Environmental Health Policy

A SHORT LATENCY BETWEEN RADIATION EXPOSURE FROM NUCLEAR PLANTS AND CANCER IN YOUNG CHILDREN

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Previous reports document a short latency of cancer onset in young children exposed to low doses of radioactivity. The standard mortality ratio (SMR) for cancer in children dying before age ten rose in the period 6–10 years after the Three Mile Island and Chernobyl accidents in populations most exposed to fallout. SMRs near most nuclear power plants were elevated 6–10 years after startup, particularly for leukemia. Cancer incidence in children under age ten living near New York and New Jersey nuclear plants increased 4–5 years after increases in average strontium-90 in baby teeth, and declined 4–5 years after Sr-90 averages dropped. The assumption that Sr-90 and childhood cancer are correlated is best supported for a supralinear dose-response, meaning the greatest per-dose risks are at the lowest doses. Findings document that the very young are especially susceptible to adverse effects of radiation exposure, even at relatively low doses.

The latency period between radiation exposure and the onset of cancer has been documented to be as long as several decades. However, some radiation-induced cancer occurs after a much shorter period. Perhaps the first evidence of a short latency was documented in the 1950s, with high rates of thyroid and other cancers typically within 10 years of X-ray irradiation to infants and young children (1–3). Leukemia rates among Hiroshima and Nagasaki survivors were elevated beginning 5 years after the 1945 bombings, reaching a peak 10 years after (4–6). Adults treated with therapeutic radiation for ankylosing spondylitis demonstrated increases in mortality from leukemia within 2 years, and prostate cancer, pancreatic cancer, and extracranial tumors, each after 5 years (7). Lung cancer after the same treatment became elevated beginning 9 years after exposure (8). Irradiation treatment for cervical cancer resulted in elevated pancreatic cancer and

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leukemia 1–4 years after exposure (9–11). Peak levels of bone cancer after injection of radium-224 occurred 8 years after treatment (12).

Even at relatively low doses, irradiated adults are at greater risk for cancer just several years after exposure. A peak of chronic myeloid leukemia incidence was observed 6–10 years after X-rays to the back, gastrointestinal tract, and kidneys (13). Mormon families in Utah living directly downwind of atmospheric nuclear weapons tests in Nevada were found to have significantly higher incidence of all cancers combined and certain radiosensitive tumors 7–15 years after the tests began (14). Four to 5 years after the Chernobyl accident, thyroid cancer among adults in the Czech Republic and Poland increased (15, 16).

The developing fetus and infant have a predisposition to cancer from various types of low-dose radiation exposure within a decade. Pelvic X-rays to pregnant women in the 1950s initially was linked to a near doubling of the risk of cancer death before 10 years of age (17, 18). Subsequent reports on larger populations confirmed this excess, for both leukemia and other childhood cancers (19–21).

Elevated levels of radiosensitive cancers in the young shortly after exposure to fallout from atmospheric nuclear weapons tests have also been documented. Peaks in acute myeloid leukemia deaths in U.S. children age 5–9 years occurred in 1962 and 1968, about 5 years after the peak testing periods of the late 1950s and early 1960s (22). From 1948–52 to 1958–62, the number of Utah residents under age 30 who had their cancerous thyroid gland removed surgically rose from 6 to 30, much faster than the national increase (23). In five Nordic countries, leukemia incidence in children under age 5 peaked during the highest periods of fallout from bomb tests (24).

More recently, an elevation in leukemia diagnosed in the first year of life was seen in children born in 1986 and 1987, just after the accident at Chernobyl, representing a latency period of less than 2 years between in utero exposure and diagnosis. These elevations were documented in multiple nations, including Belarus (25), Greece (26), Scotland (27), the United States (28), Wales (29), and West Germany (30), plus a grouping of European countries (31). A latency beginning just 4 years between the accident at Chernobyl and elevated thyroid cancer rates in children has been reported in Belarus and the Ukraine (32–34). Rising thyroid cancer incidence in children has also been reported within 10 years of the accident in the moderately exposed areas of Belgium (35), East Hungary (36), and northern England (37). While some reports have found no excess in non-thyroid cancers in children irradiated by Chernobyl fallout, elevated rates with 10 years of exposure have been documented in the Ukraine (38) and Turkey (39).

Other reports have found unexpectedly high rates of childhood cancer, often leukemia and typically diagnosed before age 10, near nuclear installations. Early childhood cancer near nuclear plants likely represents effects of exposures in utero and in infancy. In the United Kingdom alone, at least eleven such reports representing different nuclear plants exist (40–50). Similar results were observed in Canada (51), France (52), Germany (53), and the former Soviet Union (54). Reports on this topic from the United States have been limited to several examining populations near a single facility at least two decades ago (55–59). Data from a 1990 National Cancer Institute report show that cancer incidence for age 0–9 years near each of four U.S. reactors exceeds the state rate (60). A recent analysis shows that cancer incidence for age 0–9 within 30 miles of each of 14 U.S. plants exceeds the national average for 1988–97, based on 3,669 cases (61).

The many reports documenting a 5–10 year lag between radiation exposure and childhood cancer onset, plus elevated childhood cancer near nuclear power plants, illustrate the heightened sensitivity of the fetus and infant to toxins. In this report I further examine this susceptibility by analyzing temporal trends in childhood cancer in populations exposed to low-dose nuclear power plant emissions 5–10 years after initial exposure.

METHODOLOGY

The first part of this report analyzes changes in childhood cancer mortality in four U.S. populations (described below) exposed to radioactivity from nuclear reactor emissions. Mortality is used since it is easily available for each U.S. county for each year from 1979 to 2002. Deaths of children before age 10 years are used, due to the heightened sensitivity to the fetus and infant and the expected latency of 5–10 years.

