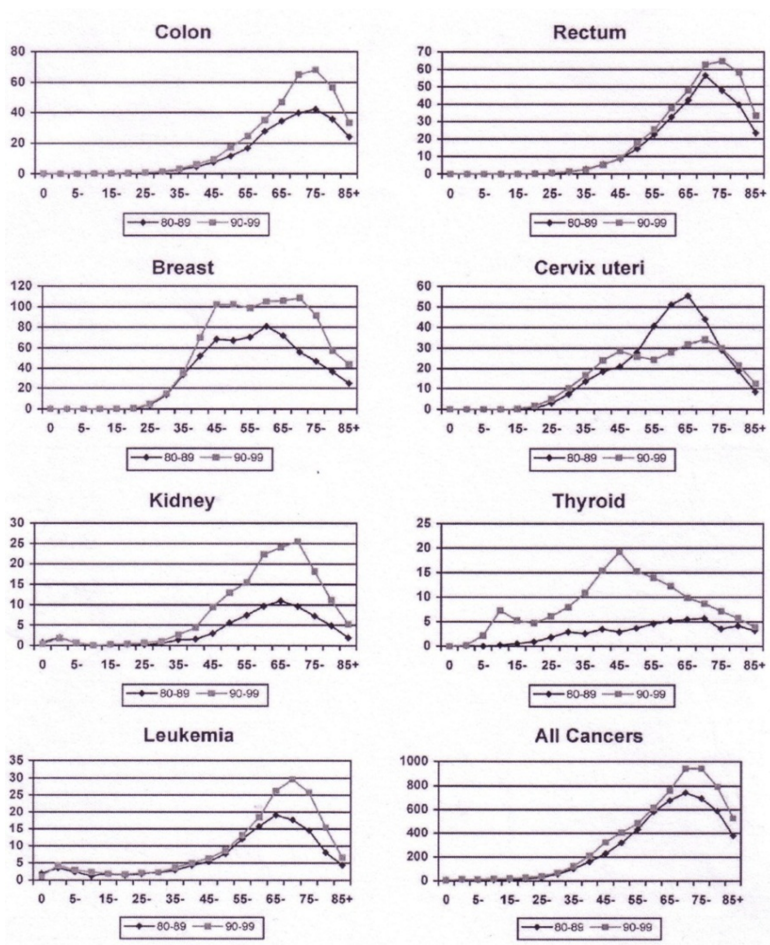


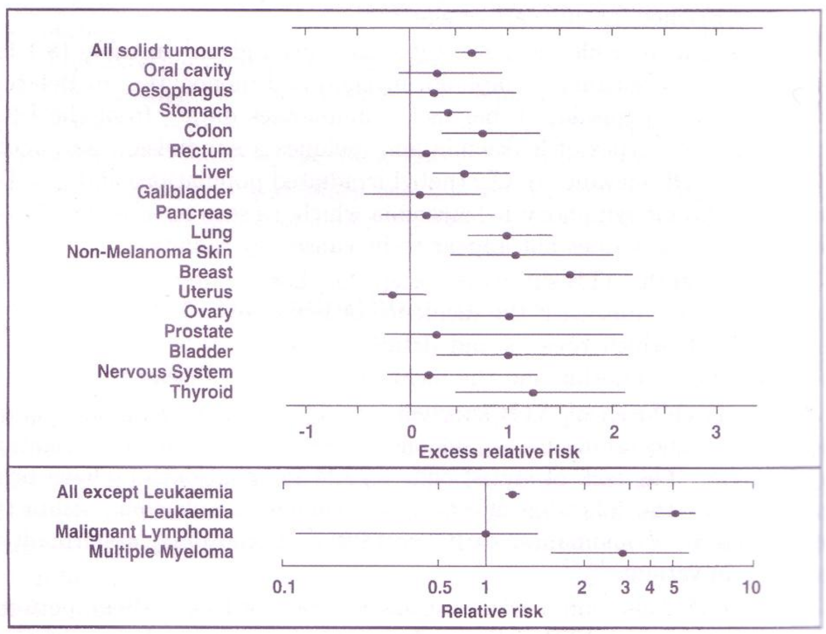
Fig. 25 Changes in Age-specific Rates of most common Cancers in Belarus for the periods 1980-1989 and 1990-1999: Females. Polyakov, et. al., Cancer incidence in Belarus after the Chernobyl accident. Elsevier Science, 2002.

The excess relative risk for solid tumors and other cancers is considered next. If the confidence limits include 0 for excess relative risk and 1 for relative risk then this indicates that there is no statistically significant association (Mould, 280). The figure displays a statistically significant excess relative risk for all solid tumors, as-well as stomach, colon, liver, lung, non-melanoma skin, breast, ovary, bladder, and thyroid. The study found no excess relative risk for the oral cavity, esophagus, rectum, gallbladder, pancreas, uterus, prostate, and nervous system. It also found a relative risk for leukemia, multiple myeloma, and all except leukemia, but no relative risk for malignant lymphoma.

