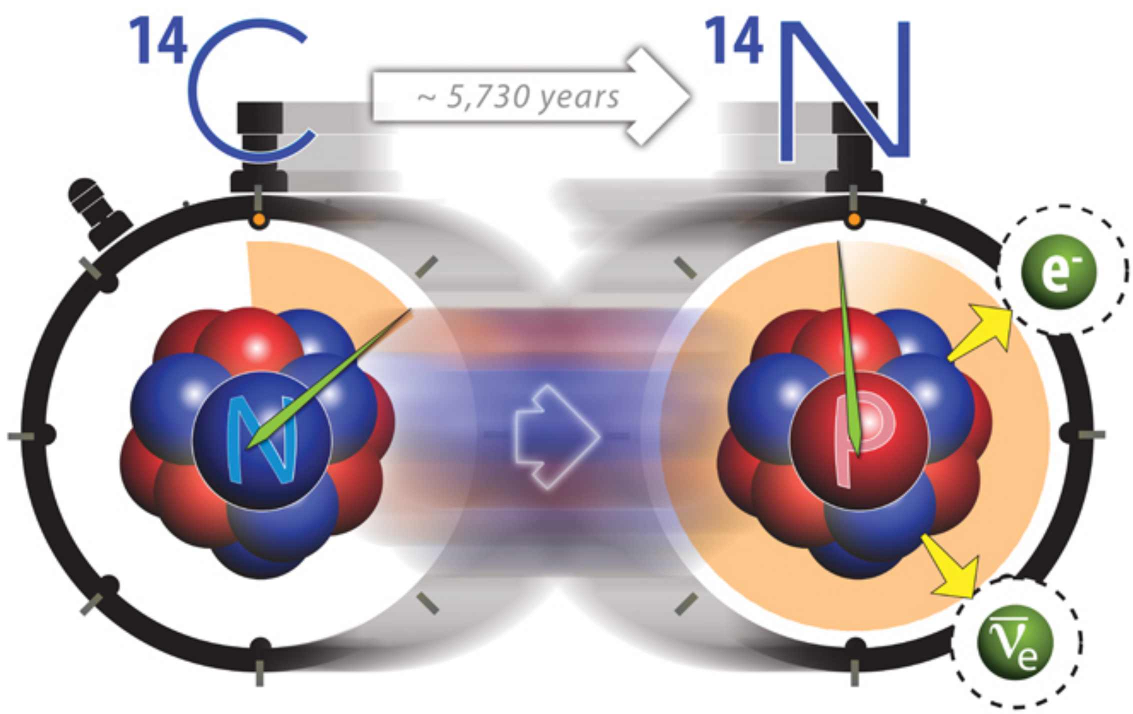
# CARBON-14: ANOTHER IGNORED DANGER FROM NUCLEAR POWER REACTORS




## *A BEYOND NUCLEAR WHITE PAPER 2016*

**Cover art: Decay of radioactive carbon-14 to stable nitrogen-14. "***When carbon-14 decays, the nucleus emits an electron and an anti-neutrino and becomes a nitrogen-14 nucleus"* **from Oak Ridge National Laboratories, Department of Energy**

***Carbon-14: another ignored danger from nuclear power reactors***

***There are a number of radionuclides released from nuclear energy facilities. This paper highlights carbon-14 for a number of reasons:***

- ***Carbon-14 is radioactive and is released into air as methane and carbon dioxide.***
- ***Before 2010, carbon-14 releases from nuclear reactors were virtually ignored in the United States. Today only estimates are required and only under certain restrictive circumstances.***
- ***There is no good accounting of releases to date, so its impact on our health, our children's health, and that of our environment remains unknown, yet environmental measurement is possible, but can be challenging under certain conditions.***
- ***Carbon-14 has a half-life of over 5700 years and the element carbon is a basic building block for life on earth. Therefore, "it constitutes a potential health hazard, whose additional production by anthropogenic sources of today will result in an increased radiation exposure to many future generations."[1]***
- ***Like tritium, it can collect in the tissues of the fetus at twice the concentration of the tissues in the mother, pointing to its disproportionate impact on the most vulnerable human lifecycle: the developing child.***

