SCIENCE & GLOBAL SECURITY
2022, VOL. 30, NO. 2, 54–61
https://doi.org/10.1080/08929882.2022.2119716

Routledge
Taylor & Francis Group

RESEARCH NOTE

The Long-Term Global Health Burden from Nuclear Weapon Test Explosions in the Atmosphere: Revisiting Andrei Sakharov's 1958 Estimates

Frank N. von Hippel

Program on Science and Global Security, Princeton University, Princeton, NJ, USA

ABSTRACT

In 1958, the Soviet physicist Andrei Sakharov published an estimate of the long-term health impacts from carbon-14 produced by nuclear test explosions in the atmosphere. At the time, Sakharov was an important contributor to the Soviet Union's development of multi-megaton thermonuclear weapons. This was Sakharov's first public expression of concern about the weapons work in which he was involved. Subsequently, he became a campaigner for human rights in the Soviet Union and for international cooperation and received the 1975 Nobel Peace Prize in recognition of the importance of his efforts. This article provides some context for his estimate and compares it with estimates based on dose estimates by the UN Scientific Committee on Effects of Atomic Radiation and dose-effect estimates by the US National Academies.

ARTICLE HISTORY
Received 3 April 2022
Accepted 8 May 2022

In 1958, Soviet physicist Andrei Sakharov published an article estimating the long-term health-impacts from radioactive carbon produced by nuclear weapon explosions in the atmosphere.[1] This article marked the beginning of his transition from a designer of nuclear explosives into the advocate for human-rights who would be awarded the 1975 Nobel Peace Prize.

Sakharov had been recruited into the Soviet program in 1948 to help develop thermonuclear weapons. He contributed key ideas and the Soviet Union developed and tested thermonuclear explosives in the mid-1950s, soon after the United States. Sakharov was given the Soviet Union's highest awards and was made a full member of the Soviet Academy of Sciences in 1953 at the age of 32.

First-generation thermonuclear warheads had explosive yields up to thousands of times greater than the fission weapons that destroyed Hiroshima and Nagasaki in August 1945. After the race to develop these terrible weapons had been completed, Sakharov had time to think about

CONTACT Frank N. von Hippel fvhippel@princeton.edu Program on Science and Global Security, Princeton University, Princeton, NJ, USA.

the implications. He worried that, even if nuclear war could be averted, the radioactivity produced by the huge atmosphere nuclear tests would cause genetic diseases including cancer.

Sakharov appears to have been alerted to the potential importance of test-produced radioactive carbon-14 by an article published by a Soviet colleague six months earlier in December 1957 in the same journal, *Atomic Energy*. O.I. Leipunskii critiqued the idea of a "clean" nuclear bomb advanced by Edward Teller, the leading U.S. advocate of thermonuclear weapons. Teller had turned President Eisenhower against a test ban by arguing that continued testing would lead to "virtually clean weapons," almost pure fusion bombs that would not produce the global radioactive fallout that had generated public opposition to atmospheric nuclear testing.[2]

Leipunskii pointed out that the huge quantities of excess neutrons emitted by fusion as well as fission explosions would convert large quantities of atmospheric nitrogen-14 into radioactive carbon-14 that would pollute the biosphere for thousands of years[3] (Carbon-14 has a 5700-year half-life).

Sakharov cited Leipunskii's article as his first reference in his own article in June 1958. In that same issue of *Atomic Energy*, Leipunskii wrote a second article in which he reviewed the new book by Edward Teller and Albert Latter, *Our Nuclear Future: Facts Dangers and Opportunities.* Leipunskii excoriated Teller and Latter for their minimization of the impact of the radioactivity from atmospheric nuclear tests. He argued that there should be concern about the impact not only on the present generation but for "illness of the twentieth generation."[4]

In Sakharov's article of June 1958, he assumed the total energy yield of the nuclear explosives that had been tested in the atmosphere up to that time as about 50 megatons (Mt) of chemical explosive equivalent.[5] He estimated the total quantity of atmospheric nitrogen-14 transmuted into carbon-14 by neutrons from those explosions, the resulting concentration of carbon-14 in the biosphere's carbon as a result, the total population dose that would accumulate over the generations as the carbon-14 decayed, and then the health consequences of that population dose. He concluded that, in a future global population of 30 billion, serious health effects from the 50 Mt of atmospheric tests would occur at an initial rate to about 40 individuals per year, a rate that would decline with the 5700-year half-life of carbon-14 but cumulate to about 330,000 people seriously affected.

The Soviet journal, *Atomic Energy,* in which Sakharov's article appeared was being translated by the U.S. government but Sakharov was unknown outside the Soviet nuclear weapon program at the time and there was no public notice of the article in the West.

