Cancer in populations living near nuclear facilities

Report of a survey by researchers at the US National Cancer Institute

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Although there have not been, in the United States, massive accidental releases of radioactivity from nuclear facilities such as the one at Chernobyl[1], questions continue to be raised about possible adverse health effects resulting from events such as the releases at Three Mile Island[2] and Hanford[3], or even from routine operation of nuclear facilities.

Higher incidence of leukaemia in children has been reported in the environs of the Sellafield fuel reprocessing facility in England,[4,5] near the Dounreay reprocessing plant in Scotland,[6,7] and in children who lived within a few kilometres of the Aldermaston or Burghfield military weapons facilities in England.[8] In a comprehensive survey, Forman et al[9] and Cook-Mozaffari et al[10,11] reported excess mortality due to leukaemia and Hodgkin's disease in young persons in the vicinity of 14 nuclear facilities, eight of them electric generating plants. Crump et al[12], however, found no variations in cancer incidence rates in the vicinity of the Rocky Flats weapons plant, and studies in France by Dousset,[13] Viel, and Richardson,[14] and Hill and Laplanche[15] found no excess mortality from leukaemia or other cancers in persons who lived near any of the six nuclear facilities (including two reprocessing plants).

Studies of populations living near power plants have yielded mixed results. In the United Kingdom, Ewings et al[16] found increased incidence of leukaemia and lymphoma in young persons near the Hinckley Point power station. Clapp et al[17] reported an excess incidence of leukaemia in men in five towns near the Pilgrim nuclear power station in Massachusetts, but Enstrom[18] found no excess mortality near the San Onofre plant in California, and Clarke et al[19] reported no increased leukaemia in Canadian children under 5 years of age who lived near any of several facilities, including plutonium refining plants.

Certain British investigators have reported that the increased occurrence of cancers in persons living near nuclear facilities could not have resulted from radioactive emissions from the facilities, as these emissions are far below the dose received from natural background radiation.[11,20] Further, there was little consistency among the several reports as to the distance from facility, time after operations began, or even age and disease groups.

To examine these issues systematically in the United States, data on deaths from cancer by county were evaluated, as well as cancer registration data, where they were available and of good quality.[21]

Methods

Kinds of cancer. The following 15 kinds of cancer were studied in addition to benign and unspecified neoplasms: leukaemia and aleukemia; all malignant neoplasms excluding leukaemia; Hodgkin's disease; other lymphoma; multiple myeloma; cancers of the stomach; cancers of the colon and rectum; primary liver cancer; cancer of any digestive organ; cancer of the trachea, bronchus, and lung; female breast cancer; cancers of the thyroid gland; bone and joint cancer; bladder cancer; and cancer of the brain and other parts of the central nervous system. Leukaemia is the radiogenic cancer that appears soonest after large radiation doses are received at high-dose rates, but risks from low doses, received at low rates, are a subject of scientific uncertainty.[22]

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Mortality and incidence data. Counties are the smallest areas for which both population estimates and annual counts of the number of deaths for specific causes are available nationwide. Counts of deaths by cause, sex, race, and 5-year age group were obtained for every county for each year from 1950 to 1984. Quality registration (incidence) data, however, were available only from Connecticut and Iowa with respect to four facilities. The analyses were, therefore, based primarily on the mortality data. Estimates of annual county populations by sex, race, and age group were obtained by interpolation in census counts for 1950 to 1969[23] and for later years were prepared by the Bureau of Census using decennial censuses and other data sources.

Study counties. Radiogenic leukaemia has a minimum latent period of at least 2 years[22], so no deaths due to leukaemia that may have resulted from exposures in 1982 or later are identified in these data. Therefore, the set of facilities studied is limited to the 62 that were in operation prior to 1982, including 52 commercial nuclear electric plants, nine facilities operated for the Department of Energy (DOE), and one former commercial fuel reprocessing plant. The 62 facilities are located in 64 counties (the Idaho National Engineering Laboratory and the Oak Ridge Laboratory each have individual plants in two counties). Although there were more than 80 commercial power reactors in operation before 1982, there are fewer study sites than reactors as some plants have more than one reactor. Facilities are sometimes located on or near the boundary between counties, and adjacent counties were included when they constituted at least 20% of the area within a 16-km radius of a facility. In a few instances, however, adjacent counties that satisfied the selection criteria were rejected because of the presence of a large city, far from the plant, that would have dominated the cancer mortality statistics. There are 107 different study counties included. The Point Beach and Kewaunee (Wisconsin) power plants, located in adjacent counties, are treated as a single installation. Data are presented, therefore, for 61 study areas.