The element carbon is found in all organic substances. Carbon is also a primary constituent of greenhouse gases that are responsible for climate change, such as carbon dioxide ($CO_2$) and methane ($CH_4$). **Carbon-14** (c-14) is a **radioactive form** of carbon that occurs in nature and is also newly formed in nuclear power processes. Carbon-14 is a health concern because **it is released from nuclear power facilities as radioactive carbon dioxide and methane**, traveling readily in the local and global environment.

Over time, carbon-14 becomes part of organic material including food, and has a half-life of approximately 5,730 years, decaying by a type of radioactive particle called a beta. Its hazardous life is 10-20 times its half-life, meaning that harmful exposure to man-made carbon-14 can last for hundreds of generations. The radioactive carbon forms as a byproduct of fissioning of uranium fuel, through a process called activation. The final step is a chemical reaction between carbon-14 and oxygen or hydrogen, which forms methane or carbon dioxide. The radioactive carbon-14 formed by this process is brand new and would not exist without nuclear fission.

During its long hazardous life, carbon-14 could be responsible for gross physical or mental defects, stillbirths and childhood deaths, embryonic and neonatal deaths into the many millions over the life of the isotope. These millions could be underestimated five times or more. Carbon-14 could also be responsible for leukemia, bone and other cancers.

## A. NATURAL CARBON-14

Carbon-14 is produced in the atmosphere naturally by cosmic ray neutron interaction with nitrogen.[2] Ten billion carbon atoms will contain just about one atom of radioactive carbon-14. [3] Natural carbon-14 has a *total* inventory of $1.4 \times 10^8$ GBq[i] in the atmosphere.[4]

Modeling or predicting the natural production rate of carbon-14 is difficult for a number of reasons. Production rates vary because of changes to the cosmic ray flux incident, such as supernovae, and due to variations in the Earth's magnetic field. The latter can create significant variations in carbon-14 production rates, although the changes of the carbon cycle can make these effects difficult to tease out.[5]

## B. MAN-MADE CARBON-14

### 1. Nuclear bombs and nuclear power reactors[ii]

Man-made carbon-14 released by the atmospheric atom bomb tests doubled the amount of carbon-14 in the atmosphere, from about 230 to 450 Bq of carbon-14/kg of stable carbon.[6] Carbon-14 produced by atmospheric atomic bomb testing is believed to be about $2.2 \times 10^8$ GBq.[7]

To this day, the amount of carbon-14 remains 7% higher than it was before the atom bomb tests, even though above ground tests stopped in 1980.[8] (and see figure 1)

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[i] Becquerel (Bq) is a measurement of radioactivity represented by disintigrations per second. 1 Bq= 1 disintegration per second.

[ii] PLEASE NOTE: much of the data on carbon-14 is produced by the nuclear industry. As such, with rare exception, major studies on this isotope are also connected to the nuclear industry. The reference *Magnusson, 2007*, states in its front matter: “The majority of the studies have been conducted on behalf of or were partly financed by the Swedish Nuclear Fuel and Waste Management Company (SKB) and the Swedish Radiation Protection Authority (SSI).” Independent assessment of carbon-14 and many other isotopes is crucial yet rare.