A few months after Sakharov's article appeared in Russian, Linus Pauling, an American physical chemist who had been awarded the Nobel Prize in Chemistry in 1954 and was an opponent of nuclear weapons and nuclear testing, published a similar article in the journal *Science*. Pauling estimated that 55,000 children would be born with "gross physical or mental defects" as a result of the carbon-14 produced by 30 Mt of atmospheric tests.[6]

Like Sakharov, Pauling believed that carbon-14 produced by atmospheric tests would cause more cumulative genetic damage than fission products. In part, this simply reflected the facts that 45 times more carbon-14 atoms would be produced than the most important fission product, cesium-137 and that carbon is a major constituent of the body (12% of the atoms).[7]

The fission products were receiving much more attention at the time because there is no natural background and their presence was readily detectable and being reported, most notably, strontium-90 in baby teeth.[8] In contrast, the carbon-14 from atmospheric testing raised the natural level by about 2%.[9]

The driving force of the nuclear arms race prevailed for the following few years. Despite a two-year testing moratorium during 1959–1960, the total yield of Soviet tests during 1958–1962 was an astonishing 236 Mt and U.S. plus U.K. and French tests during that period totaled 77 Mt, for a combined total of 314 Mt.[10] Most of this testing occurred during 1961–1962, while Soviet-U.S. tensions ramped up over U.S., French, and U.K. access to West Berlin and then climaxed during the Cuban Missile Crisis. During this two-year period, the Soviet Union and United States set off 176 nuclear tests with combined power of 264 Mt, with the largest Soviet test having a power of 50 Mt (the largest nuclear explosion in history).

Soviet, U.S. and U.K. testing in the atmosphere ended in 1962. By that time, their combined nuclear megatonnage released in the atmosphere had risen to 409 Mt.[11]

It was the planned binge of high-yield Soviet tests in 1958–1962 that moved Sakharov to argue to then Soviet leader, Nikita Khrushchev, that those tests were not all necessary. Khrushchev believed, however, that they were important to Soviet nuclear deterrence. In his memoirs, Sakharov recounts Khrushchev declaring, "I'd be a jellyfish and not Chairman of the Council of Ministers if I listened to people like Sakharov!"[12]

The sobering effect of the 1962 Cuban Missile Crisis on top of the continuing worldwide protests over the global radioactive fallout from atmospheric testing helped bring nuclear testing in the atmosphere to an end. When negotiations on a Test Ban Treaty became stuck over the annual number of allowed on-site inspections of suspect seismic events, Sakharov urged that the Soviet Union agree to a ban on tests everywhere except underground. This time the Soviet leadership listened[13] and, in 1963, the Soviet Union, United States and United Kingdom agreed to a Partial Test Ban Treaty that ended their testing in all environments except underground.

Pauling was awarded the Nobel Peace Prize in 1963 for his leadership in the international campaign to end atmospheric testing.[14] Although Sakharov's efforts inside the Soviet bureaucracy were not recognized at the time, he was awarded the Nobel Peace Prize 12 years later for his larger "struggle for human rights, for disarmament, and for cooperation between all nations [with] peace as its final goal."[15]

France, which carried out its first nuclear test in 1960, and China, which tested first in 1964, continued to test in the atmosphere until 1974 and 1980, respectively, raising the total yield by another 31Mt to 440 Mt by the time all nuclear testing in the atmosphere finally ended in 1980.

Scaling Sakharov's estimate of the number of people who would be genetically affected by nuclear-explosion-produced carbon-14 from 50 to 440 Mt increases his estimate of the number of serious health effects to 3 million over thousands of years.

Estimating the health impact of atmospheric nuclear testing

Estimates of the health impacts of carbon-14 are a product of two factors:

1. The population radiation dose, i.e., the sum over hundreds of generations of the estimated radiation doses to individuals from the radioactive decay in their bodies of carbon-14 produced by atmospheric nuclear explosions.
2. The dose-effect coefficients that translate the population dose into health effects.

Current estimates of these factors are reviewed below and the resulting consequence estimates are compared to Sakharov's.

Population radiation doses

The last atmospheric nuclear test was conducted by China in 1980. In 1982, 1993, and 2000, the U.N.'s Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimated and re-estimated the cumulative effective radiation population whole-body dose equivalent to the world's past, current and future population. In 1982, and again in 1993, the estimated total dose cumulated from bomb-produced radioactive carbon-14 was estimated as 26 million person-Sievert, with an additional 4 million person-Sievert from fission products and 0.2 million person-Sievert from plutonium and americium.[16]

Most of the population dose commitment from the fission products has already occurred. Carbon-14, however, has a radioactive half-life of 5,700 years and leaks from the biosphere only very slowly. UNSCEAR-1982 estimated that 90% of the dose commitment from carbon-14 will occur after 2050.[17] The population dose from carbon-14 is therefore the summed dose to hundreds of generations. The doses are due to carbon-14 emitting a high-energy electron when it decays back into nitrogen-14. The genetic damage due to the ionizing energy deposited in tissue is measured in Sievert units (Sv).

