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Infant Death and Childhood Cancer Reductions after Nuclear Plant Closings in the United States

JOSEPH J. MANGANO
JAY M. GOULD
ERNEST J. STERNGLASS
JANETTE D. SHERMAN
JERRY BROWN
WILLIAM McDONNELL
Radiation and Public Health Project
Brooklyn, New York

ABSTRACT. Subsequent to 1987, 8 U.S. nuclear plants located at least 113 km from other reactors ceased operations. Strontium-90 levels in local milk declined sharply after closings, as did deaths among infants who had lived downwind and within 64 km of each plant. These reductions occurred during the first 2 yr that followed closing of the plants, were sustained for at least 6 yr, and were especially pronounced for birth defects. Trends in infant deaths in proximate areas not downwind, and more than 64 km from the closed plants, were not different from the national patterns. In proximate areas for which data were available, cancer incidence in children younger than 5 yr of age fell significantly after the shutdowns. Changes in health following nuclear reactor closings may help elucidate the relationship between low-dose radiation exposure and disease.

<Key words: childhood cancer, downwind, infant death, nuclear plant closings, nuclear reactors, radioactivity>

THERE IS A RELATIVE PAUCITY of research that documents the beneficial health effects to humans following a reduction in the level of environmental toxins. Existing data provide evidence for immediate responses, as well as for responses with longer latencies. Motor vehicle restrictions during the 1996 Summer Olympic Games resulted in a 28% drop in peak ozone concentration and a more than 40% reduction in asthma admissions/emergency room visits among Atlanta children.[1] The decline in smoking for U.S. adult males, from 52% in 1965 to 28% in 1990,[2] was not followed by a reduction in age-adjusted incidence of lung-bronchial cancers until 1984.[3]

Reduction of ionizing radiation in the environment, and hence in the food chain, occurred after enactment of the Partial Test Ban Treaty of 1963 that prohibited atmospheric atomic weapons testing by the United States, the (then) Soviet Union, and Great Britain. In the United States, dietary levels of short-lived isotopes, such as iodine-131 (I-131) and strontium-89 (Sr-89), with respective biological half-lives of 8 and 50 days, fell dramatically. Even concentrations of a long-lived isotope such as strontium-90 (half-life = 28.7 yr) in raw milk declined by one-half in 9 U.S. cities from the peak of April/May 1964 to November/December 1965. This decline, from an average of 30 to 15 picocuries per liter, fell further to 6 by 1970.[4,5]

Diminishing radioactivity levels in the diet were accompanied by immediate and significant morbidity and mortality reductions among infants and young children. U.S. infant deaths per 1,000 births fell from 24.7 to 19.1 from 1965 to 1971, respectively—a rate of decrease more than 4 times greater than for 1951–1965,[6] respectively. (Note: Atmospheric bomb testing in Nevada began in January 1951.[7]) Cancer incidence in children who were younger than 5 yr of age and who lived in Connecticut—the only U.S. state that operated a comprehensive tumor registry—dropped 30% from the

1962–1964 peak of 20.38 cases/100,000 to 14.21 by 1967–1969, following a 40% rise during the time of atmospheric bomb testing.[8]

Although most permanent shutdowns of nuclear power reactors are relatively recent, periods that follow unexpectedly large releases of airborne emissions offer an example of reduced environmental radioactivity. In the 1960s, declines in local infant mortality were documented after substantial reductions in gaseous emissions from several nuclear facilities.[9] In downwind areas within 64 km of 5 closed reactors, infant deaths declined at an unexpectedly rapid rate in the first 2 yr that followed closing.[10] We propose to extend that report by presenting data on all reactors for which post-shutdown data are currently available. Mortality 2 yr and 6 yr after reactor closings will be reviewed, the purpose of which will be assessment of whether immediate reductions are sustained over longer periods of time. Proximate areas that are not downwind from closed reactors and 64–129 km downwind will be examined. Finally, childhood cancer incidence trends near closed reactors will also be considered.

Method

Subsequent to 1987, 13 nuclear power reactors in the United States have been closed permanently. In addition, 5 other reactors have been nonoperational for at least 2 consecutive calendar years (see Table 1). The 8 regions in which closings left no operating power reactor within a 112-km radius of the closed facility are the focus of this report. Preliminary data have already been presented for 5 of the 8 regions.[10] Of these 8 regions, 6 have involved permanent shutdowns. The Pilgrim reactor in Massachusetts did not operate from April 1986 until late 1988. During the winter of 1995–1996, all 4 Connecticut reactors—3 at Millstone in Waterford and 1 in Haddam Neck, 29 km to the northwest—were closed. Millstone units 2 and 3 resumed operations in July 1999 and July 1998, respectively.