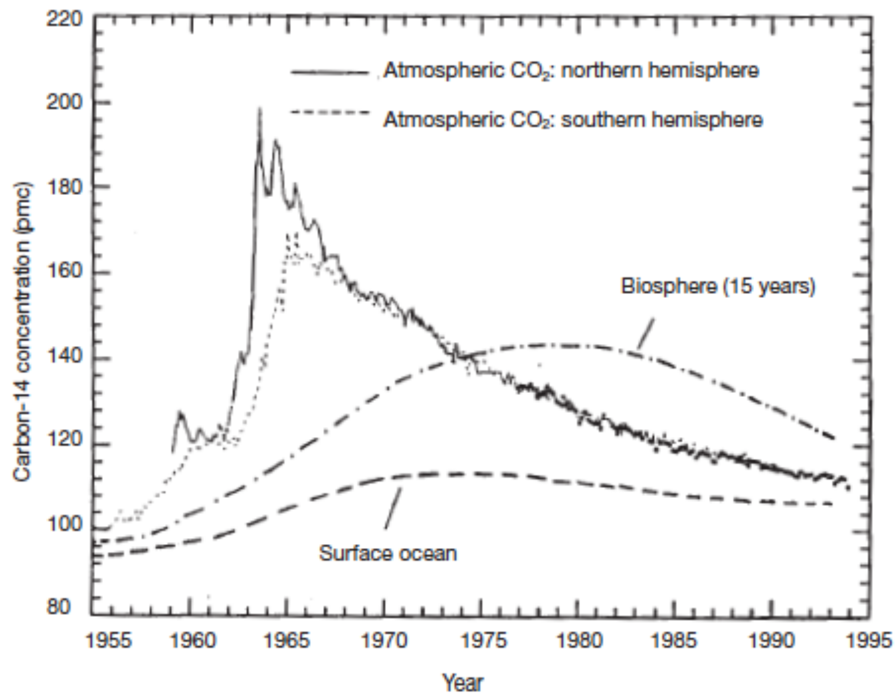


*FIG. 1. Carbon-14 concentration in the atmosphere: 1955–1994.*

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Today, the nuclear power industry is the major producer of carbon-14.[10] "Carbon-14 in the nuclear fuel cycle is produced by neutron interaction with…[carbon-13, nitrogen-14 and -15, and oxygen-16 and -17]…, which may be present in the nuclear fuels and the moderator and primary coolant systems of nuclear reactors."[11]

"The substrate atoms for the activation reactions (i.e. nitrogen, oxygen and carbon) occur widely in fuel, and in cladding, moderator, coolant or structural material, either as major constituents or as impurities. In consequence, $^{14}C$ produced in a nuclear power reactor can be released directly to the environment from the coolant and/or moderator in a gaseous form or in much smaller quantities as liquid effluents."[12]

Estimates of the amount of carbon-14 *produced* in different types of nuclear power reactors and nuclear fuel reprocessing facilities vary widely.[13] The amount of carbon-14 *released* by nuclear power reactors is rarely directly measured. (see Table 18, which is estimated.[14])

Measurements and estimates of gaseous carbon-14 releases (mostly methane and carbon dioxide) range widely between reactor types, and even among reactors of basically the same design, and between years of reactor operation.[15, 16, 17] Therefore, comparison between reactors, even of the same design, is a dicey proposition.

Direct release measurements of carbon-14 seem to be too few to get a real idea of just how much has been released by nuclear power.

The few times carbon-14 compounds have been measured out of the effluent points, this measurement is primarily made by industry and the requirement to measure varies by country.[18] Measurements by industry are fraught with incomplete data and a clear conflict of interest that would not be present with outside, independent monitoring which is desperately needed.

For instance, in the United States, carbon-14 emissions did not have to be "accounted for" until 2010, over 50 years after the advent of commercial nuclear power in 1957. If the carbon-14 emissions are deemed to be a large proportion of radioactive releases, then they need to be "accounted for" or estimated. There is otherwise no indication that carbon-14 releases have to be measured at any point.[19]

TABLE 18. ARISINGS AND RELEASES OF $^{14}C$ FROM VARIOUS TYPES OF REACTOR

| | Installed capacity (MW(e)) | Gaseous waste (GBq/a) | Liquid effluent (GBq/a) | Solid waste (decommissioning) (GBq/a) |
|---|---|---|---|---|
| LWR–PWR | 1000 | 129.5 | 1.3 | 647.5 |
| LWR–BWR | 1000 | 259.0 | 1.3 | 1165.5 |
| HWR | 600 | 3108 | Small | 703[a] |
| GCR–MGR | 480 | 373.7 | Small | 2982.2 |
| GCR–AGR | 660 | 255.3 | Small | 2479 |
| GCR–HTGR | 600 | 14.8 | Small | Small |
| FBR | 1250 | 0.65 | Small | Small |

[a] Value taken from Dubourg [11].