The population dose is obtained by multiplying the individual dose commitments by a world population of a size appropriate to the period during which most of the dose would be incurred and adding up those doses over generations. For the most important fission products, which have half-lives of 30 years or less, UNSCEAR assumed the global population in 1963 when the United States and Soviet Union ended their atmospheric testing (3.2 billion). In the case of carbon-14, however, the size of the world population hundreds and thousands of years in the distant future is unknown.

Sakharov assumed a future world equilibrium population of 30 billion. UNSCEAR has assumed 10 billion. In 2019, the global population was about 7.7 billion and the United Nations was projecting 9.7 billion in 2050 and nearly 11 billion in 2100.[18]

Dose-effect coefficients

All the dose-effect coefficients discussed below are associated with the standard "linear hypothesis" that health risks from radiation scale linearly with dose at low individual doses. This makes it possible to add dose health consequences without knowing the distribution of doses within the population or even between generations.

Sakharov estimated the lifetime risk of cancer induction as 1–2% per Sievert. The most recent (2006) U.S. National Academies report on the subject, *Health Risks from Exposure to Low Levels of Ionizing Radiation* (hereafter NA-2006), estimates the cancer risk from low-rate whole-body exposure to gamma and beta radiation in the United States as significantly higher: 5–20% per Sievert.[19]

NA-2006 also gives the mortality rate for this mix of cancers as about 50%.[20] Due to improved screening and treatment, however, cancer survival has been increasing in advanced countries and could change greatly in the future.

Sakharov worried also that the increased doses of ionizing radiation from carbon-14 would increase the incidence of hereditary diseases, such as "schizophrenia, hemophilia, diabetes, and many others." Based on mice experiments, he estimated the probability of causing a heritable disease as about 1% per Sievert. NA-2006 estimates genetic risks to the first generation as 0.3–0.47% per Sievert.[21] The report also notes, however, that there has been a "lack of demonstrable adverse genetic of radiation" among the best studied population, the survivors of the Hiroshima and Nagasaki bombings.[22]

Finally, Sakharov suggested that radiation might damage the immune system with life-shortening effects. NA-2006 did find an increase with dose of death from some causes other than cancer, notably "heart disease, stroke, and diseases of the digestive, respiratory and hematopoietic systems."[23]

Overall, Sakharov estimated 0.06 serious health effects per Sievert, which is at the lower end of the NA-2006 cancer-risk range of about (0.05–0.20)/Sv.

Using the National Academy report estimates, a population dose from carbon-14 of 26 million person-Sv would result in 1.3–5.2 million serious health effects from atmospheric testing compared with the scaled Sakharov estimate of 3 million. Sakharov's higher assumption for the size of the future global population was offset by his lower estimate for the coefficient of cancer induction by ionizing radiation.

One effect that both Sakharov and UNSCEAR left out is the dilution of carbon-14 in the atmosphere and biosphere by the nonradioactive carbon that humanity has been injecting into the atmosphere by burning fossil fuels. This is described as the "Suess effect" after Hans Suess who noted in 1955 that this had complicated carbon-14 dating in the modern era.[24] The concentration of atmospheric CO_2 increased by 30% between 1958 and 2020,[25] due mostly to the burning of fossil fuels.[26] The dose from carbon-14—both natural and explosion-made—has been reduced in proportion to that increase. The resulting decrease in the concentration of natural carbon-14 is already an order of magnitude greater than the increase due to atmospheric testing.

Although amounting to millions of people over thousands of years, the increase in the numbers of cancers and other genetic effects from the carbon-14 created by atmospheric nuclear testing will not be statistically detectable in the huge background of these same effects from other causes that vary due to other changes in human environments and lifestyles. Those who will suffer from health effects from atmospheric nuclear tests will not know the cause but their suffering will be no less. Sakharov took personal responsibility for that future suffering from carbon-14 created by Soviet nuclear explosions and acted to help end nuclear testing in the atmosphere. Achieving his larger goal of eliminating war remains a challenge for us all.

Acknowledgments

This article was originally invited by Leonid Gurvits as a comment on Sakharov's article on the health effects of atmospheric nuclear tests for a forthcoming collection of Sakharov's scientific works. It has benefited greatly from suggestions by Bemnet Alemayehu, Jan Beyea, Zia Mian, and M.V. Ramana.