Demographic characteristics of the 8 areas are presented in Table 2. Population density varied greatly; some regions were urban settings, and some were sparsely populated areas. Poverty rates and percentages of Blacks and Hispanics in the population were less than the U.S. standard in each area.

An approximation of change in environmental radioactivity before and after a reactor shutdown may be observed with annual measures of Sr-90 in pasteurized milk, reported each July by the U.S. Environmental Protection Agency in 60 U.S. cities.[11] Readings for cities located within 64 km of closed reactors are also provided. The analysis of levels of long-lived Sr-90 has likely underestimated the reduction in environmental radioactivity inasmuch as short-lived isotopes emitted by reactors would no longer be present after a shutdown.

Short-lived airborne radioactive particulates often decay before entering the food chain. However, they can enter the body through inhalation. Persons with the greatest uptake from this vector are those who live downwind from the source, inasmuch as prevailing winds carry the majority of particles in the downwind direction. Longer-lived isotopes can also be inhaled, but they are also returned to earth by precipitation, after which they are again consumed in the diet. Again, levels are most likely highest in downwind, rainy areas. This principle is illustrated in the patterns of fallout from atmospheric atomic bomb tests in Nevada. For example, after the large "Smoky" test on August 31, 1957, U.S. government officials documented elevated levels of radioisotopes in raw milk. The typical concentration of Sr-89 (< 5 picocuries/l) was exceeded in Cincinnati, Ohio (i.e., 150 picocuries/l); in New York (160 picocuries/l); in Sacramento, California (30 picocuries/l); in Saint Louis, Missouri (290 picocuries/l); and in Salt Lake City, Utah (120 picocuries/l).[12] The only upwind city—Sacramento—had the lowest concentration of Sr-89. In addition, the total in Salt Lake City (i.e., city closest to Nevada) was exceeded by the much rainier Cincinnati (Ohio), New York, and Saint Louis (Missouri) areas.

Given that airborne radioactive particulates are propelled by prevailing winds, in this analysis we focused on counties located downwind and mostly or totally within 64 km of the closed reactors. Prevailing wind directions for the large city or cities nearest to each closed reactor were used.[13] Winds in Portland, Oregon—near the closed Trojan reactor—emanate from the east-southeast and northwest during 6 individual months; therefore, "downwind" counties are situated in both directions.

Infant deaths that occurred during the first year of life were obtained from the National Center for Health Statistics. County-specific deaths and population information were available on the world wide web (http://www.cdc.gov/data and statistics/CDC Wonder). The accuracy of the count of infant deaths is likely very high; all U.S. states have reported death data to the federal government, subject to reliability tests since 1933. Coding the reason for death should also be consistent over time; the 9th revision of the International Classification of Diseases (ICD) coding system was used for the classification of all deaths from 1979 to 1998. The county of residence for an infant death (i.e., mother's residence) has been a standard data element collected in the hospital medical record for many years.

Infant mortality rates before and after reactors ceased operations were compared. The period before a reactor is closed is defined as the last 2 yr of operation, including the year of closing. For example, the LaCrosse reactor ceased operations on April 30, 1987; therefore, the "before" period of operation is 1986–1987. Given that cellular damage from radioactive exposures is most pronounced in the fetal period, many births that followed the closing of a reactor (but in the same year) were subject to exposures from reactor operations *prior to birth*. Rates for the 2 yr before closing are contrasted with rates for the subsequent 2- and 6-yr periods.

The report also reviewed infant mortality from congenital anomalies (ICD codes 740.0–759.9) known to be sensitive to the effects of radiation. Approximately 1 of every 4 deaths in the first year of life results from a birth defect. Approximately one-half of the infant con-

Table 1.—U.S. Nuclear Reactors Closed Subsequent to 1987

Reactor name (location)	Started/ closed	Prevailing wind direction*	Cities located downwind (< 64 km from closed reactor)	1990 Population (*n*)
LaCrosse	07/11/67	South	LaCrosse, WI	97,904
(Genoa, WI)	04/30/87	(LaCrosse)	Vernon, WI	25,617
Rancho Seco	09/16/74	Southwest	Amador, CA	30,039
(Clay Station, CA)	06/07/89	(Sacramento, CA)	El Dorado, CA	125,995
			Placer, CA	172,796
			Sacramento, CA	1,041,219
Fort St. Vrain	01/31/74	South	Larimer, CO	186,136
(Platteville, CO)	08/18/89	(Denver, CO)	Weld, CO	131,821
Trojan	12/15/75	East-southeast/	Columbia, OR	37,557
(Prescott, OR)	11/09/92	northwest	Clark, WA	238,053
		(Portland, OR)	Cowlitz, WA	82,119
			Multnomah, OR	583,887
			Wakhiakum, WA	3,832
Maine Yankee	10/23/72	South	Kennebec, ME	115,904
(Wiscasset, ME)	08/05/97	(Portland, ME)	Knox, ME	36,310
			Lincoln, ME	30,357
Big Rock Point	09/27/62	West-northwest	Antrim, MI	18,185
(Charlevoix, MI)	08/29/97	(Sault Ste. Marie, IL)	Charlevoix, MI	21,468
		Southwest	Cheboygan, MI	23,800
		(Alpena, MI)	Emmet, MI	25,040
			Otsego, MI	17,957
		Temporary shutdowns		
Haddam Neck	07/24/67	South	Middlesex, CT	143,196
(Haddam Neck, CT)	—	(Hartford, CT)	New London, CT	254,957
Millstone 1,2,3	10/26/70	Southwest	Tolland, CT	128,699
(Waterford, CT)	—	(Providence, RI)	Windham, CT	102,525
			Kent, RI	161,135
			Washington, RI	110,006
Pilgrim	06/16/72	Southwest	Plymouth, MA	435,276
(Plymouth, MA)	04/30/86	(Boston, MA)		