[20]

Measuring carbon-14 in the environment is tricky because environmental measurements of carbon-14 may underestimate carbon-14 releases from nuclear reactors if there are fossil fuel facilities close by.[21]

Additionally, environmental sampling of carbon-14 is subject to natural growth patterns and reactor fuel outages, meaning that lack of reactor created carbon-14 in tree rings doesn't necessarily mean none was released.[22]

Although fossil fuels add carbon in the form of carbon dioxide and methane to the environment, fossil fuels do not add *radioactive* carbon-14 and methane because almost all of the carbon-14 has decayed by the time these substances are burned for fuel.[23]

Pressurized water reactors release carbon-14 primarily in batches and primarily in the form of methane. Boiling water reactors release continuously, primarily as carbon dioxide.[24] Canadian reactors release carbon-14 at rates well above reactors in the U.S. (see Table 7 below)

TABLE 7. COMPARISON OF THE CHEMICAL FORMS (RELATIVE PERCENTAGE OF EACH SPECIES) OF $^{14}C$ IN AIRBORNE RELEASES FROM VARIOUS TYPES OF REACTOR

| | $^{14}CO_2$ | $^{14}CO$ | $^{14}C$ hydrocarbons |
|---|---|---|---|
| HWR (Bruce unit 7, Canada)[a] | 65.5–72.8 | 0.2–3.7 | 26.7–34.4 |
| HWR (Gentilly 2, Canada)[b] | 77.9–97.5 | 0.01–0.09 | 25.0–22.0 |
| PWR (USA and Europe) | 5–25 | — | 75–95 ($CH_4$ and $C_2H_6$) |
| BWR (USA and Europe) | 80–95 | — | 5–20 |

[a] Data were measured by Atomic Energy of Canada Limited in November 1994.
[b] Data were measured by Atomic Energy of Canada Limited in September and October 1995.

[25]

### 2. Waste isolation and reuse

Storage of nuclear power waste is a concern for public health over the long term because large quantities of carbon-14 remain in the form of lingering radioactive contamination in a closed nuclear facility. The facility components will be decommissioned and sent to a waste storage facility, from which the carbon-14 can leach out over generations.[26] At this point it is worth noting that every single low level radioactive waste dump built up until 1987 in the U.S. has leaked.[27] With dumps built since then, it seems only a matter of time. WIPP was not supposed to leak for thousands of years, but it took only 15.

Many waste cask designs use pass through air circulation for cooling in which the air actually passes between the inner fuel canister and the outer concrete over-pack and neutron shield. In these designs the nitrogen in the cooling air is exposed to unshielded neutrons producing radioactive carbon dioxide by activation of atmospheric nitrogen. These designs are cheaper than cask designs that circulate air outside the neutron shield and would not produce radioactive carbon dioxide. This carbon-14 production is not measured, even though it could be. Instead, the industry insists vehemently on estimating the carbon-14.[28]

Per facility, reprocessing plants (which break down and process irradiation nuclear fuel to separate out fissile uranium-235 and/or plutonium-238 for reuse)[29] release over seven times more carbon-14 than the next highest release from CANDU (Canadian Deuterium-Uranium) reactors (see Table 6 below). Any proposed nuclear technology which relies for its fuel on reprocessing technology, will feed into this release of radioactive carbon. The more of these reactors built, the more carbon-14 will be released by reprocessing facilities, primarily as the greenhouse gas carbon dioxide.[30] Even though these reactors are operating outside of the United States, carbon-14's impact on health needs to be assessed according to its GLOBAL environmental inventory because of the long hazardous life of the isotope.