Because of the expected brief latency between exposure and disease onset, cancer deaths at age 0–9 in the periods 1–5 and 6–10 years after startup (used in the 1990 National Cancer Institute study of 52 U.S. nuclear power plants) can serve as controls and cases, respectively. Temporal changes in the standard mortality ratio (SMR), representing the ratio of observed to expected (local vs. national) rates, are examined. Significance of differences in observed and expected changes is tested using a standard z-score test.

Three Mile Island. On March 28, 1979, reactor unit 2 at the Three Mile Island nuclear installation in Pennsylvania experienced a partial core meltdown resulting from loss of cooling water. The damaged reactor emitted elevated (but still relatively low) levels of radioactivity; the total of 14.2 curies of airborne iodine-131 and effluents (all radioisotopes with a half-life of more than eight days) was about 400 times the average annual emissions from the plant to that time (62). The majority of fallout from the accident traveled with prevailing winds, in a north-northeasterly direction, being detected in elevated levels in the environment in distant locations such as Albany, NY (63), and Portland, ME (64).

This study considers cancer mortality for children age 0–9 years residing in the 34 contiguous counties north and northeast of Three Mile Island (see Appendix I).

Of these, 28 counties are in Pennsylvania and six in New Jersey, and all lie within 130 miles of the plant. SMRs in the period 1979–83 (1–5 years after the accident) and 1984–88 (6–10 years after) are compared. ICD-9 diagnosis codes 140.0–239.9 are used to identify all cancers combined, in all four study groups in this report. SMR changes for leukemia (ICD-9 204.0–208.9) and all other cancers combined are also reviewed.

Chernobyl. On April 26, 1986, reactor unit 4 at the Chernobyl plant in the Ukraine experienced a total core meltdown. Fallout from the disaster was propelled well into the stratosphere and across the globe. In the United States, elevated but relatively low levels of environmental radioactivity were observed beginning May 5, as precipitation returned fallout to earth. Short-lived radioisotopes remained elevated during the remainder of May and June; and long-lived isotopes did not return to pre-accident levels for another three years (65).

U.S. government measurements during May and June identified areas of the country that received the greatest levels of Chernobyl fallout. The upper Midwest and Pacific northwest, along with New York City, Washington, DC, and Maine, had the highest concentrations of iodine-131 (half-life of 8.05 days) in pasteurized milk from May 6 to June 30, 1986 (Table 1).

The change in SMR for cancer at age 0–9 years from the period 1986–90 to 1991–95 (1–5 and 6–10 years after the accident) for 17 states and the District of Columbia is compared with that of the remaining U.S. states. In New York, only the New York City area is included, since the average I-131 concentration in Buffalo and Syracuse was 8.0 picocuries per liter of pasteurized milk, well below the New York City average (14.0). In California, only the 29 northern counties are included, as I-131 averages for Sacramento and San Francisco (19.6 and 17.2) were well above that for Los Angeles (6.7). See Appendix II for a list of states and counties studied.

Counties near New Nuclear Plants—Startup before 1982. The 1990 study by the National Cancer Institute examined cancer mortality before and after startup of 52 nuclear power plants. The 1990 report calculated SMRs for 5-year intervals (1–5 years before and after startup, 6–10 years before and after startup, etc.) for various age groups. This report examines the change in SMR from 1–5 years after startup to 6–10 years after startup for children age 0–9 years living near plants. Included are data from each of the 20 areas near nuclear plants (defined by the 1990 study) with the largest populations, which account for 89 percent of annual cancer deaths at age 0–9 near the 52 plants. More than 18.3 million persons lived in these counties in 2000 (Table 2).

Counties near New Nuclear Plants—Startup since 1982. Beginning in 1982, a total of 23 U.S. nuclear plants began operations at installations with no existing nuclear reactors. These were not included in the 1990 study, because of the late

Table 1

U.S. sites with highest average concentrations of iodine-131 in pasteurized milk after the Chernobyl accident

Site	No. of samples	Average I-131[a]
Boise, ID	8	71.0
Spokane, WA	12	42.0
Helena, MT	12	30.8
Rapid City, SD	12	27.8
Salt Lake City, UT	12	25.6
Seattle, WA	11	24.8
Wichita, KS	10	19.7
Sacramento, CA	13	19.6
Portland, OR	10	18.8
Minneapolis, MN	10	18.1
San Francisco, CA	13	17.2
Des Moines, IA	9	16.8
Grand Rapids, MI	10	16.5
Las Vegas, NV	13	15.5
Omaha, NE	10	15.4
New York, NY	12	14.0
Oklahoma City, OK	11	13.6
Minot, ND	12	12.9
Portland, ME	11	12.6
Washington, DC	11	11.6
Detroit, MI	10	11.1
Other U.S. sites		8.0

Source: Office of Radiation Programs (65).
[a]Average picocuries of iodine-131/liter of pasteurized milk, May 6–June 30, 1986.

startup date. For purposes of this report, proximate areas were defined as those counties situated completely or mostly within 30 miles of the plant. Of the areas proximate to these 23 plants, the most populated 14 (with 88% of the childhood cancer deaths a decade after startup) were selected for study. One of these, near the Catawba plant in South Carolina, was excluded from the analysis, since it lies close to the McGuire plant, which began operations four years before Catawba startup, and is included in the previous analysis. More than 17.5 million Americans lived in counties proximate to these plants in 2000 (Table 3). The SMRs for childhood cancer at age 0–9 for the periods 1–5 years and 6–10 years after startup are compared near each plant. If a plant began operations in 1982, the periods 1983–87 and 1988–92 are used.