Mould supports the Polyakov results on male and female cancer incidence during the 1980-1989 and 1990-1999 decades. The former paper finds an excess relative risk of ~0.75 for all solid tumors for people that were exposed to 1 Sv of radiation (Mould 280). Similarly, Polyakov finds that both males and females reported more cases of all cancers in the 1990-1999 period following the disaster (257-258). The studies reinforce each other and suggest that an increase in non-thyroid cancer incidence in Belarus is possible. Other similarities include colon cancer risk, lung, breast, bladder, uterus, and leukemia. All display an increased risk except for cancer of the uterus for which case both studies display an actual decrease in risk. Mould displays no statistically significant association between 1 Sv of dose equivalent and cancer of the uterus, while Polyakov finds that the level in the later decade is almost half of the cases reported during the earlier decade for the ~47 to ~76 year old age group. According to Polyakov, this result is untypical and more research should be performed in this area to better understand this occurrence (259).

Table 15

Estimated Excess Relative Risks at 1 Sv with 95% Confidence Intervals



Source: Mould, R.F. Chernobyl Record: The Definitive History of the Chernobyl Catastrophe. London: Institute of Physics Publishing, 2000.

According to one recent ecological epidemiological study conducted by a team of scientists from the Finnish, Belarusian, and Ukrainian Cancer Registries, as well as the IARC Radiation Group of France and the Ukrainian Radiation Protection Institute, an increase in breast cancer incidence has been found in the Mogilev and Gomel oblasts since the Chernobyl accident. According to Ron, ecological epidemiological studies are based on grouped data, by geographic region, for example (S31). They are usually based on existing databases and may, therefore be a less costly and simple research method. However, some disadvantages of this approach could be lack of data on individual exposures, health histories, and other unknown confounding factors that create greater uncertainty in the results and a potential for bias (Ron, S31). Nevertheless, the National Cancer Registry of Belarus screens potential cases to be registered by sending cases to oncological hospitals in the patients' region or to the Institutes of Oncology in Minsk or Kiev diagnostic confirmation (Pukkala, et. al. 651). It also includes complete individual information of cancer cases from 1973, except for 1979-1984 due to technical reasons, and considers a large group (Pukkala, et. al. 651).

The figure below presents the cumulative dose estimates in mSv for the regions being observed in the Pukkala et. al. study: Mogilev and Gomel. Average annual whole-body dose estimates were reconstructed by using a model and instrumental measurements that used moluminiscent dosimeters and whole body counters (Pukkala, et. al. 652). The figure displays the results and between 1986 and 2001, Gomel and Mogilev contained whole body doses that ranged from <5.0 mSv to 40+ mSv. The Southern areas closest to the reactor site as well as the Northern Gomel area was found to have the highest levels of radiation from 20-40+ mSv (Pukkala, et. al 652). Other areas that are mostly further from the reactor site showed levels ranging from <5 -19.9 mSv. The high levels of pollution found in Gomel and Mogilev can be partially explained by the 2006 IAEA Report discussed earlier, that uncovered that radioactivity was largely spread over Belarus because of wind and precipitation patterns.

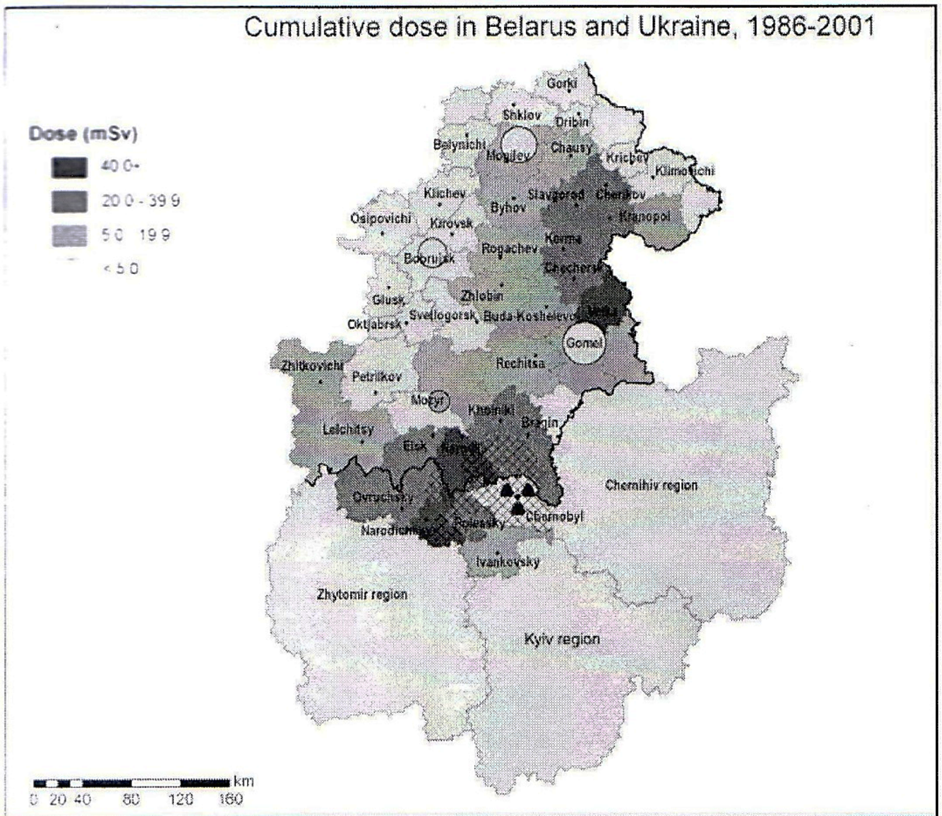


Fig. 26 Absorbed Whole-Body Equivalent Doses in mSv. Pukkala, et. al "Breast Cancer in Belarus and Ukraine after the Chernobyl Accident." International Journal of Cancer 119 (2006): 651–658.