Notes and References

1. A. Sakharov, "Radioactive Carbon from Nuclear Explosion and Non-threshold Biological Effects," *Soviet Journal Atomic Energy* 4 (1958): 757–62. Following Sakharov's death in 1989, the U.S. Government translation was reprinted in *Science and Global Security* 1 (1990): 175–87. https://scienceandglobalsecurity.org/archive/1990/01/radioactive_carbon_from_nuclea_1.html, along with a review by the current author. Both were reprinted in the Thirtieth Anniversary Issue, *Science and Global Security* 17 (2009): 159–69.
2. Katherine Magraw, "Teller and the 'Clean' Bomb Episode," *Bulletin of the Atomic Scientists* 44 (1988): 32–7.
3. O.I. Leipunskii, "Harmful Effects of the Radioactivity from Explosion of Pure Hydrogen Bombs and Ordinary Atomic Bombs," *Soviet Journal of Atomic Energy* 3 (1957): 1413–25.
4. O.I. Leipunskii, Review of "E. Teller and A. L. Latter, *Our Nuclear Future: Facts, Dangers, and Opportunities* (New York, NY: Criterion books, 1958), *The Soviet Journal of Atomic Energy* 4 (1958): 801–4. A book about Leipunskii, his brother and his sister—all three physicists—has been published in Russian by B. S. Gorobets, *The Three from the Atomic Project: Top-Secret Physicists Leipunskiis* (Moscow: LKI, 2008). For a review in English, see http://archive.ujp.bitp.kiev.ua/files/journals/53/3/530314p.pdf.
5. There had actually been about 95 Mt of tests in the atmosphere by the end of 1957, U.N. Scientific Committee on the Effects of Atomic Radiation, *Ionizing Radiation: Sources and Biological Effects* (United Nations, 2000) (hereafter UNSCEAR-2000) Annex C, 207, https://www.unscear.org/docs/publications/2000/UNSCEAR_2000_Annex-C-CORR.pdf.
6. Linus Pauling, "Genetic and Somatic Effects of Carbon-14," *Science* 128 (1958): 1183–86. Pauling also estimated 170,000 stillbirths and 425,000 embryonic and neonatal deaths.
7. Sakharov estimated about $2x10^{26}$ carbon-14 atoms would be produced per megaton in the atmosphere. UNSCEAR-2000, 213 estimated that 440 Mt of atmospheric testing had produced an amount of carbon-14 corresponding to 213 PBq (213×10^{15} disintegrations per second), which would correspond to 1.3×10^{26} per Mt. By comparison, UNSCEAR-2000, 213, estimated 2.15 PBq (0.029×10^{26} atoms) of cesium-137 per Mt.
8. "St. Louis Baby Tooth Survey, 1959–1970" (Washington University School of Dental Medicine, St. Louis, undated) http://beckerexhibits.wustl.edu/dental/articles/babytooth.html.
9. Carbon-14 is produced naturally in the atmosphere at a rate of about 1.54 PBq/year by neutrons generated by cosmic ray collisions with atmospheric nuclei. This yields a cumulative inventory of 12,740 PBq (UNSCEAR-2000, 115, Table 4).
10. UNSCEAR-2000, 195–204.

11. UNSCEAR-2000, 205.
12. Andrei Sakharov, *Memoirs* (New York: Alfred A. Knopf, 1990), 217.
13. Andrei Sakharov, *Memoirs,* 230–1.
14. Presentation speech for Nobel Peace Prize award to Pauling, https://www.nobelprize.org/prizes/peace/1962/ceremony-speech/.
15. Presentation speech for Nobel Peace Prize award to Sakharov, https://www.nobelprize.org/prizes/peace/1975/ceremony-speech/.
16. UNSCEAR-1993, 129.
17. UNSCEAR-1982, 215.
18. United Nations, "Population," 2019, https://www.un.org/en/global-issues/population.
19. *Health Risks from Exposure to Low Levels of Ionizing Radiation* (Washington, DC: National Academy Press, 2006) (hereafter NA-2006), 281, https://nap.nationalacademies.org/catalog/11340/health-risks-from-exposure-to-low-levels-of-ionizing-radiation.
20. NA-2006, Table 12–4.
21. NA-2006, 117, Table 4–6.
22. NA-2006, 114.
23. NA-2006, 152–4.
24. Hans Suess, "Radiocarbon Concentration in Modern Wood," *Science* 2 (1955): 415–7.
25. "Climate Change: Atmospheric Carbon Dioxide" (U.S. National Oceanic and Atmospheric Administration, 2020) https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide.
26. Since 1750 "the combustion of fossil fuels was responsible for about 64% ± 15%, growing to an 86% ± 14% contribution over the past 10 years" to the increase in carbon dioxide in the atmosphere, International Panel on Climate Change, *Climate Change 2021, The Physical Science Basis, Technical Summary*, 80, https://www.ipcc.ch/report/ar6/wg1/.

ORCID

Frank N. von Hippel http://orcid.org/0000-0002-7934-9584