Table 2

U.S. nuclear plants started before 1982 and proximate counties, as defined by the National Cancer Institute, with largest populations in 2000

Plant	Startup	Counties	Population
Shippingport	1957	Beaver, PA; Hancock, WV	214,079
Dresden	1960	Grundy, Will, IL	539,801
Yankee Rowe	1960	Berkshire, Franklin, MA	206,488
Indian Point	1962	Rockland, Westchester, NY	1,210,212
San Onofre	1962	Orange, San Diego, CA	5,660,122
Fermi	1963	Monroe, MI	145,945
Oyster Creek	1969	Ocean, NJ	510,916
Millstone	1970	New London, CT	259,088
Pilgrim	1972	Plymouth, MA	472,822
Quad Cities	1972	Rock Island, Whiteside, IL	210,027
Turkey Point	1972	Dade, FL	2,253,362
Zion	1974	Kenosha, WI; Lake, IL	793,933
Duane Arnold	1974	Benton, Linn, IA	217,009
Rancho Seco	1974	Amador, Sacramento, San Joaquin, CA	1,822,197
Three Mile Island	1974	Dauphin, Lancaster, York, PA	1,104,207
Cook	1975	Berrien, MI	162,453
Fort St. Vrain	1976	Boulder, Larimer, Weld, CO	723,718
Salem	1976	New Castle, DE; Salem, NJ	564,550
Sequoyah	1980	Hamilton, TN	307,896
McGuire	1981	Gaston, Lincoln, Mecklenberg, NC	949,599
Total 20 areas			18,328,424

Source: Bureau of the Census, 2000 Census of the United States, State/County quick facts, www.census.gov.

The second part of this study examines the effects of radioactive emissions, as detected in the bodies of children. The average strontium-90 concentration in baby teeth was measured for more than 4,000 American children, most residing near nuclear power plants. The amount of Sr-90 per gram of calcium at birth in each baby tooth was measured in a radiochemistry laboratory, using a scintillation counting technique.

Average Sr-90 concentrations were analyzed by birth year of the tooth donor, since much of the Sr-90 uptake in deciduous teeth occurs during pregnancy and early infancy. Temporal trends in Sr-90 averages were compared with trends in cancer incidence for children under age 10 in the counties near nuclear plants for which the largest numbers of teeth were available. These plants include Suffolk County (NY; near the Brookhaven National Laboratories); Monmouth and Ocean

Table 3

U.S. Nuclear plants started since 1982 and proximate counties with largest populations in 2000 at sites with no previously existing reactors

Plant	Startup	Counties	Population
Summer	1982	Chester, Fairfield, Lexington, Newberry, Richland, Union, SC	660,202
Susquehanna	1982	Carbon, Columbia, Luzerne, Montour, Schuylkill, Sullivan, Wyoming, PA	645,411
Diablo Canyon	1984	San Luis Obispo, Santa Barbara, CA	586,028
Limerick	1984	Berks, Bucks, Chester, Montgomery, Lehigh, PA	2,466,961
Byron	1985	Boone, De Kalb, Ogle, Stephenson, Winnebago, IL; Rock, Walworth, WI	755,250
Fermi 2	1985	Lenawee, Monroe, Washtenaw, Wayne, MI	2,628,892
Palo Verde	1985	Maricopa, AZ	3,072,149
River Bend	1985	E./W. Baton Rouge, E./W. Feliciana, Pointe Coupee, LA; Wilkinson, MS	503,999
Waterford	1985	Ascension, Jefferson, Lafourche, Orleans, St. Charles, St. James, St. John the Baptist, LA	1,219,073
Perry	1986	Ashtabula, Cuyahoga, Geauga, Lake, OH	1,815,112
Braidwood	1987	Grundy, Kankakee, Kendall, Will, IL	698,178
Harris 1	1987	Chatham, Durham, Harnett, Lee, Orange, Wake, NC	1,168,781
Seabrook	1990	Rockingham, Strafford, NH; Essex, MA; York, ME	1,299,753
Total 13 areas			17,529,789

Source: Bureau of the Census, 2000 Census of the United States, State/County quick facts, www.census.gov.

Counties (NJ; near the Oyster Creek plant); and Putnam, Rockland, and Westchester Counties (near the Indian Point plant). The correlation between these two trends is assessed using a Poisson regression analysis testing the hypothesis that they are related. Linear and quadratic correlations are tested using the actual value, square root, and fourth root of Sr-90 averages.

The specific methodology to calculate Sr-90 concentration for each tooth is described elsewhere (66, 67). Teeth from Suffolk County were analyzed using a Wallac WDY 1220X Quantulus low-level scintillation spectrometer; a Perkin-Elmer 1220-003 Quantulus Ultra Low-Level Liquid Scintillation Spectrometer was used for other teeth. In addition, the method used to clean teeth before testing differed between Suffolk County and other teeth; a more sophisticated preparation for non-Suffolk teeth, plus use of a different counter, allowed more Sr-90 to be detected. However, results for each area are internally consistent, allowing Sr-90 patterns and trends to be analyzed.

Strontium-90 results are compared with cancer incidence diagnosed in children age 0–9 years who resided in counties near nuclear plants at the time of diagnosis. Cancer registries from the states of New Jersey and New York provided counts of incident cases, while U.S. Census Bureau counts and inter-censal estimates are used for resident population. Three-year moving averages, rather than individual years, are used for both Sr-90 and cancer rates, to increase the statistical power of the comparison.

RESULTS

Three Mile Island

In the 34 downwind (north and northeast) counties closest to Three Mile Island, the SMR for cancer in children age 0–9 years rose 23.8 percent (0.87 to 1.08) from 1979–83 to 1984–88, the periods 1–5 years and 6–10 years after the accident. The crude cancer mortality rate at age 0–9 in the 34 counties increased 3.6 percent, compared with a national decline of 16.4 percent. Because the number of local deaths in each 5-year period (127 and 135) was relatively small, the rise in SMR is of borderline significance at $P < .09$ (Table 4). While the SMR for leukemia fell from 0.95 to 0.88, the ratio for all other cancers combined rose from 0.83 to 1.17, statistically significant at $P < .03$.