Control counties. Three comparison counties were selected for each study county. It was not always possible to choose a different control set for each study county, and 292 different control counties were selected. Control counties were matched to study counties by the following characteristics: percentages of persons in the population over age 25 that were white, black, American Indian, Hispanic, urban, rural, employed in manufacturing and high school graduates; mean family income; net migration rate; infant death rate; and popula-

Nuclear facilities included in survey

Facility	County	State	Start-up Year*
Department of Energy facilities			
Fernald	Hamilton	Ohio	1951
Hanford	Benton	Washington	1943
Idaho National Engineering Laboratory	Bingham, Butte	Idaho	1949
Mound	Montgomery	Ohio	1947
Nuclear Fuel Services	Cattaraugus	New York	1966
Oak Ridge	Anderson, Roane	Tennessee	1943
Paducah Gaseous Diffusion	Ballard	Kentucky	1950
Portsmouth Gaseous Diffusion	Pike	Ohio	1952
Rocky Flats	Jefferson	Colorado	1953
Savannah River	Barnwell	South Carolina	1950
Electric utilities			
Arkansas	Pope	Arkansas	1974
Big Rock Point	Charlevoix	Michigan	1962
Browns Ferry	Limestone	Alabama	1973
Brunswick	Brunswick	North Carolina	1975
Calvert Cliffs	Calvert	Maryland	1974
Cook	Berrien	Michigan	1975
Cooper Station	Nemaha	Nebraska	1974
Crystal River	Citrus	Florida	1977
Davis Besse	Ottawa	Ohio	1977
Dresden	Grundy	Illinois	1960
Duane Arnold	Linn	Iowa	1974
Farley	Houston	Alabama	1977
Fermi	Monroe	Michigan	1963
Fort Calhoun	Washington	Nebraska	1973
Fort St. Vrain	Weld	Colorado	1976
Ginna	Wayne	New York	1969
Haddam Neck	Middlesex	Connecticut	1967
Hallam	Lancaster	Nebraska	1962
Hatch	Appling	Georgia	1974
Humboldt Bay	Humboldt	California	1963
Indian Point	Westchester	New York	1962
Kewaunee	Kewaunee	Wisconsin	1973
La Crosse (Genoa)	Vernon	Wisconsin	1967
McGuire	Mecklenburg	North Carolina	1981
Maine Yankee	Lincoln	Maine	1972
Millstone	New London	Connecticut	1970
Monticello	Wright	Minnesota	1971
Nine Mile Point	Oswego	New York	1969
North Anna	Louisa	Virginia	1978
Oconee	Oconee	South Carolina	1973
Oyster Creek	Ocean	New Jersey	1969
Palisades	Van Buren	Michigan	1971
Pathfinder	Minnehaha	South Dakota	1964
Peach Bottom	York	Pennsylvania	1974
Pilgrim	Plymouth	Massachusetts	1972
Point Beach	Manitowoc	Wisconsin	1970
Prairie Island	Goodhue	Minnesota	1973
Quad Cities	Rock Island	Illinois	1972
Rancho Seco	Sacramento	California	1974
Robinson	Darlington	South Carolina	1970
St Lucie	St Lucie	Florida	1976
Salem	Salem	New Jersey	1976
San Onofre	San Diego	California	1967
Sequoyah	Hamilton	Tennessee	1980
Shippingport/Beaver Valley	Beaver	Pennsylvania	1957
Surry	Surry	Virginia	1972
Three Mile Island	Dauphin	Pennsylvania	1974
Trojan	Columbia	Oregon	1975
Turkey Point	Dade	Florida	1972
Vermont Yankee	Windham	Vermont	1972
Yankee Rowe	Franklin	Massachusetts	1960
Zion	Lake	Illinois	1972

* Sixty-two nuclear facilities were analysed in the survey, including the following: 10 Department of Energy facilities, including one former commercial fuel reprocessing plant (Nuclear Fuel Services): and 52 electric utilities with start-up years between 1957 and 1969 (15), 1970 and 1974 (25), and 1975 and 1981 (12).

Data for nuclear facilities and counties included in survey

	Study Counties	Control Counties
No of counties	107	292
Population (1980)		
Total	18 720 000	32 980 000
Median	62 900	41 600
Area, km^2		
Largest	10 951	52 156
Median	1 503	1 498
Smallest	218	234
No. of deaths (1950–1984)		
Leukemia	37 200	78 500
Other cancers	838 000	1 794 000

tion size. All data were for the year 1979, except for population data, which were for 1980.

The large differences among cancer death rates in different geographic areas cannot, however, be accounted for completely from routinely available population statistics. Data on diet or specific ethnic background, for example, were not available. Since the distributions of these factors tend to vary over broad geographic areas (e.g. ethnicity in the Southwest), control counties were chosen from the same region as the study counties.