TABLE 6. ESTIMATED $^{14}C$ ANNUAL RELEASE RATES IN THE ABSENCE OF CONTROL FROM REACTORS AND REPROCESSING PLANTS

| | Number of units | Estimated $^{14}C$ release rate (GBq/a) | Total (GBq/a) |
|---|---|---|---|
| PWR | 207 | 185 | 38 295 |
| BWR | 93 | 295 | 27 435 |
| HWR (CANDU) | 35 | 2 590 | 90 650 |
| Graphite reactor | 35 | 555 | 19 425 |
| RBMK reactor | 14 | 1 850 | 25 900 |
| WWER reactor | 47 | 1 850 | 86 950 |
| Subtotal | 431 | | 288 655 |
| Reprocessing plants[a] | 3 | 18 500 | 55 500 |
| Total | | | 344 155 |

**Note:** RBMK: high power channel type reactor; WWER: water cooled, water moderated power reactor.

[a] The reprocessing plants taken into account are La Hague (COGEMA, France), Sellafield (BNFL, UK) and Chelyabinsk (Russian Federation).

[31]

Sources seem divided on whether certain forms of reprocessing (like pyro-processing in the integral fast reactor designs) exist that would prevent the eventual release of carbon-14 in a gaseous form or otherwise.[32, 33]

Many transmutation proponents agree that long-lived components of radioactive waste, such as carbon-14, “cannot be transformed into less dangerous forms because of fundamental limitations that cannot be overcome by technology development.”[34]

“…[M]ost transmutation proposals do not specify how they will handle the carbon-14…”.[35]

Although methods for the separation of radioactive carbon dioxide and non-radioactive carbon dioxide (generated by removal of carbon-14) may be available for use in some forms of irradiated waste reprocessing, they are relatively costly,[36] which presents a strong disincentive for their use.

## C. HEALTH AND ENVIRONMENTAL IMPACTS

**Natural carbon-14 accounts for a miniscule fraction of natural carbon, the rest of which is stable, that is, non-radioactive. It accounts for less than one percent of our radiation dose from natural sources.[37] Adding artificial carbon-14 to this dose increases risk of disease from radiation exposure.**

Carbon-14 replaces stable (non-radioactive) carbon, exposing cells to damaging radiation energy and decaying to a different element (nitrogen) which will not act as carbon structurally.

Because carbon-14 has a half-life of over 5700 years and the element carbon is a basic building block for life on earth, "…it constitutes a potential health hazard, whose additional production by anthropogenic sources of today will result in an increased radiation exposure to many future generations."[38]

An Environmental Protection Agency Advisory Panel concluded that, although release of carbon-14 from waste sites would be under the regulatory limit, these small, allowable individual doses would result in a large overall population dose, causing a projected increase in cancers over thousands of years.[39]

Linus Pauling, winner of the Nobel Prize for Chemistry and the Nobel Peace Prize stated "[t]he estimated effects of carbon-14 from 1 year of bomb testing…are 12,000 children with gross physical or mental defect, 38,000 stillbirths and childhood deaths, and 90,000 embryonic and neonatal deaths." This number is based on population remaining constant at 1958 levels and is over the life of the carbon-14 isotope. Greater population will mean a greater number of these effects proportionally and some of these impacts may overlap, meaning one individual may experience more than one effect. [40]

Pauling concludes that "[t]hese estimates must be recognized as highly uncertain…they might be 5 times too high or 5 times too low, or more, but that we are better off estimating even very crudely what the numbers involved are than not making any numerical estimates at all. I agree with this statement."[41]

There were approximately 17 years of above ground bomb tests. Therefore, according to Pauling's calculation, and allowing for the uncertainty of the estimates being 5 times too low or high, we could see anywhere from 40,800-1,020,000 children with gross physical or mental defects, 129,200-3,230,000 stillbirths and childhood deaths and 306,000-7,650,000 embryonic and neonatal deaths, assuming a constant 1958 world population level.