Comparison of reactors closed subsequent to 1987 with physical locations of additional operating reactors located < 113 km from closed reactor specified

Reactor name (location)	Date closed	Reactor name and distance/direction from closed reactor
Handford-N (Richmond, WA)	02/01/88	Washington Nuclear 2; same site as closed reactor
Yankee Rowe (Rowe, MA)	10/01/91	Vermont Yankee; 24 km northeast
San Onofre (San Clemente, CA)	11/30/92	San Onofre 2 and 3; all 3 reactors located at same site
Clinton (Clinton, IL)	Autumn of 1996	LaSalle 1; 113 km north
LaSalle County 2 (Seneca, IL)	Autumn of 1996	LaSalle 2; same site as closed reactor
Zion 1,2 (Zion, IL)	01/16/98	Byron 1; 104 km west

Notes: WI = Wisconsin, CA = California, CO = Colorado, OR = Oregon, WA = Washington, ME = Maine, MI = Michigan, CT = Connecticut, MA = Massachusetts, IL = Illinois, and RI = Rhode Island.
*In this column, specific cities that appear within parentheses are located downwind in the wind direction cited.

genital anomaly deaths involves heart defects. Chromosomal defects (including Down's, Edwards', and Patau's syndromes), and nervous system defects (including anencephalus and spina bifida) account for another quarter of deaths.[6]

Childhood cancer data were also analyzed because of the increased sensitivity of the developing fetus to the carcinogenic effects of ionizing radiation. Cancer incidence data were available only from state registries of California, Colorado, and Wisconsin. These states operated comprehensive tumor registries before and after closings (i.e., reporting of cancer cases was mandated by state law, reporting originated from several sources, and the reporting system was complete and accurate). Cases diagnosed before an individual's 5th birthday, which likely represented a fetal origin, were analyzed.

Trends in infant mortality near closed nuclear facilities were compared with U.S. patterns. Aggregated data

Table 2.—Demographic Data and Downwind Counties Located < 64 km from Nuclear Reactors that Had Closed

Reactor name	Population per km² in 1997	Percentage Black (1995)	Hispanic (1995)	Low SES persons (%) (1995)
U.S.	29.2	12.7	11.0	13.8
LaCrosse	40.1	0.5	0.8	10.2
Rancho Seco	127.0	7.4	13.6	13.6
Fort St. Vrain	22.3	6.6	14.4	10.8
Trojan	133.5	4.5	4.2	12.0
Maine Yankee	42.3	0.2	0.5	11.7
Big Rock Point	17.6	0.3	1.4	10.5
Haddam Neck/Millstone	144.3	3.0	2.3	6.5
Pilgrim	270.1	5.1	2.8	7.8
Areas with higher concentrations than U.S.	6	0	2	0
Areas with lower concentrations than U.S.	2	8	6	8

Notes: SES = socioeconomic status; low SES refers to those individuals whose incomes were below the poverty line.

Table 3.—Change in Average Strontium-90 Concentrations in Pasteurized Milk in Cities Located < 64 km from Nuclear Plants that Had Closed

City/state	Closest reactor	Years included BC	AC	Average strontium-90 concentration* BC	*n*	AC	*n*	Change (%)
Sacramento, CA	Rancho Seco, CA	1983–1988	1989–1994	0.92	6	0.48	6	–47.1
Denver, CO	Fort St. Vrain, CO	1983–1988	1989–1994	1.52	6	0.50	2	–67.1
Portland, OR	Trojan, OR	1987–1992	1993–1994	1.25	6	0.65	2	–48.0
U.S. (23 cities)		1983–1988	1989–1994	1.97		1.30		–34.0

Notes: BC = before closing reactor, AC = after closing reactor, CA = California, CO = Colorado, and OR = Oregon.
*Concentrations of strontium-90 are expressed in picocuries of Sr-90 per liter of milk.