The Pukkala et. al. paper shows that breast cancer incidence has increased since the accident in the study regions of South and Eastern Belarus and for all whole body dose levels. A total of 35.4 million person-years and 13,412 cases of breast cancer were available for the entire study period (Pukkala et. al 653). The darkened squares on the graph represent an average cumulative dose of 40+ mSv, the light squares represents a 20-39.9 mSv dosage, the shaded circle is 5-19.9 mSv, and the light circle represents <5 mSv average cumulative dose. It shows that roughly 78% of the total number of breast cancer cases was registered after the accident, between 1986 and 2001. The graph results show a slight increase per 100,000 person years in breast cancers between 1979-1986. Following 1986, however, the number of cases reported more than doubles for doses <5 mSv and greater. A particularly drastic increase is seen at the 40+ mSv average cumulative dose level (Pukkala et. al. 654). From approximately 1986 to 1998, the quantity gradually increases from about 20-25 cases per 100,000 person years. Then from 1998 to 2001, it increases drastically to approximately 90 cases per 100,000 person years (Pukkala et. al. 654). This suggests that there is a correlation between time after exposure, dose, and breast cancer development in Belarus.

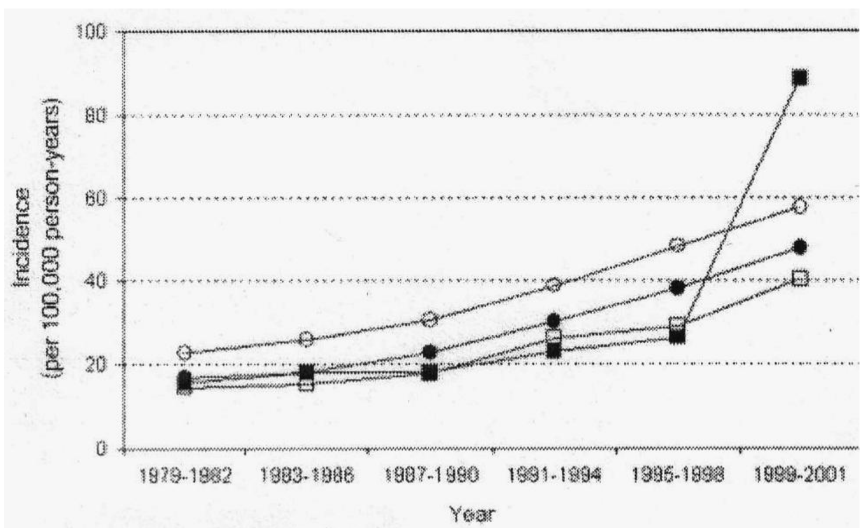


Fig. 27 Trends of Age-Adjusted Breast Cancer Incidence in Belarus over the Period 1979-2001. Pukkala, et. al., "Breast Cancer in Belarus and Ukraine after the Chernobyl Accident." International Journal of Cancer 119 (2006): 651–658.

The results displayed in the Pukkala et. al. study are reinforced by the Polyakov et. al. and the Mould paper mentioned earlier. For instance, Pukkala et. al. displays a sharper increase in breast cancer incidence from 1990 to 2001 than from 1979 to 1990. The latter 11 year period shows an increase of about 70 cases per 100,000 person-years for the 40+ mSv dose level. The earlier 11 year period, on the other hand, increases by about 5 cases. The Polyakov et. al. study displays a similar trend; between the 1980-1989 period the breast cancer incidence rate averages at about 80, however. The later period of 1990-1999 peaks at approximately a rate of 107 (Polyakov et. al 258). This comparison reveals a possibly higher incidence of breast cancer in the later years following the accident. The higher incidence rate observed during the later period suggests that incidence rate increased due to the Chernobyl fallout of 1986. It also confirms the WHO Report findings that breast cancer has a minimum latency period of ~5 years. Finally, the Pukkala et. al. study is also reinforced by the Mould Report, which found that the excess relative risk for breast cancer increases with higher doses.

Several studies show some increase in leukemia cancers in Belarus. The 2006 WHO Report notes one 1998 paper by Ivanov et. al., that observed annual incidence rates and found that the highest annual incidence rate of those exposed in utero was in 1987 and again, in the most contaminated regions of Gomel and Mogilev (55). The time at which the increase was observed suggests that the cases where caused by the excess radiation. This is not uncommon, because following Hiroshima and Nagasaki, an elevated risk for leukemia was also observed among survivors. Another example of elevated leukemia risk, albeit at a later time, is seen in the Polyakov et. al. findings, which shows a drastic increase in leukemia cases in 1990-1999 period, as opposed to the 1980-1989 period. This could be due to the latency period required for leukemia to develop. Finally, another study that looks at leukemia in Mogilev and Gomel is found below.

According to research put forth by the Academy of Sciences in Belarus and the Division of Ecological Science in UNESCO, the number of leukemia cases in the most highly polluted oblasts of Belarus shows some increase since 1986. Table 12 below shows the results:

Table 16

Leukemia (no. of cases per 100,000 inhabitants)

	1986	1988	1989	1990
Gomel Oblast	3.49	7.95	9.23	7.34
Mogilev Oblast	4.92	6.26	7.24	8.68

Source: Savchenko, V.K. The Ecology of the Chernobyl Catastrophe: Scientific Outlines of an International Programme of Collaborative Research. Paris, France: UNESCO and the Parthenon Publishing Group, 1995.