These numbers do not account for synergistic effects with other pollutants, including other radionuclides, or the additional carbon-14 effluent from worldwide nuclear power, [42] nor do they include any additional effect not listed in these three categories or account for underground nuclear test leakage to the air. [43]

"In addition, … there would be produced a larger but unknown number of minor or intangible defects, which might represent the major part of the damage, because by virtue of their being milder they are less likely to cause the sterility or death of the person who possesses them and therefore are more likely to persist in the population and thus to affect a larger number of persons."[44]

"…we calculate that the total number of cases of leukemia and bone cancer expected to be caused by carbon-14 is about equal to the number expected to be caused by fission products, including strontium-90, and that the number of cases of cancer of other sorts expected to result from radiation damage to tissues other than bone marrow and bone tissue is greater for bomb-test carbon-14 than for fission products."[45]

There is a "highly statistically significant 37% increase in childhood leukemias within 5 km of almost all NPPs [nuclear power plants] in the UK, Germany, France and Switzerland."[46],[47] Carbon-14 could be, in part, responsible for this increase along with other routinely released isotopes such as tritium.

A fetus can collect carbon-14 at twice the concentration ratio in its tissues as compared to the mother, meaning that per mass, the fetus can become twice as contaminated as the adult female at a particularly vulnerable time of development.[48]

In a nasty irony, release of non-radioactive carbon by fossil fuel combustion had diluted the uptake of naturally occurring radioactive carbon, actually lowering the dose humans received, thereby mitigating natural carbon-14's radioactive impact on human health. Called the Seuss effect, it was overtaken after about 1950 with the carbon-14 release from nuclear power and nuclear weapons.[49] What happens when the non-radioactive carbon from fossil fuel production is replaced by carbon-14 producing nuclear power? Will biological systems take up not only more naturally occurring carbon-14, as before, but also more carbon-14 from nuclear emissions?

Carbon atoms can reside in the human body for at least ten years or more depending on the organ, the form of uptake, and other circumstances.[50]

Gaseous releases of carbon-14 give radioactive doses to local or global populations, first through the air, then by contaminating food.[51] Liquid releases are considered an insignificant amount of total releases, but fish accumulate radioactive carbon from their environment to a very high degree, having concentration factors as high as 5000 times.[52] This indicates that a radioactive carbon dose from fish to humans could be significant, not because of the amount released initially, but because carbon-14 biomagnifies. Any time carbon-14 is elevated in grass, soil or water, the chance of it getting into the human food supply increases.

Grass around CANDU reactors was found to contain carbon-14 (from releases of carbon dioxide) as high as 28% above contemporary background levels.[53]

Samples of grass and tree leaves around a Lithuanian RBMK reactor showed carbon-14 as much as 42% higher than background. Mosses and soil around these reactors was found to be 2000 times background, but researchers concluded this contamination was not from carbon dioxide off-gassing, but from pieces of graphite from the Chernobyl explosion that reached Lithuania. The reactor that exploded at Chernobyl was an RBMK design.[54]

The Sellafield reprocessing facility had carbon-14 levels in grass 80% above natural background.[55]

Pickering station in Canada had 20 times the natural carbon-14 in nearby grass samples.[56]

Natural and man-made carbon-14 has decreased in the atmosphere over the years because the deep ocean is functioning as a sink for it.[57] While carbon-14 is used for dating and understanding deep sea biochemical processes,[58] there seems to be little information on how an increase in radioactive carbon-14 is affecting ocean life or those that consume it.

Nuclear power reactors have never been "zero emissions". The nuclear fuel chain emits significantly more greenhouse gases at the front and rear ends than do renewable energies.[59] Nuclear reactors themselves are routinely emitting radioactivity into the air and water.[60] And, yes, some of these emissions are not only radioactive, they are also greenhouse gases.

Prepared by Cindy Folkers for Beyond Nuclear. 2016.

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