Chernobyl

From 1986–90 to 1991–95 (1–5 years and 6–10 years after the accident) the SMR for cancers at age 0–9 years in the 18 states with the most fallout from the

Table 4

Three Mile Island: change in standard mortality ratio, children age 0–9, after the March 28, 1979, accident, 1979–83 vs. 1984–88, 34 counties north/northeast and closest to Three Mile Island

	SMR (deaths)		
Type of cancer	1979–83	1984–88	% Change SMR
All cancers combined	0.87 (127)	1.08 (135)	+23.8 ($P < .09$)
Leukemia	0.95 (48)	0.88 (35)	–6.8 ($P < .90$)
All other cancers	0.83 (79)	1.17 (100)	+41.0 ($P < .03$)

Source: U.S. Centers for Disease Control and Prevention, http://wonder.cdc.gov; underlying cause of death; uses ICD-9 codes 140.0–239.9.

Chernobyl accident rose from 0.97 to 1.06, a significant increase ($P < .02$). The crude cancer death rate at age 0–9 declined 6.6 percent in the 18 states, compared with a reduction of 14.0 percent elsewhere in the United States. The SMR rise for leukemia (0.90 to 1.01) exceeded that for all other cancers (1.00 to 1.07). Neither increase achieved statistical significance ($P < .10$ and $P < .13$, respectively) (Table 5).

Counties near Nuclear Plants—Startup before 1982

The SMR for all cancers in children dying before their tenth birthday in the 20 most populated areas near nuclear power plants cited in the 1990 National Cancer Institute report (startup before 1982) increased for 17 of the 20 areas from 1–5 to 6–10 years after plant startup. Table 6 shows the total SMR rose from 0.99 to 1.18. Because of the large number of deaths in each period (587 and 590), the change was statistically significant at $P < .003$. Only one of the 20 changes near individual plants (Shippingport) was statistically significant. The increase in SMR for leukemia (1.00 to 1.22) exceeded that for all other cancers (0.98 to 1.15). Both increases achieved statistical significance ($P < .03$ and $P < .05$, respectively).

Counties near Nuclear Plants—Startup since 1982

Table 7 shows that the cancer SMR for age 0–9 in the 13 most populated areas near nuclear plants started since 1982 rose from 0.92 to 1.05, which is of borderline significance ($P < .08$). The ratio rose in nine of the 13 areas near nuclear plants, declined near three, and was essentially unchanged in another. The crude rate near the 13 plants fell just 1.6 percent, compared with larger declines nationwide. The SMR increase for leukemia (0.85 to 1.04) was roughly double that of all other cancers (0.96 to 1.06). Neither of these changes achieved statistical significance ($P < .12$ and $P < .28$, respectively).

Table 5

Chernobyl: change in standard mortality ratio, children age 0–9, after the April 26, 1986, accident, 1986–90 vs. 1991–95, 18 states with sites with highest average I-131 measurements

	SMR (deaths)		
Type of cancer	1986–90	1991–95	% Change SMR
All cancers combined	0.97 (1,501)	1.06 (1,466)	+8.7 ($P < .02$)
Leukemia	0.90 (434)	1.01 (422)	+11.5 ($P < .10$)
All other cancers	1.00 (1,067)	1.07 (1,040)	+7.0 ($P < .13$)

Source: U.S. Centers for Disease Control and Prevention, http://wonder.cdc.gov; underlying cause of death; uses ICD-9 codes 140.0–239.9.

Table 6

Counties near nuclear power plants that began operations before 1982: change in cancer mortality, children age 0–9, 1–5 years vs. 6–10 years after startup, 20 most populated areas

	SMR (deaths)		
Type of cancer	1–5 yrs after	6–10 yrs after	% Change SMR
All cancers combined	0.99 (587)	1.18 (590)	+19.3 ($P < .003$)
Leukemia	1.00 (276)	1.22 (264)	+22.9 ($P < .03$)
All other cancers	0.98 (311)	1.15 (326)	+16.6 ($P < .05$)
All cancers by plant			
Shippingport	0.84 (20)	1.47 (29)	+73.7 ($P < .05$)
Dresden	1.00 (22)	1.26 (26)	+26.6
Yankee Rowe	0.65 (11)	1.23 (17)	+89.9
Indian Point	0.98 (75)	1.22 (79)	+23.9
San Onofre	1.07 (186)	1.11 (153)	+3.4
Fermi 1	0.68 (7)	1.18 (10)	+73.2
Oyster Creek	1.12 (15)	0.69 (8)	–38.6
Millstone	1.34 (17)	0.60 (5)	–55.6
Pilgrim	1.02 (19)	1.10 (16)	+8.3
Quad Cities	1.03 (11)	1.48 (12)	+43.3
Turkey Point	0.94 (48)	1.12 (49)	+18.3
Zion	0.74 (18)	1.01 (20)	+36.2
Duane Arnold	1.06 (8)	1.29 (8)	+22.3
Rancho Seco	1.14 (44)	1.43 (55)	+25.1
Three Mile Island	0.87 (28)	1.29 (36)	+47.4
Cook	1.35 (9)	1.54 (8)	+14.1
Fort St. Vrain	0.67 (10)	1.11 (16)	+67.0
Salem	0.79 (12)	1.01 (13)	+27.5
Sequoyah	1.60 (13)	1.51 (10)	–5.6
McGuire	0.78 (14)	1.16 (20)	+49.2
Total	0.99 (587)	1.18 (590)	+19.3

Source: National Cancer Institute, *Cancer in Populations Near Nuclear Facilities,* U.S. Government Printing Office, Washington, DC, 1990.