(i.e., 1988–1996) from states and cities that made up approximately 47% of the U.S. population were used for cancer incidence because no national registry exists. (Areas include the states of California, Connecticut, Florida, Hawaii, Iowa, Massachusetts, New Jersey, New Mexico, New York, Pennsylvania, Utah, and Wisconsin; and the Standard Metropolitan Statistical Areas of Atlanta, Denver, and Seattle.) Infant mortality and childhood cancer trends in counties near nuclear plants were also compared with all other counties in the state. For Millstone, "other state" represents Connecticut and Rhode Island combined, whereas for Trojan, "other state" represents Oregon and Washington combined.

Results

Change in environmental radioactivity. Sr-90 concentrations in pasteurized milk over a 12-yr period before and after shutdown were available for 3 cities within 64 km of closed nuclear plants. These were compared with trends in 23 U.S. cities for which an annual reading was reported each year from 1983–1994 (Table 3). In each area near a closed reactor, the average Sr-90 concentration fell by more than the U.S. decline (67.1%, 48.0%, and 47.1%, compared with 34.0%). This comparison was hampered by the availability of only 1 annual measurement, thus raising the chance of random fluctuation.

Infant mortality—all causes. Infant mortality in each of the 8 downwind areas decreased during the first 2 yr following closing (Table 4). Each decline exceeded the U.S. average 2-yr reduction of 6.4%, and the total decline of 17.4% was significant ($p < .01$). Each decline also exceeded the trend for other counties in the state; the total reduction in other counties of 6.7% was significantly different from the "nuclear" counties ($p < .01$).

Infant mortality data for 6 yr post-shutdown were available for counties near 4 of the 8 plants; the other plants closed too recently or they were re-started (Table 5). In each of the 4 areas, reductions continued to exceed the U.S. standard, and the total decline of 26.9% was significantly greater than the national trend ($p < .0001$). Reductions near the Rancho Seco and Trojan plants were also significant. Rates also fell faster than in other counties in respective states.

Table 4.—Change in "All-Causes" Death Rates of Infants during Their First Year of Life and Who Were Located < 64 km Downwind of Reactors, 2 Years before vs. 2 Years after Nuclear Plant Closings

Reactor	Year closed	Infant deaths		Live births		Deaths/1,000		Change (%)	
		BC	AC	BC	AC	BC	AC	Local	Other state
LaCrosse, WI	1987	36	30	3,507	3,452	10.27	8.69	–15.4	–1.9
Rancho Seco, CA	1989	418	390	44,500	49,414	9.39	7.89	–16.0	–9.2
Ft. St. Vrain, CO	1989	83	72	9,725	9,977	8.53	7.22	–15.4	–5.2
Trojan, OR	1992	253	204	30,320	29,799	8.34	6.85	–17.9	–5.9
Big Rock Point, MI	1997	25	15	2,922	3,040	8.56	4.93	–42.4	+2.0
Maine Yankee, ME	1997	19	18	3,841	4,013	4.95	4.49	–9.3	+22.8
Pilgrim, MA	1986	97	76	12,956	13,412	7.49	5.67	–24.3	–13.1
Millstone, CT	1995	166	130	22,261	21,093	7.46	6.16	–17.4	–5.4
Totals for 8 areas		1,097	935	130,032	134,200	8.44	7.00	–17.4*	–6.7
U.S. average for 2-yr change	1986–1998							–6.4	

Notes: BC = 2 yr before closing reactor, AC = 2 yr after closing reactor, WI = Wisconsin, CA = California, CO = Colorado, OR = Oregon, MI = Michigan, ME = Maine, MA = Massachusetts, and CT = Connecticut.
*$p < .01$ (nuclear counties vs. both U.S. and other state totals).

Table 5.—Change in "All-Causes" Death Rates of Infants during Their First Year of Life and Who Were Located < 64 km Downwind of Reactors, 2 Years before vs. 6 Years after Nuclear Plant Closings

Reactor	Year closed	Infant deaths		Live births		Deaths/1,000		Change (%)	
		BC	AC	BC	AC	BC	AC	Local	Other state
LaCrosse, WI	1987	36	69	3,507	10,302	10.27	6.70	–34.8	–7.7
Rancho Seco, CA	1989	418	1,038	44,500	144,770	9.39	7.17	–23.6	–16.5
Ft. St. Vrain, CO	1989	83	192	9,725	30,129	8.53	6.37	–25.3	–15.2
Trojan, OR	1992	253	523	30,320	92,649	8.34	5.64	–32.4	–12.7
Totals for 4 areas		790	1,822	88,052	277,880	8.97	6.56	–26.9*	–15.1
U.S. average for 6-yr change	1986–1998							–11.9	

Notes: BC = 2 yr before closing reactor, AC = 6 yr after closing reactor, WI = Wisconsin, CA = California, CO = Colorado, and OR = Oregon.
*$p < .0001$ (nuclear counties vs. both U.S. and other state totals). Rancho Seco difference ($p < .05$) and Trojan difference ($p < .0001$) were significant.