Form of analysis

Individual facilities. For each type of cancer and each county the "expected" number of deaths, based on concurrent US experience, was calculated for each year during the 35-year study period (1950 to 1984). Annual US death rates were multiplied by the estimated populations, separately by 5-year age group, sex, and race (white, nonwhite). The values for the two races and two sexes were then summed for all counties in the study area (if more than one) and for all of the corresponding control counties. The data were then summed for all of the years from 1950 until the facility went into service, and for all of the years after the start-up through 1984, thus producing numbers of deaths expected before and after plant start-up.

The ratio of the actual number of deaths to the number expected at US rates is the standardized mortality ratio (SMR). Similarly, the ratio of the number of incident cancer cases registered to the number expected at overall state rates is the standardized registration ratio (SRR). Ratios of the SMRs or SRRs for the study and control counties were called "relative risks" (RRs), although this is not the traditional usage of the term *relative risk*. Ratios were not calculated if the number of deaths in the study or control areas was less than three, or if their sum was less than 10. The difference between each RR and 1.00 was assessed by calculation of the probability that a difference of the observed magnitude, or larger, might have arisen by chance.

Combinations of facilities. The mortality data were also examined for combinations of facilities using an adaptation of the Mantel-Haenszel procedure for stratified data.[24] Each study area and associated control area served as one stratum. Data for electric power reactors and DOE facilities were examined separately as well as together.

Results

Mortality. The data show that, for childhood leukaemia mortality, for each group of facilities, whether they were electric utilities or DOE facilities, the RRs comparing the study counties with the control counties were smaller after start-up than before. (It should be noted that some DOE facilities began operating in the 1940s, and since the time periods available for this study commenced in 1950, data for most of the DOE facilities are limited to their experience after start-up). For no facility was the RR for childhood leukaemia mortality significantly elevated. For deaths of children from cancer other than leukaemia, for no facility, or group of facilities, was the RR comparing study with control areas after start-up significantly raised.

Data concerning leukaemia mortality in all age groups combined also shows smaller RRs after start-up than before. After start-up, the RRs were all less than 1.00; the deficits are significant (P less than 0.05) for the combined DOE plants and for all facilities combined.

The data for all age groups for all types of cancer except leukaemia show that the RRs after start-up were all close to 1.00 and vary only between 0.98 and 1.04. The RR for the DOE plants is significantly high (1.04) but smaller than the corresponding RR before start-up. More than 2 million deaths are included in the tabulation, so even such small variations of the RRs from 1.00 are sometimes statistically significant.

Incidence. Incidence data were available only for counties in Connecticut and Iowa. Since incidence data were not available for all of the control counties the evaluation is based on the standardized registration ratios (SRRs)

Results of survey

Mortality due to leukaemia, under age 10 years, by type of facility

Type of Facility	Before Start-up					After Start-up				
	Study		Control			Study		Control		
	Deaths Observed	SMR	Deaths Observed	SMR	RR	Deaths Observed	SMR	Deaths Observed	SMR	RR
Department of Energy	39	1.18	48	0.84	1.45	601	1.01	1009	0.96	1.06
Electric utilities										
1957–1969	593	1.09	1035	1.05	1.03	534	1.03	993	1 00	1.00
1970–1974	996	1.06	2383	0.98	1.09*	227	1.00	482	0.94	1.06
1975–1981	392	1.07	785	0.95	1.11	28	0.70	88	0.93	0.82
Total	1981	1.07	4203	0.99	1.08*	789	1.01	1563	0.98	1.01
All Facilities	2020	1.07	4251	0.99	1.08*	1390	1.01	2572	0.97	1 03

Mortality due to leukaemia, all ages, by type of facility

Type of Facility	Before Start-up					After Start-up				
	Study		Control			Study		Control		
	Deaths Observed	SMR	Deaths Observed	SMR	RR	Deaths Observed	SMR	Deaths Observed	SMR	RR
Department of Energy	258	1.01	401	0.92	1.07	6 077	1.00	11 657	1.03	0.96*
Electric utilities										
1957–1969	4 088	1.02	7 235	0.99	1.05*	8 478	1.00	15 474	1.01	0.99
1970–1974	8 354	0.97	21 172	0.97	1.00	5 615	0.97	12 823	1.00	0 98
1975–1981	3 307	0 99	7 163	0.94	1.04	1 006	0.92	2 620	0.95	0.98
Total	15 749	0.99	35 570	0.97	1 02	15 099	0.98	30 917	1.00	0.99
All Facilities	16 007	0 99	35 971	0.97	1.02	21 176	0.98	42 574	1 01	0.98*