Strontium-90 Trends and Childhood Cancer Incidence

Figures 1, 2, and 3 illustrate the comparisons of average Sr-90 in baby teeth and cancer incidence in children under age 10 years (Ca 0–9) near three nuclear plants. Each represents between 10 and 14 three-year periods (moving average) covering persons born in the 1980s and the early 1990s. The analyses include a large

Table 7

Counties near nuclear power plants that began operations since 1982: change in cancer mortality, children age 0–9, 1–5 years vs. 6–10 years after startup, 13 most populated areas

	SMR (deaths)		
Type of cancer	1–5 yrs after	6–10 yrs after	% Change SMR
All cancers combined	0.92 (353)	1.05 (368)	+14.7 ($P < .08$)
Leukemia	0.85 (115)	1.04 (124)	+21.6 ($P < .12$)
All other cancers	0.96 (238)	1.06 (244)	+10.6 ($P < .28$)
All cancers by plant			
Summer	0.95 (14)	0.76 (10)	–19.8
Susquehanna	0.41 (6)	0.87 (11)	+113.0
Diablo Canyon	0.54 (7)	0.77 (10)	+42.9
Limerick	0.76 (39)	0.99 (48)	+30.8
Byron	0.59 (10)	1.26 (19)	+112.6
Fermi 2	0.94 (64)	1.20 (73)	+28.2
Palo Verde	1.01 (55)	0.89 (49)	–11.6
River Bend	0.83 (11)	1.18 (13)	+41.7
Waterford	0.69 (24)	0.94 (26)	+35.6
Perry	1.10 (47)	1.31 (48)	+18.6
Braidwood	0.57 (8)	0.71 (10)	+25.3
Harris 1	1.67 (31)	1.06 (19)	–36.7
Seabrook	1.37 (37)	1.37 (32)	–0.3
Total	0.92 (353)	1.05 (368)	+14.7

Source: U.S. Centers for Disease Control and Prevention, http://wonder.cdc.gov; underlying cause of death; uses ICD-9 codes 140.0–239.9.

number of teeth and cancer cases (453 and 390 for Suffolk County, 167 and 434 for Monmouth and Ocean Counties, and 239 and 371 for Putnam, Rockland, and Westchester Counties). The three areas indicate a similarity of trends in Sr-90 and childhood cancer, with a four-year latency between the two in New York and a five-year latency in New Jersey. For example, the average Sr-90 level in Suffolk County teeth steadily rose from 0.97 to 1.68 picocuries of Sr-90 per gram of calcium from 1981–83 to 1984–86. The rate of Suffolk children age 0–9 diagnosed with cancer steadily rose from 1.518 to 2.075 cases per 10,000 persons from 1985–87 to 1988–90.

The correlation was statistically significant ($P < .05$) for Monmouth/Ocean and Suffolk Counties, but fell short of significance for Putnam/Rockland/Westchester. It was also significant for all three areas combined, after taking into account that