When comparing the number of cases seen per 100,000 inhabitants from the Gomel and Mogilev oblasts in 1986 and later in 1990, one sees that the number more than doubled for Gomel and nearly doubled for Mogilev. This data supports the additional findings mentioned above. The International Consortium for Research on the Health Effects of Radiation case-control study of childhood leukemia in Ukraine, Belarus, and Russia is an ongoing study of childhood exposure and leukemia (WHO 57). When results become available, they will provide further insight into leukemia incidence in Belarus following the accident.

Countermeasures:

Sarcophagus:

The release of radionuclides into the atmosphere decreased substantially 10 days after the explosion, when the reactor cooled down. The left over mess represented an enormous and dangerous mountain of nuclear waste. Inside the reactor there remained 1,659 containers of nuclear fuel, amounting to roughly 180 tons of radioactive material that were mixed with the remains of the destroyed reactor (Savchnko 15). The amount of radioactive fission product was high because the test had been performed at the end of the fuel cycle, when the older, used fuel was ready to be replaced. If the test was performed with fresh nuclear fuel at the start of its cycle, there would have been less radioactive fission product present inside, and the test would have been performed under much safer conditions.

Due to the amount of radioactive waste still present inside the reactor, it was decided that a sarcophagus should be built to cover and prevent any additional releases. The dome shaped concrete and steel structure spanned 55 m, was equipped with neutron censors, and temperature gauges were installed above and below the sarcophagus (Savchenko 16). These safety mechanisms were put in place in order to detect the initiation of a nuclear chain reaction and any increased temperature and fires that may have formed. Additionally, the surface soil around the reactor was removed, and the area was covered with concrete and asphalt (Savchenko 16). This was done to eliminate and contain the contaminated soil, while preventing the absorption of any future radioactive fallout. Inside of the reactor, near the core, the radiation levels were constantly being monitored by a special device. An increase in temperature would be a signal indicating nuclear activity.

In November of 1986, the massive project was finished with hope that the structure would remain intact for decades to come. But only 5 years later, the sarcophagus began showing signs of deterioration (Savchenko 16). Since the sarcophagus was constructed to contain any further releases of radioactivity, its inner shell had accumulated large amounts of radioactive particles that weaken the structure. A collapse would cause another catastrophe, sending dangerous particles back into the atmosphere and surrounding environment. Ukrainian and Russian scientists, experts of the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD), and European Community experts expressed concern and warned that the ten metric tons of radioactive dust located on the inside wall of the sarcophagus could be released (Liberatore 65). Other concerns were the possibility of leaching into nearby water, weakening of the reactor's original supporting structures, and the possibility of an explosion or fire within the sarcophagus (Liberatore 65). The issue of the deteriorating sarcophagus was at the forefront, and after considering several options, the Ukrainian government, along with members of the international scientific and engineering communities, decided to cover the present sarcophagus with a larger, 220m in length, 80m wide, and 92m high structure.

Agriculture:

Agriculture was remediated using several methods. These include, land use changes, crop changes, ploughing, application of fertilizers and other additives, changes in milk and meat production, and through radio ecological control. Crop species that accumulate radionuclides easily were replaced by species that uptake less radioactive elements from soil. For example, grain crops, potatoes, and maize were grown instead of leguminous crops like peas and clover that were known to have a higher affinity for contaminants. Also, beets, carrots and currants were also replaced by cabbage, cucumber and tomatoes, which were known to accumulate less radionuclides (Savchenko 53). Ploughing was used to transfer the upper polluted layers of soil to a depth of 40-50 cm, making the contaminants unavailable for plant uptake and limiting their contact with living beings. Potassium and phosphorus fertilizers were also used in combination with liming to reduce crop uptake of ^{90}Sr and ^{137}Cs. In Belarus, for example, 239,500 ha (2,395 km^2) were limed and 248,900 ha (2,489 km^2), fertilized in this fashion (Savchenko 53). For cleaner milk and meat, animals were fed uncontaminated food by treating the land used for fodder crops (2003-2005 Chernobyl Forum 27-28). Prussian blue was also administered to trap radioactive caesium in the intestines of livestock, while keeping it from being absorbed by the body. From there, it is excreted through the bowels, reducing the degree of contamination in the meat. Prussian blue, together with the other methods mentioned above made it possible to continue using large tracts of land for agriculture in Belarus. Although the countermeasures limiting radiocaesium levels in meat and milk were often successful, economic problems proved to be a limiting factor. From the mid-1990's remediation measures used in agriculture slowed due to economic problems. This resulted in heightened contamination in plant and animal food products (2003-2005 Chernobyl Forum 28).

While countermeasures taken by the Soviet government and later, the independent state of Belarus significantly reduced the radiation doses received by local populations, improvements could have been made in waste disposal. According to Fesenko et al., the total averted doses for the three most affected countries were 30-40% of the internal collective dose, with the exclusion of radioiodine (21). In 1986-1989, 24 million m^2 of settlements and 6 million m^2 of territory were decontaminated in total (Savchenko 144). The efforts have lowered contamination in 944 settlements including 418 in Gomel, 190 in Mogilev, 56 in Kiev, 93 in Jitomir and 157 in the Briansk oblasts (Savchenko 144). The most effective countermeasure was the exclusion of pasture grasses from animal diets, the rejection of milk, and feeding animals with "clean" fodder (27). While these measures proved to be beneficial, other issues arose like the storage of radioactive waste.