Table 6.—Change in "Congenital Anomalies" Death Rates of Infants during Their First Year of Life and Who Were Located < 64 km Downwind of Reactors, 2 Years before vs. 2 Years after Nuclear Plant Closings

Reactor	Year closed	Infant deaths		Live births		Deaths/1,000		Change (%)	
		BC	AC	BC	AC	BC	AC	Local	Other state
LaCrosse, WI	1987	7	4	3,507	3,452	2.00	1.16	–42.0	+1.3
Rancho Seco, CA	1989	90	79	44,500	49,414	2.02	1.60	–20.8	–10.1
Ft. St. Vrain, CO	1989	20	24	9,725	9,977	2.06	2.41	+17.0	–6.6
Trojan, OR	1992	61	41	30,320	29,799	2.01	1.38	–31.3	–1.0
Big Rock Pt., MI	1997	10	4	2,922	3,040	3.42	1.32	–61.5	+1.0
Maine Yankee, ME	1997	6	5	3,841	4,013	1.36	1.25	20.2	+5.4
Pilgrim, MA	1986	26	23	12,956	13,412	2.01	1.71	–14.9	–32.5
Millstone, CT	1995	51	37	22,261	21,093	2.29	1.75	–23.6	–7.7
Totals for 8 areas		271	217	130,032	134,200	2.08	1.62	–22.4*	–5.6
U.S. average for 2-yr change	1986–1998							–5.5	

Notes: BC = 2 yr before closing reactor, AC = 2 yr after closing reactor, WI = Wisconsin, CA = California, CO = Colorado, OR = Oregon, MI = Michigan, ME = Maine, MA = Massachusetts, and CT = Connecticut.
*$p < .05$ (nuclear counties vs. both U.S. and other state totals).

Table 7.—Change in "Congenital Anomalies" Death Rates of Infants during Their First Year of Life and Who Were Located < 64 km Downwind of Reactors, 2 Years before vs. 6 Years after Nuclear Plant Closings

Reactor	Year closed	Infant deaths		Live births		Deaths/1,000		Change (%)	
		BC	AC	BC	AC	BC	AC	Local	Other state
LaCrosse, WI	1987	7	17	3,507	10,302	2.00	1.65	–17.5	–7.7
Rancho Seco, CA	1989	90	228	44,500	144,770	2.02	1.57	–22.3	–17.4
Ft. St. Vrain, CO	1989	20	52	9,725	30,129	2.06	1.73	–16.0	–14.3
Trojan, OR	1992	61	123	30,320	92,649	2.01	1.33	–34.0	–4.9
Totals for 4 areas		178	420	88,052	277,850	2.02	1.51	–25.2*	–14.8
U.S. average for 6-yr change	1986–1998							–10.9	

Notes: BC = 2 yr before closing reactor, AC = 6 yr after closing reactor, WI = Wisconsin, CA = California, CO = Colorado, and OR = Oregon.
*$p < .02$ (nuclear counties vs. U.S.), and $p < .08$ (nuclear counties vs. other state totals). The Trojan trend was significantly different from those for U.S. ($p < .03$) and for other state ($p < .006$).

Table 8.—Change in "All Causes" Death Rates of Infants during Their First Year of Life and Who Were Located 64–129 km Downwind of Reactors, 2 Years before vs. 2 Years after Nuclear Plant Closings

Reactor	Year closed	Infant deaths		Live births		Deaths/1,000		Change (%)
		BC	AC	BC	AC	BC	AC	
LaCrosse, WI	1987	13	14	1,570	1,467	8.28	9.54	+15.3
Rancho Seco, CA	1989	67	101	9,637	10,426	6.95	9.68	+39.3 ($p < .01$)
Ft. St. Vrain, CO	1989	33	28	3,347	3,229	9.86	8.67	–12.1
Trojan, OR	1992	9	11	1,605	1,608	5.61	6.84	+22.0
Big Rock Pt., MI	1997	5	16	1,131	1,180	4.42	13.56	+206.8
Maine Yankee, ME	1997	7	7	1,778	1,762	3.94	3.97	+0.8
Pilgrim, MA	1986	No data: Atlantic Ocean is downwind area						
Millstone, CT	1995	312	285	53,078	51,247	5.88	5.56	–5.4
Totals for 8 areas		446	462	72,146	70,890	6.18	6.52	+5.4