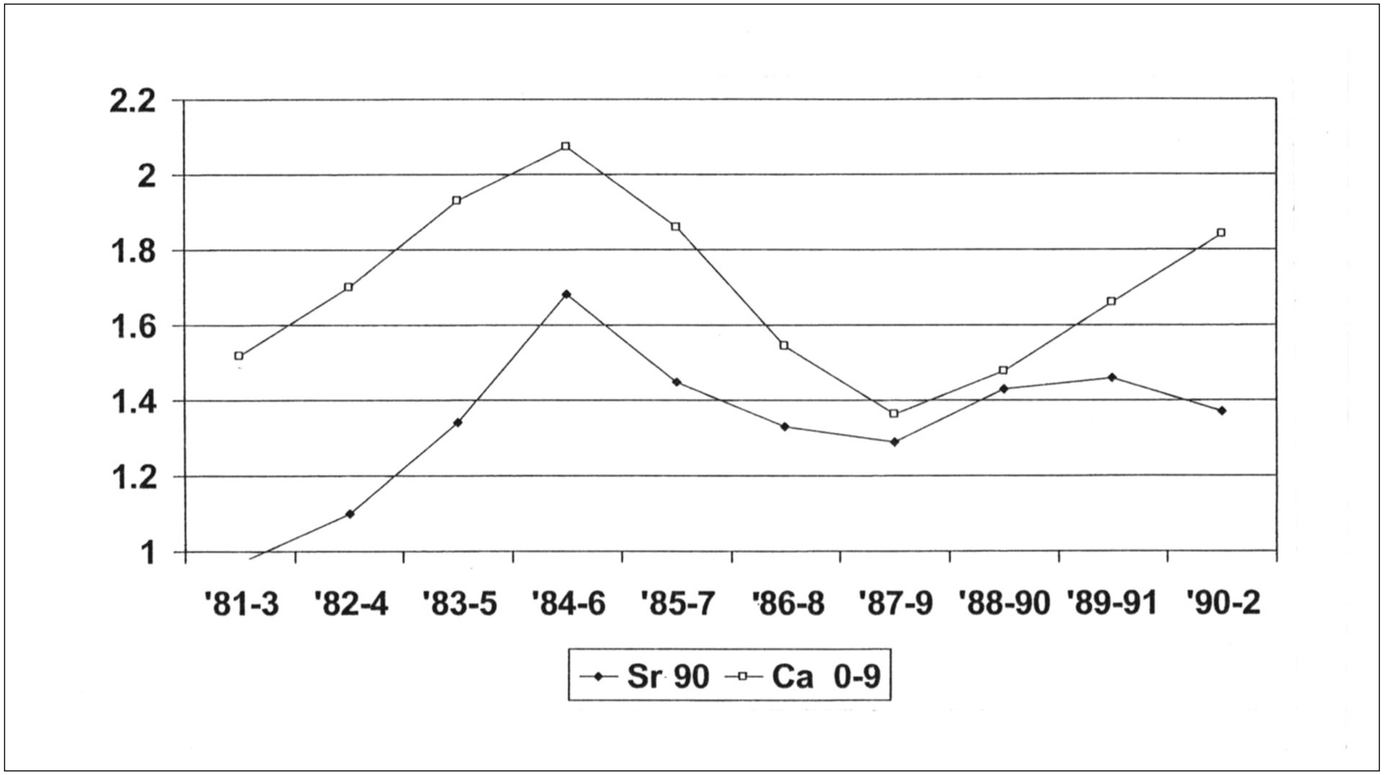

Figure 1. Strontium-90 in baby teeth vs. cancer incidence at age 0–9 years, Suffolk County, NY. Picocuries of Sr-90 per gram of calcium; cancer cases (Ca) per 10,000 population; four-year lag (Sr-90 begins 1981–83; Ca begins 1985–87).

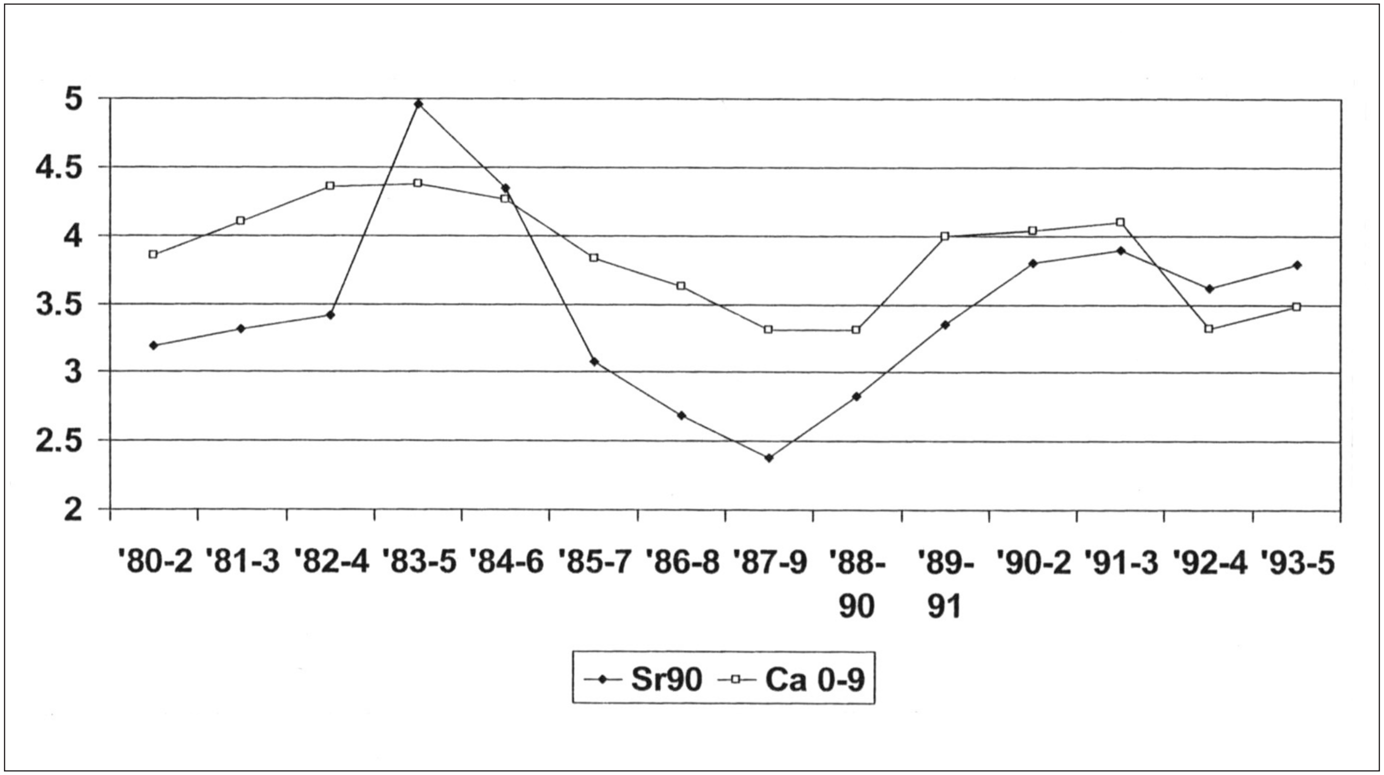

Figure 2. Strontium-90 in baby teeth vs. cancer incidence at age 0–9 years, Monmouth and Ocean Counties, NJ. Picocuries of Sr-90 per gram of calcium; cancer cases (Ca) per 2,000 population; five-year lag (Sr-90 begins 1980–82; Ca begins 1985–87).