Currently, decontamination measures are continuing in more than 2,700 towns and villages in Belarus with pollution levels at or above 1 Ci/km^2. Although remediation efforts are taking place in places where contaminants were found, there is strong need for a special system of monitoring to be set up for ^{137}Cs, ^{90}Sr, ^{131}I, plutonium isotopes, and other isotopes, in order to properly manage the unsafe areas while being able to identify new sources of pollution (Savchenko 18). In addition, a system designed to manage radioactive waste is also in great need.

Soil Treatment:

Radical improvement is a technique used to remediate Belarusian soils and meadows. It is a combination of countermeasures including ploughing, reseeding and/or the application of nitrogen, phosphorus, potassium fertilizers, and lime (IAEA 79). Ploughing treats the top soil layers that readily accumulate strontium and caesium. Reseeding and new plant growth cleans soil as new plant roots absorb contaminants. They are then collected and disposed of in waste holding and treatment facilities, allowing clean soils to be used for agriculture and other purposes. Fertilizers are also used in the process to increase plant production and dilute radioactivity; they are used to reduce root uptake into plants that will become food (IAEA 79). According to the IAEA 2006 Report, a significant reduction of soil to plant transfer has been achieved for radiocaesium and radiostrontium when fertilizer is used to reduce root uptake (80). This system increases the availability of "clean" produce for Belarusian residents. Figure 28 displays gradual decreases in the use of radical improvement methods in Belarus. It shows that this treatment type has steadily decreased since 1986, which could be due to its success and the relative increase in "clean" food crops.

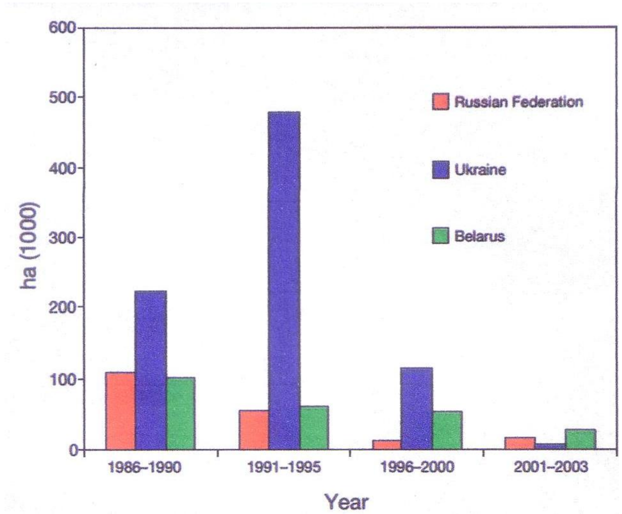


Fig. 28 Areas of Radical Improvement in the Countries Most Affected. "Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience: Report of the Chernobyl Forum Expert Group "'Environment.'" Radiological Assessment Report Series. 2006. 20 September 2009. International Atomic Energy Association, Vienna Austria. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1239_web.pdf.

Thyroid Cancer:

Following the disaster, stable iodine tablets should have been immediately administered to exposed populations. However, they were distributed 11 days following the accident at a time when ^{131}I, with its 8 day half-life could have already caused great damage. According to Mould, the delay was due to the Soviet government's lack of iodine tablet reserves (78). This highlights the need for governments to secure access to stable iodine in cases of emergency. By May 7th, 5.3 million people did receive the tablets, including 1.6 million children, but many children were still left without emergency aid (Mould 78). Sadly, many children were exposed to ^{131}I because they did not receive priority for the emergency aid, as they should have. While the failed emergency response occurred due to lack of reserves and mismanagement, according to Mould, it also occurred because of unreliable radiation data and inadequate communication amongst local populations and the governments of Belarus, Ukraine, and Russia (78). For example, authorities failed to notify the population of the risks associated with remaining outdoors and consuming contaminated agricultural products. In cases of emergency, governments should have stable iodine in reserve, a responsible management plan, reliable data, and effective communication methods in order to protect their populations.

Conclusions:

Environmental Contamination:

Belarus experienced some of the largest levels of contamination following the disaster. Approximately 14 EBq[5] of radionuclides were released consisting of 1.8 EBq of ^{131}I, 0.085 EBq of ^{137}Cs, 0.01 EBq of ^{90}Sr, and 0.003 EBq of plutonium radionuclides (2003-2005 Chernobyl Forum 22). Atmospheric winds dispersed the radioactive plume over Belarus. Once there, precipitation patterns caused radioactive rain to enter the country. Over 200,000 km^2 of Europe received levels of ^{137}Cs that were over 37 kBq/m^2; approximately 70% of the particles fell on Belarus, Russia, and the Ukraine and 46, 420 km^2 of Belarusian land received amounts exceeding 37 kBq/m^2 (2003-2005 Chernobyl Forum 22). Studies using random soil samples from the entire country of Belarus, Veprin, Gomel, and Lake Svyatoe show that ^{137}Cs and ^{90}Sr have remained within the top 15 cm of the soil and primarily in exchangeable states.

Agriculture-

Agriculture suffered and small-scale farmers experienced greater hardship than large, government-owned farms. Between 1986 and 1990, 256,700 ha (2567 km^2) of farmland were withdrawn from production because contamination was higher than 1480 kBq/m^2 (Savchenko 53). Subsistence farmers could not decontaminate their plots because they lacked the resources and were often forced to abandon their farms or continue working on contaminated land. Livestock accumulated large doses of radiation and cattle located about 14-35 km from the reactor suffered from extremely high doses of 90-260 Gy. Radiation was often transferred into milk, and today Gomel, as-well as Mogilev continue to produce milk that exceeds the Belarusian national limit of 100 Bq/L. Initially following the accident, highly contaminated foods were reprocessed into butter, cheese, salami, sausages, and other items that authorities felt would not be consumed often.