Notes: BC = 2 yr before closing reactor, AC = 2 yr after closing reactor, WI = Wisconsin, CA = California, CO = Colorado, OR = Oregon, MI = Michigan, ME = Maine, MA = Massachusetts, and CT = Connecticut.
Counties included Buffalo (Wisconsin), Jackson (Michigan), Trempealeau (Wisconsin)—*LaCrosse reactor;* Douglas (Nevada), Lyon (Nevada), Story (Nevada), Washoe (Nevada)—*Rancho Seco reactor;* Albany (Wyoming), Laramie (Wyoming)—*Fort St. Vrain reactor;* Hood River (Oregon), Wasco (Oregon), Pacific (Washington)—*Trojan reactor;* Alpena (Michigan), Montmorency (Michigan), Presque Isle (Michigan)—*Big Rock Point reactor;* Franklin (Maine), Somerset (Maine)—*Maine Yankee reactor;* Norfolk (Massachusetts), Worcester (Maine), Providence (Rhode Island)—*Millstone reactor.*

Infant mortality—congenital anomalies. During the first 2 yr following reactor shutdown, infant deaths from congenital anomalies declined 22.4%, compared with an average 2-yr decline in the U.S. of 5.5% ($p < .05$) and a total decline of 5.6% combined for other counties in the state where reactors were located. Declines in 7 of the 8 areas exceeded that of the U.S.; declines in 6 of the 8 areas exceeded those of other counties in the state (Table 6). During the first 6 yr following the closing of the reactor (for the 4 areas for which data were available), declines near each reactor continued. The change near the Trojan reactor in Oregon is significant, compared with both the U.S. and other counties in Oregon and Washington (Table 7).

Infant mortality—downwind 64–129 km from the plant. Infant mortality in downwind counties located 64–129 km from the closed reactors rose near 5 of the 7 plants (the area downwind from the Pilgrim reactor is the Atlantic Ocean). The overall increase of 5.4% was not significantly different from the 6.4% average national decrease. The 39.3% rise near the Rancho Seco reactor was significant at $p < .01$ (Table 8).

Infant mortality—counties not downwind. In 6 of 8 regions, reductions in infant mortality rates occurred in the first 2 yr following shutdown in non-downwind counties located less than 64 km from closed facilities. However, none of the reductions were significant, and the combined change of 7.1% was equivalent to the average U.S. 2-yr decline (Table 9).

Incidence—childhood cancer. In the states that operated comprehensive cancer registries at the time of reactor shutdown, incidence of newly diagnosed cancers in children under age 5 yr declined in downwind counties within 64 km. The decline measures the 2 yr prior to closing with 7 yr post-shutdown. The total reduction of 25.0% was significantly different from the

Table 9.—Change in "All Causes": Death Rates of Infants during Their First Year of Life and Who Were Located < 64 km—and Not Downwind—from Reactors, 2 Years before vs. 2 Years after Nuclear Plant Closings

Reactor	Year closed	Infant deaths BC	Infant deaths AC	Live births BC	Live births AC	Deaths/1,000 BC	Deaths/1,000 AC	Change (%)
LaCrosse, WI	1987	57	63	7,431	7,176	7.67	8.78	+14.4
Rancho Seco, CA	1989	310	324	36,944	40,073	8.39	8.09	−3.6
Ft. St. Vrain, CO	1989	537	530	58,790	59,923	9.13	8.84	−3.2
Trojan, OR	1992	66	73	11,826	12,296	5.58	5.94	+ 6.4
Big Rock Pt., MI	1997	13	12	2,184	2,288	5.95	5.24	−11.9
Maine Yankee, ME	1997	45	37	9,254	8,990	4.86	4.12	−15.4
Pilgrim, MA	1986	579	528	57,466	60,619	10.08	8.71	−13.6
Millstone, CT	1995	637	555	86,642	83,920	7.35	6.61	−10.0
Totals for 8 areas		2,244	2,122	270,537	275,285	8.29	7.71	−7.1

Notes: BC = 2 yr before closing reactor, AC = 2 yr after closing reactor, WI = Wisconsin, CA = California, CO = Colorado, OR = Oregon, MI = Michigan, ME = Maine, MA = Massachusetts, and CT = Connecticut.
Counties included Allamakee (Iowa), Clayton (Iowa), Winnishiek (Iowa), Fillmore (Minnesota), Houston (Minnesota), Winona (Minnesota), Crawford (Wisconsin), Grant (Wisconsin), Monroe (Wisconsin), Richland (Wisconsin)—*LaCrosse reactor*; San Joaquin (California), Solano (California), Sutter (California), Yolo (California)—*Rancho Seco reactor*; Adams (Colorado), Arapahoe (Colorado), Boulder (Colorado), Gilpin (Colorado), Grand (Colorado), Jefferson (Colorado)—*Fort St. Vrain reactor*; Clatsop (Oregon), Washington (Oregon)—*Trojan reactor*; Grand Traverse (Michigan), Leelanau (Michigan)—*Big Rock Point reactor*; Androscoggin (Maine), Cumberland (Maine), Sagadahoc (Maine)—*Maine Yankee reactor*; Barnstable (Massachusetts), Bristol (Massachusetts), Dukes (Massachusetts), Norfolk (Massachusetts), Suffolk (Massachusetts), Bristol (Rhode Island), Newport (Rhode Island)—*Pilgrim reactor*; and Hartford (Connecticut), New Haven (Connecticut), and Suffolk (New York)—*Millstone reactor.*