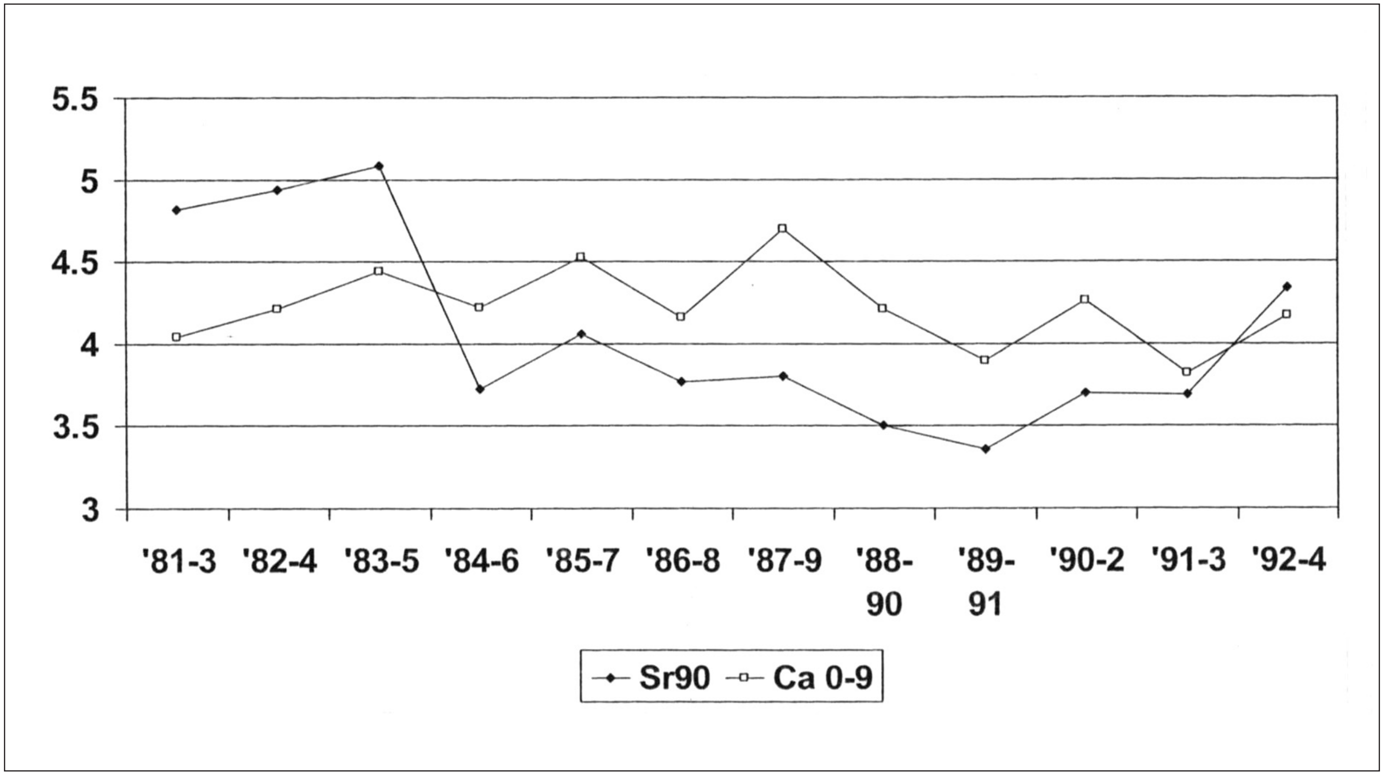

Figure 3. Strontium-90 in baby teeth vs. cancer incidence at age 0–9 years, Putnam, Rockland, and Westchester Counties, NY. Picocuries of Sr-90 per gram of calcium; cancer cases (Ca) per 2,000 population; four-year lag (Sr-90 begins 1981–83; Ca begins 1985–87).

Table 8

Poisson regression results, average Sr-90 concentration and cancer incidence, age 0–9, areas near New York and New Jersey nuclear power plants

Counties	*P* value	95% CI	IRR
Monmouth/Ocean, NJ			
Actual Sr-90 value	.039	1.005–1.201	1.099
Square root of Sr-90	.038	1.020–2.003	1.430
Fourth root of Sr-90	.038	1.058–6.716	2.665
Suffolk, NY			
Actual Sr-90 value	.043	1.011–2.029	1.432
Square root of Sr-90	.049	1.002–4.908	2.218
Fourth root of Sr-90	.053	0.978–28.886	5.314
Putnam/Rockland/Westchester, NY			
Actual Sr-90 value	.704	0.912–1.146	1.022
Square root of Sr-90	.693	0.688–1.755	1.099
Fourth root of Sr-90	.688	0.346–5.029	1.316
All areas combined			
Actual Sr-90 value	.020	1.005–1.064	1.035
Square root of Sr-90	.021	1.017–1.223	1.115
Fourth root of Sr-90	.021	1.041–1.650	1.311

Note: CI, confidence interval; IRR, incidence rate ratio.

there may be confounding factors. *P* values were similar whether the actual value, square root, or fourth root of the Sr-90 measurements was used. However, the quadratic (fourth root) of Sr-90 best fits the assumption that the two variables are related; the incidence rate ratio (IRR) is highest for each area when the fourth root is used for Sr-90 (Table 8).

DISCUSSION

The minimum latency period between radiation exposure of the fetus and infant and onset of cancer has often been documented as about 5–10 years. This latency includes various types of radiation exposure (from X-rays, nuclear weapons test fallout, the Chernobyl accident) and various types of cancer (leukemia, thyroid cancer, and other malignancies). In the United States, the issue of whether nuclear reactor operations have affected childhood cancer risk is largely unexamined. Reactor operations is a pertinent area of study, since atmospheric and subterranean weapons tests ceased in 1963 and 1992, respectively. The 103 U.S. nuclear power reactors now in operation represent nearly one-fourth of the world's total, and include some of the oldest reactors.

This report analyzes cancer mortality in children exposed to radioactivity from nuclear power reactors who died before their tenth birthday. Because the lag between exposure and diagnosis can often be 5–10 years, the periods 1–5 years and 6–10 years after initial exposure were compared. Excess cancer deaths among children during the first 5 years after exposure would not be expected, and thus represent a control group, while an elevated level of cancer deaths 6–10 years after exposure would be expected.