Forests-

The Polissya Region of Belarus suffered from the accident. 1/4 of the forest area, or roughly 1.7 million ha (17, 000 km^2) were contaminated while 188,000 ha (1,880 km^2) were found to be situated in a zone that reached between 555 and 1,480 kBq/m^2 (Savchenko 37). According to the 2003-2005 Chernobyl Forum, particularly high ^{137}Cs concentrations were found in the past 2 decades in mushrooms, berries, and game (25). This changed the lifestyle of residents whom once enjoyed recreational activities like hiking, picking mushrooms, hunting, and camping, amongst other outdoor activities. The economy also suffered as valued wood was no longer permitted for use.

Water-

The Pripyat and Dnieper Rivers are gradually seeing decreases of radiation, while an interesting dynamic has also been observed. A decline of ^{90}Sr and ^{137}Cs was found in the Pripyat River from 1987-1999 and although ^{131}I contamination in the Dnieper and Pripyat Rivers appear to have been significantly elevated immediately following the disaster, the levels are also decreasing. Southern countries, however, are experiencing higher radiation due to the rivers' natural decontamination process. These areas should be closely monitored and managed to mitigate the effects of this process. Studies have also found that deeper waters contain more radioisotopes than surface waters (Savchenko 15). This may open certain areas up for boating and fishing where contamination has settled in deep waters.

Wildlife-

Mutations, cytogenetic effects, and chromosomal abberations have increased in the Polissya Region near the reactor site. In their paper entitled, "Biological consequences of Chernobyl: 20 years on," Drs. Møller and Mousseau compiled 33 studies that investigate mutations and cytogenetic effects on irradiated plants and animals in Polissya. Plants and animals were also collected from control areas that contained little or no radiation. The results show that there is considerable heterogeneity in mutations and cytogenetic abnormalities, with 25 of the studies showing an increase in abnormalities (Møller, et. al. 202). Møller and Mousseau also observed 9 organisms that were affected by various degrees of chromosomal aberration along with various genetic markers. 7 out of the 9 organisms included in this compilation showed a significant increase in somatic mutations.

A study of the barn swallow population before and after the accident finds that the frequency of partial albinism has increased 5-10 fold following the disaster (Møller and Mousseaux, 204). Higher frequencies of bilateral asymmetry in wings were also seen in several organisms located near the accident site. According to Møller and Mousseau, brightly colored birds that migrate long distances, like the barn swallow, have weaker DNA repair mechanisms and are most likely to be affected (Gill, 2). The influence of partial albinism, bilateral asymmetry, and compromised DNA on migration patterns, ecology, and life cycle of the barn swallow is an area in need of further study.

Forests-

Scots pine samples collected from field populations in Polissya had an increase of chromosomal aberrations by a factor of 3 (Møller, et. al. 205). The samples also contained a mutation at the enzyme loci that had been increased by a factor of 20 (Møller, et. al. 205). Pine trees that had received absorbed doses ranging from 0.4 to 12 Gy could expect to undergo a mutation in the seeds endosperm for 7 allozyme loci at a rate of 10 times higher than the spontaneous mutation rate found in control groups (Savchenko 107).

Health Consequences:

ARS-

ARS occurred in a group of Chernobyl emergency workers and operators. According to Baverstock and Williams, about 150 people were treated for ARS; 28 died shortly after and 20 others have died since (1313). The Chernobyl Forum has put forth similar findings where ARS was diagnosed in 134 emergency workers, while 28 died from the syndrome (14). ARS usually occurs when a human accumulates an absorbed dose of at least 1 Gy and it is characterized by 4 stages.

Mental Health-

The WHO Report notes that mental health ailments are the largest health consequence of the nuclear disaster to date. Mental anguish is widespread and a result of the complex web of events and long-term difficulties following the disaster. The problems include relocation, an unstable economy, health consequences of current and most-likely future generations, and other stressors that resulted in physical and emotional imbalance (WHO 95). Lack of information, rumors, and a general feeling of chaos also permeated Belarus. The psychological stress that followed is still present today and should be a health priority for government, organizations, the United Nations, and other authorities. Counseling, support groups, a stable environment, and society are some of the strategies that can mitigate psychological distress.

Thyroid Cancer-

Thyroid cancer has significantly increased in Belarus following the accident. When considering the birth cohort from 1 January 1968 to 31 December 1985 and looking at the National Thyroid Cancer Registry of Belarus, the study finds that between 1986 and 1999, there were 1292 thyroid cancer cases in all of Belarus and 569 in Gomel. Female thyroid cancer was twice as high as male in Gomel, and children from 0-14 years of age were more susceptible to developing the disease than older children and young adults (Jacob Peter et. al 218). An alternate study looks at the cohort born from 1 January 1968 to 26 April 1986 that developed thyroid cancer from 1986-2000. The data was taken from the medical history of patients whom underwent treatment in the Republican Scientific-Practical Center of Thyroid Oncopathology in Belarus, as well from the Belarusian Cancer Registry. The total of 1495 cases in the year 2000 is very similar to the study above, which found that by the year 1999, the number of cases was 1292. When the same birth cohort was studied to determine the cancer incidence for 2 additional years, until 2002, it discovered that thyroid cancer had increased by 515 cases, while the majority of reports were found in young children, ages 0-14.