Table 10.—Changes in the Incidence Rates of All Cancers during the First 5 Yr of Life of Children Who Lived in Counties that Were Downwind 64 km from Closed Nuclear Plants at 2 Years before vs. 7 Years after Closure of Reactors

Reactor	Year closed permanently	Cancer cases (*n*) BC	Cancer cases (*n*) AC	Population 0–4 yr of age BC	Population 0–4 yr of age AC	Cases/100,000 BC	Cases/100,000 AC	Change (%) Local	Change (%) Other state*
LaCrosse, WI	1987	7	15	17,492	61,053	40.02	24.57	−38.6	−5.1
Rancho Seco, CA	1989	50	153	208,302	854,118	24.00	17.91	−25.4	−1.0
Ft. St. Vrain, CO	1989	10	32	49,156	178,742	20.34	17.90	−12.0	+32.9
Total for 3 areas		67	200	274,950	1,093,913	24.36	18.28	−25.0†	−0.5
U.S. change	1988–1989 to 1990–1996							+0.3	

Notes: BC = 2 yr before the reactor was closed, AC = 7 yr after the reactor was closed, WI = Wisconsin, CA = California, and CO = Colorado.
*"Other" category for Colorado includes Denver area (i.e., Adams, Arapahoe, Boulder, Denver, Douglas, and Jefferson counties), approximately 55% of the state's population 0–4 yr of age.
†$p < .005$ (nuclear counties vs. U.S.), and $p < .006$ (nuclear counties vs. other state total). Rancho Seco trend differed significantly from trends from U.S. ($p < .02$) and other state ($p < .004$).

stable U.S. trend ($p < .005$) and from the trend in other counties in the state ($p < .006$) (Table 10). The reduction near the Rancho Seco plant in California was significant, compared with the reduction in the United States ($p < .02$) and in the remainder of the state ($p < .004$).

Discussion

Research on changes in health in populations exposed to reduced levels of radioactivity has been scant. However, falling infant mortality and a decrease in childhood cancer immediately after atmospheric nuclear weapons testing was halted in 1963 suggest that "smaller" exposures may result in measurable improvements in health, especially in infants and young children.

In each of 8 areas downwind and proximate to closed nuclear power plants, infant deaths declined in excess of national trends during the first 2 yr following shutdown. Declines in mortality from congenital anomalies among local infants were particularly sharp. These trends were consistent for 2-yr and 6-yr periods after plant closings. Although declines near each reactor have fallen short of statistical significance, the possibility that similar trends should occur in each area by random chance is low.

The unexpectedly large decline in infant mortality occurred only in downwind counties that were located less than 64 km from closed nuclear facilities. Non-downwind counties located less than 64 km from reactors have nonsignificant declines in infant deaths. In downwind counties located 64–129 km from the plants, infant death rates increased, but the increases were not significant. Therefore, any beneficial effect of reactor shutdowns may apply only to the closest downwind counties. This finding illustrates the importance of analyzing the health of populations that live near nuclear facilities by *direction*, rather than as a whole. It also suggests that inhalation of airborne radioactive gases and particles, by which process the fetus absorbs radioactivity through the placenta,[14] may be a significant vector of exposure, along with dietary intake.

Cancer diagnosed in children under the age of 5 yr was also reduced in proximate downwind counties with available data. This trend is meaningful because it takes into account disease incidence, which cannot be affected by life-saving technological innovations, and may, therefore, be a more sensitive indicator of radiation effects than mortality.

No demographic characteristic predisposes these areas to health improvements. Reduced infant mortality rates occurred in both rural and urban regions. The relatively small proportions of minorities and poor individuals should not affect short-term changes inasmuch as it is unlikely that the racial distribution of studied counties changed appreciably in 2 yr. In addition, during the 20th century, improvements in infant health have yielded relatively equal benefits for all races and socioeconomic classes (i.e., similar reductions in infant mortality have occurred for all races).

The data support prior research that has shown that in utero exposures to radioactivity are most deleterious given the heightened sensitivity of the developing fetus and newborn infant. In the United States, infant deaths have been linked to exposure to fission products from atmospheric weapons tests.[15] In both Germany[16] and the United States,[17] increases in infant mortality have been attributed to fallout from the 1986 Chernobyl accident. Increased incidences of various congenital malformations have been documented in several European nations after Chernobyl.[18–21] Elevated rates of childhood cancer near U.S. nuclear reactors have also been reported.[22–24]

In addition to reduced exposures to fission products, there may be other explanations for the decline. One such possibility is a demographic shift (i.e., closing of a nuclear power facility results in loss of employment for plant workers, who leave the area in search of work). Although some nuclear workers remain after reactors are closed to assist in deactivating the plant, many, in fact, lose their jobs. The processes of operating a reactor and deactivating it are distinctly different.