In areas of the United States exposed to the greatest levels of fallout from accidents at Three Mile Island and Chernobyl, and areas proximate to newly started nuclear reactors, increases in the standard mortality ratio 6–10 years after initial exposure in children under age 10 were observed. Increases in SMR ranged from 8.7 to 23.8; each of these temporal changes achieved or approached statistical significance. For each of the four areas studied other than the area near Three Mile Island, the SMR increase for leukemia exceeded that for all other cancers. All SMRs were less than 1.00 in the period 1–5 years after initial exposure, and were greater than 1.00 in the period 6–10 years after; this indicates that populations with cancer rates below the national average changed to those with rates above the national average in just a few years.

In addition, the report examines the relationship between temporal trends of in-body radioactivity (i.e., Sr-90 in baby teeth at birth) and childhood cancer incidence near three U.S. nuclear installations. For each area, the pattern of childhood cancer increasing 4–5 years after a rise in Sr-90 (and decreasing 4–5 years after a Sr-90 decline) was consistent. While the relationship achieved statistical significance in just two of the three areas, plus all three areas combined, the results suggest a link between fetal/infant exposures from nuclear plant emissions and cancer in childhood. Much of the Sr-90 in deciduous teeth of children living near nuclear plants probably represents emissions from the plant that are ingested in air and food (67).

An important finding in the comparison of Sr-90 and childhood cancer trends is that the quadratic (fourth root) value of Sr-90 in baby teeth provides the highest incidence rate ratio, and thus supports the theory that a quadratic of Sr-90 fits the assumption of a link better than does linearity. Thus, the upward supralinear dose-response best describes the relationship between in-body Sr-90 and childhood cancer risk. This relationship indicates that the greatest per-dose risk occurs at the lowest dose levels, which is critical to understanding the health risks of radioactive environmental emissions routinely released from nuclear facilities.

The findings of this in-depth examination of temporal childhood cancer patterns near U.S. nuclear plants are important in several ways. They support the pattern of a relatively short lag period between exposures early in life and disease onset. The pattern of children exposed to radiation being especially susceptible to leukemia as opposed to other types of cancer is consistent with many earlier findings. Perhaps the most important aspect of the report is documentation of an apparent childhood cancer risk at relatively low levels of exposure. Many previous studies involved considerably larger doses, including fallout from atomic bomb tests and radiation from the Chernobyl accident. Radioactivity levels in the United States from the Three Mile Island and Chernobyl accidents were considerably lower than that in Belarus/Ukraine after Chernobyl. While environmental emissions of fission products from nuclear plants vary, they are typically lower than those released in major accidents or in bomb test fallout. Results indicate that ongoing exposure to radioactivity may present an increased health risk to infants and children not previously understood. Exposures such as Hiroshima and medical use of X-rays represent a single dose, while nuclear plant emissions are continuous, and long-lived isotopes from Three Mile Island/Chernobyl remained in the U.S. food chain for years.

The study has limitations that should be addressed in subsequent research efforts. Perhaps the most important of these is the need to continue to improve dose estimates for exposures from nuclear plant emissions and to further explore epidemiological comparisons of health risks. A case-control comparison of in-body doses of radioactivity in children with and without a disease such as cancer who live proximate to nuclear facilities would be useful to fill this need. This report isolates only one specific type of cancer (leukemia). It examines potential effects only on young children, not adolescents or adults. It examines patterns of cancer mortality only in the first decade after initial exposure, and not thereafter. Not all increases in SMR, or all correlations between Sr-90 in baby teeth and childhood cancer incidence, are statistically significant.

Despite these shortcomings, the epidemiological findings documented here represent a novel contribution to the understanding of radiation risks to the very young. With tens of millions of Americans living close to nuclear reactors, more detailed studies should be pursued forthwith.

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APPENDIX I
Counties Included in Table 4

Pennsylvania and New Jersey counties located north/northeast of Three Mile Island and within 130 miles of the plant that are included in analysis in Table 4:

Pennsylvania Counties

Berks	Monroe
Bradford	Montour
Bucks	Northampton

Pennsylvania Counties (cont'd.)

Carbon	Northumberland
Columbia	Perry
Cumberland	Pike
Dauphin	Schuylkill
Juniata	Snyder
Lackawanna	Sullivan
Lebanon	Susquehanna
Lehigh	Tioga
Luzerne	Union
Lycoming	Wayne
Mifflin	Wyoming

New Jersey Counties

Hunterdon
Mercer
Morris
Somerset
Sussex
Warren

Populations Age 0–9

	PA/NJ Counties	*U.S.*
1979–83	2,981,889	165,992,436
1984–88	3,058,676	175,532,642

APPENDIX II
States and Counties Included in Table 5

States and counties with highest iodine-131 averages in milk, measured during May and June 1986, after the Chernobyl accident, that are included in analysis in Table 5:

States

California (29 counties)	Nebraska
District of Columbia	Nevada
Idaho	New York (7 counties)
Iowa	North Dakota
Kansas	Oklahoma
Maine	Oregon

Michigan	South Dakota
Minnesota	Utah
Montana	Washington

California Counties

Amador	Placer
Butte	Plumas
Colusa	Sacramento
Contra Costa	San Francisco
Del Norte	Shasta
El Dorado	Sierra
Glenn	Siskiyou
Humboldt	Solano
Lake	Sonoma
Lassen	Sutter
Marin	Tehama
Mendocino	Trinity
Modoc	Yolo
Napa	Yuba
Nevada	

New York Counties

Bronx
Kings
New York
Queens
Richmond
Rockland
Westchester

Populations Age 0–9

	States with High I-131	*Other U.S.*
1986–90	39,082,847	141,343,373
1991–95	40,863,580	151,355,461

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