Non-Thyroid Cancer-

The 2006 WHO Report finds that regarding non-thyroid cancer cases, there is, apart from pre-menopausal breast cancer and leukemia in liquidators, a lack of statistically significant evidence to show a clear increase that can be related to Chernobyl (66). Some studies, however, have identified what appears to be an increase in certain non-thyroid cancer cases. A team of scientists in 2002 from the Belarusian Center for Medical Technologies, Informatics, Health Care Administration and Management, have discovered a moderate increase of the cancer incidence rate for thyroid and other types of cancers. The Polyakov et. al. study, also displays a clear increase in non-thyroid cancer incidence in most cancers that were considered. The data on incidence cases registered in the Belarusian Cancer Registry for males for the latter decade clearly shows an increase in over the previous decade. Similar to the male findings, female cancer rates appear to have increased during the second decade (1990-1999) for all female cancer types under study, except for one, cervix uteri. The Mould Report supports the Polyakov et. al. findings. It shows a statistically significant excess relative risk for all solid tumors, as well as stomach, colon, liver, lung, non-melanoma skin, breast, ovary, bladder, and thyroid. It also finds a relative risk for leukemia. The non-thyroid cancer incidence increase presented here suggests that a further, more detailed analysis of the methodologies and findings should be initiated and compared to the UN Chernobyl Forum findings. Also, non-thyroid cancer incidence research should continue to further clarify or refute the results presented here, and to consider other forms of cancer not mentioned in this paper.

The Pukkala et. al. study shows that breast cancer incidence has increased since the accident in the regions of South and Eastern Belarus and for all whole body dose levels. The results also suggest that there is a correlation between time after exposure, dose, and breast cancer development in Belarus. This is reinforced by the Polyakov et. al. findings and is also similar to the WHO Report that discovered an increase in pre-menopausal breast cancer following the accident.

Several papers find some increase in leukemia incidence in Belarus. Ivanov et. al. (1998) displays annual incidence rates and finds that the highest annual incidence rate of those exposed in utero was in 1987, and again, in the most contaminated regions of Gomel and Mogilev (WHO 55). This suggests that the excess radiation influenced an increase in leukemia. This observation is further reinforced by Polyakov et. al., which also discovers increases, albeit later (1990-1999). According to a paper by the Academy of Sciences in Belarus and the Division of Ecological Science in UNESCO, the number of leukemia cases in the most highly polluted oblasts of Belarus showed some elevation since 1986.

Countermeasures:

A sarcophagus was built on November 1986 after only 5 years the massive dome began deteriorating (Savchenko 16). Since the sarcophagus was constructed to contain any further releases of radioactivity, its inner shell had accumulated large amounts of radioactive particles that weakened the structure. A collapse would cause another catastrophe, sending dangerous particles back into the environment. After considering several remedial options, the Ukrainian government, along with members of the international scientific and engineering communities, decided to cover the present sarcophagus with a larger, 220m long, 80m wide, and 92m high structure.

Several methods were used to remediate agriculture, including land use changes, crop changes, ploughing, fertilizers and other additives, changes in milk and meat production, and radio-ecological control. In some cases, crop species that accumulate radionuclides easily were replaced by species that uptake less radioactive elements from soil, making more crops available for consumption. For cleaner milk and meat, animals were fed uncontaminated food (2003-2005 Chernobyl Forum 27-28). Prussian blue was also administered to trap radioactive caesium in the intestines of livestock, while keeping it from being absorbed by the body.

Radical improvement is a popular technique used to remediate meadows. It is a combination of countermeasures including ploughing, reseeding and/or the application of nitrogen, phosphorus, potassium fertilizers, and lime (IAEA 79). The 2006 IAEA Chernobyl Forum Report finds that the need for this treatment type has steadily decreased since 1986. This could be due to its success in mitigating contamination.

Stable iodine tablets should have been immediately administered to exposed populations. However, they were distributed 11 days after the accident at a time when 131I, with its 8 day half-life, could have already caused great damage. According to Mould, the delay was due to the Soviet government's lack of iodine tablet reserves (78). By May 7th, 5.3 million people did receive the tablets, including 1.6 million children, but many children were still left without emergency aid (Mould 78). While the failed emergency response occurred due to lack of reserves and mismanagement, according to Mould, it also occurred because of unreliable radiation data and failure to communicate to the local population and amongst the governments of Belarus, Ukraine, and Russia (78).

After the accident, household pets and livestock were forced to remain in evacuation zones where they would later be shot by authorities. They were mismanaged and suddenly abandoned without adequate food, water, or shelter. Animals were forced to suffer and as a result, their owners also experienced unnecessary psychological distress. Household pets and farm animals are sentient beings that rely on humans for their survival and well-being. They must also be humanely treated in the event of an emergency, not only for their benefit, but for the well-being of their owners.

Questions or Problems that Remain:

Several reports covering isotope deposition focused mainly on ^{137}Cs because of its harm to human health and the relative ease with which it can be measured. Other contaminants such as ^{85}Krypton, with a half-life of 10.72 years and ^{242}Curium, with a 18.1 year half-life were not well documented. Research in this area would help determine which ecosystems and populations were affected so that appropriate remediation and aid can commence.