Some evidence, however, suggests that this population shift may not account for the unexpectedly large infant death and childhood cancer decreases in their entirety.

1. Nuclear plant workers are generally healthier than other workers of childbearing age. They are sufficiently healthy to hold full-time jobs, and their employer-based health insurance allows them access to medical care (including prenatal care—an important determinant of infant mortality risk). Thus, any departure of these workers from a downwind county after reactor closing would leave a higher-risk population than existed prior to closing of the reactor.

2. In urban areas, such as Sacramento, California, and Portland, Oregon, workers at the nuclear plant likely represent a small percentage of the overall workforce, and they have little impact on the postclosing infant death and cancer rates. Even in rural areas, numbers of live births did not decline rapidly following the closure of the reactor.

3. Workers are as likely to live upwind as they are to live downwind from the plant; however, consistent improvements in infant health occurred only in downwind areas.

4. Two of the plants were closed only temporarily. They did not lay off large numbers of workers, yet disease and death trends were similar to those obtained for the permanently closed reactors.

Whereas a substantial lag period between exposure and disease manifestation may be observed for adult cancers exposed to external x-rays, a much shorter lag period has been documented for very young individuals. Pelvic x-rays administered in utero are linked with increased cancer deaths before an individual's 10th birthday,[25] and 2/3 of these malignancies are diagnosed before the age of 5 yr. Thyroid cancer among children under 15 yr of age who lived near the Chernobyl facility began a sustained increase just 4 yr after the April 26, 1986, accident.[26–28] In 3 Pennsylvania counties located closest to the Three Mile Island facility, cancer deaths in persons under the age of 10 yr jumped from 28 to 36 in the 5 yr following the March 28, 1979, accident.[29]

A relatively short latency period that followed the addition of radioactivity raises the question of whether a similarly short lag exists between reduced exposures and declining disease rates. Short-lived airborne radioisotopes emitted from reactors are completely removed from the environment/diet within several months of the plant shutdown. Long-lived isotopes decay slowly, but existing data on dietary levels of Sr-90 suggest that these may be reduced substantially within several years after plant closing.

The data indicate that improvements in health occur after relatively slight reductions in dietary radioactivity. Sr-90 concentrations measured in milk samples in 9 U.S. cities fell from 30 to 15 picocuries per liter over an 18-mo period following cessation of large-scale atmospheric nuclear weapons tests in the mid-1960s. In contrast, Sr-90 reductions in milk near closed nuclear reactors fell from approximately 1.0 to 0.5 picocuries after shutdown. Changes in health status after a relatively small reduction support the effects of low-dose exposures on laboratory animals.[30] In light of these data, the current understanding of the relationship between low-dose radiation exposure and disease should be reconsidered.

Several factors limit this study from being more meaningful. There is a dearth of research on health effects of reduced exposures to ionizing radiation and other toxic substances with which to compare results. Small population sizes in several of the areas near closed facilities make significant findings elusive. The 60 cities with federally reported dietary levels of radioactivity are often not proximate to nuclear sites. Moreover, routine reports of particular isotopes (e.g., barium-140, cesium-137, iodine-131, strontium-89) are no longer available. Reliance on annual strontium-90 levels in milk is a relatively basic measure of radiation burden on local residents. The use of weekly or monthly levels of a variety of isotopes (i.e., both short- and long-lived) would make dose estimates more meaningful. Moreover, given that locally consumed milk is often not produced locally, radioisotope concentrations in air and water would be useful.

The current report was based on aggregate data. In this report, we did not measure levels of radioactivity in the bodies of individual decedents or of infants who survived the first year of life. More dose information—not just in environmental/dietary levels—but *in vivo*, is needed. U.S. government programs that measure Sr-90 in deciduous teeth, children's vertebrae, and adult vertebrae were discontinued in the 1970s and early 1980s.[31] A recent project in which Sr-90 concentrations were measured in deciduous teeth of persons living near nuclear reactors indicated a link between Sr-90 levels and childhood cancer incidence.[32]

More research on how intrauterine exposure to radiation affects health in later life is critical in understanding effects of nuclear reactors. With more than 400 such facilities operating worldwide, such data can play a vital role in any program of disease prevention and health promotion.

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Requests for reprints should be sent to Joseph J. Mangano, M.P.H., M.B.A., National Coordinator, Radiation and Public Health Project, 786 Carroll Street, #9, Brooklyn, NY 11215.

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