Although the countermeasures limiting radiocaesium levels in meat and milk were often successful, economic problems proved to be a limiting factor. From the mid-1990's remediation measures used in agriculture slowed due to economic problems. This resulted in heightened contamination in plant and animal food products (2003-2005 Chernobyl Forum 28). Currently, decontamination measures are continuing in more than 2,700 towns and villages in Belarus with pollution at or above 1 Ci/km^2. Although remediation is taking place in places in contaminated areas, there continues to be a strong need for a special system of monitoring to be set up for ^{137}Cs, ^{90}Sr, ^{131}I, plutonium isotopes, and other isotopes, in order to properly manage the unsafe areas while being able to identify new sources of pollution (Savchenko 18). In addition, a system designed to manage radioactive waste is also in great need.

While thyroid cancer incidence was clearly established, other types of cancers, genetic disorders, and diseases should continue to be monitored because the effects of radioisotopes may not surface until later years.

The populations in Gomel and Mogilev that continue to produce highly contaminated milk should be monitored and their land managed accordingly.

Recommendations for Further Work:

Studies using random soil samples from the entire country of Belarus, Veprin, Gomel and Lake Svyatoe show that ^{137}Cs and ^{90}Sr have remained within the top 15 cm of the soil. The radionuclides were mainly found in exchangeable states. Thus, allowing for plant uptake and human intake through internal pathways. Studying additional contaminated sites would help determine if the ^{137}Cs and ^{90}Sr remain in the top soil horizons or if they migrate into greater depths in other soil types.

^{137}Cs, ^{90}Sr, and ^{131}I that remain in the Pripyat and Dneiper Rivers should continue to be monitored. Decontamination measures to date should also be assessed and additional methods of remediation should be initiated where appropriate. ^{90}Sr should most likely be given remediation priority because ^{137}Cs has decreased more rapidly in the Pripyat River. Radionuclides that have entered catchment soils at the bottom of the Pripyat, and are slowly being transferred to river water through erosion of soil particles, and by desorption would require collection and relocation of contaminated catchment soils.

Nuclear waste sites are the largest contributors to nuclear water pollution following the accident. Their location, near 2 main sources of water that serve many cities, towns, and villages are a great risk and an example of the improper engineering preparations during the post-accident phase. Another example of the insufficient planning is the disposal sites that were constructed in sandy soil in '2 to 3.5m deep trenches with no isolating covers or liners (Smith, et. al 11). Lack of protective barriers fails to isolate and contain the radiation within the designated site. Groundwater contamination has occurred largely due to the construction and placement of these faulty waste disposal sites and the French-German initiative for the IAEA Chernobyl Forum has demonstrated that some of the temporary radioactive waste facilities that were initially constructed during the post-accident phase, have a significant influence on groundwater transport (157). According to the national temporary permissible levels for ^{90}Sr in drinking water, which are 3.7 Bq/kg, the groundwater levels found in the exclusion zone are unfit for consumption. The information contained herein, shows that waste management facilities should be redesigned, relocated and existing sites should be remediated, and given priority.

Mutations and cytogenetic effects in animals and plant life in the Polissya Region near the reactor site have shown signs of increase since the accident. Other results, reported no significant rate of increase. This could be the result of small sample sizes with low statistical power. Studies with large sample sizes should be further investigated to determine what effects genetic consequences have on individuals, the species as a whole, and how this changes the integrity and function of their ecosystems.

Plants in Gomel and Mogilev have responded to the excess radiation with various mutations, but certain species have developed a natural defense mechanism in response to the post-accident radiation. According to Bhanoo, some plants that are located in contaminated areas are actually flourishing in the soil (1). The group found that the adaptation capability stemmed from the alternations in the plants' protein levels (Bhanoo 1). The plants' ability to adapt to excess radiation contrasts the weaker DNA repair mechanisms that were found in brightly colored birds (Gill, 2). The response differences amongst species should be further researched to provide further insight on the adaptation capabilities of species.

Since only 24 years have passed since the accident, it is likely that with time more non-thyroid cancer cases will surface and this must be monitored to ensure that the correct care is being delivered to patients and to learn more about the aftermath of the accident. Our knowledge of current non-thyroid cancer prevalence should be strengthened by supporting or refuting the Polykov et. al Mould, and Pukkala et. al studies presented in this paper. Several papers have discovered some increase in leukemia in Belarus. Ivanov et. al (1998) observes annual incidence rates and shows that the highest annual rate of those exposed in utero was in 1987 and again, in Gomel and Mogilev (WHO 55). Leukemia, like other cancers has been associated with exposure to radiation. Therefore, exposed populations should continue to be monitored.

Thyroid cancer was a definite consequence of the accident. New cases will develop with time and should be monitored. The 1968-1985 birth cohort should also continue to be monitored in order to determine whether cancer cases continue to develop past 2002. Earlier birth periods should also be studied to determine thyroid cancer incidence in older people, because studies have mainly focused on younger patients.

Acknowledgments:

I would like to thank Dr. Petryna, Professor Laskowski, Dr. Bordeaux, Dr. Giegengack, and Dr. Doheny for their continued guidance, support, encouragement, and inspiration. They have made my experience at the University of Pennsylvania truly rewarding and this project would not have been possible without them. I would also like to thank the faculty, students, and staff with whom I had the pleasure of working with. Their knowledge and passion for scholarship has driven me to become a better student and a better person. Last, but not least I would like to thank my husband and family for their unconditional help and positive influence. Thank you for everything.

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