Mortality due to all types of cancer except leukaemia, all ages, by type of facility

Type of Facility	Before Start-up					After Start-up				
	Study		Control			Study		Control		
	Deaths Observed	SMR	Deaths Observed	SMR	RR	Deaths Observed	SMR	Deaths Observed	SMR	RR
Department of Energy	5 780	1.04	8 991	0.96	1 06*	141 635	1.06	247 308	0.99	1.04*
Electric utilities										
1957–1969	79 902	1.00	157 745	1.06	1.00	197 158	1.02	364 675	1.05	1.01
1970–1974	179 208	0.99	471 890	1.02	0.98*	139 175	0.99	317 206	1.02	0.98*
1975–1981	69 310	0.96	157 884	0.96	1.02*	26 325	0.98	68 785	1.01	0.99*
Total	328 420	0.98	787 519	1.01	0.99	362 658	1 01	750 666	1.04	0.99
All Facilities	334 200	0.99	796 510	1.01	1.00	504 293	1.02	997 974	1.02	1.01

Incidence of leukaemia in Connecticut and Iowa study counties in relation to time of plant start-up

	Before Start-up		After Start-up	
	Deaths Observed	SRR	Deaths Observed	SRR
Under age 10 years at diagnosis				
Haddam Neck, Conn (1967), Middlesex County	15	0.96	16	0.97
Millstone, Conn (1970), New London County	49	1 19	44	1.55**
Fort Calhoun, Neb (1973), Harrison County, Iowa	1	1.91	4	3.13
Duane Arnold, Iowa (1974), Linn and Benton Counties	9	1.04	17	1.26
Total	74	1.13	81	1.36**
All ages, facilities combined	577	0.92*	850	1.01

Notes: SRR indicates standardized registration ratio and is the ratio of the number of cancer cases registered to the number expected at concurrent statewide registration rates.
SMR indicates standardized mortality ratio and is the ratio of the number of deaths observed to the number expected at concurrent US national death rates.
RR indicates relative risk and compares the risks in the study and control areas. The RR for combined facilities is obtained by a Mantel-Haenszel-type procedure and sometimes differs from the simple ratio of the SMRs.
* $P \leq 0.05$.
** $P \leq 0.01$.

before and after plant start-up. For childhood leukaemia, for the four facilities combined, the SRR before start-up was 1.13 (not significant) but increased to 1.36 (P less than 0.01) after start-up. Only for the Millstone plant, in New London County, Connecticut, was there a significantly raised SRR after start-up, 1.55 (P less than 0.01). The SRRs were 1.46 in 1971 to 1975, 1.34 in 1976 to 1980, and 2.02 in 1981 to 1984 based on a total of 44 cases. During the 10 years before start-up (1961 to 1970), however, there were 30 cases of leukaemia in children (SRR 1.34). For all ages combined, there were no significantly increased SRRs for leukaemia after start-up for any individual facility or for all facilities combined.

The SRRs for cancers other than leukaemia among children did not vary significantly from 1.00. Similarly, the SRRs for breast cancer or thyroid cancer (all ages) did not vary significantly from 1.00 after start-up.

Comment

This survey was stimulated by the study reported by the British Office of Population Censuses and Surveys.[9,10] The US survey covered a much longer time frame (35 years), enabling more detailed analyses, including comparisons of plants before and after start-up and comparisons with both control areas and the entire United States. Also, there are many more nuclear facilities in the United States than in the United Kingdom. Cancer registration (incidence) data were available to the Office of Population Censuses and Surveys study, but because of concerns about the comparability of case ascertainment in different areas, the authors chose to base inferences on only the mortality data. In evaluating incidence in the US survey, we have restricted attention to the limited set of facilities and counties for which registration data of good quality were available.

No general increase in cancer mortality was found in counties in the United States with or near nuclear electricity generating plants. Unlike some studies reported from the United Kingdom,[4-8] no excess incidence of leukaemia was found in children who lived near reprocessing and weapons plants.

The cancer data reported herein resulted from a *survey*, not an experimental study. No information on radiation exposures to individuals was available. Although counties were matched using available data concerning racial composition, urban-rural mix, income, and other factors, it is not possible to choose control counties that are exactly comparable with the study counties. Counties vary with respect to industries, occupations, educational levels, and life-style. Moreover, the matching was based on data for the years 1979 and 1980. Since county characteristics in the 1950s and 1960s were undoubtedly different from those in 1979, the matching of study and control counties in the earlier years may have been inadequate in some instances. Cancer deaths in each county were also compared with the numbers expected on the basis of concurrent US mortality rates and, when possible, the number of incident cases with the number expected on the basis of statewide rates. National or state disease rates, however, are not necessarily appropriate bases of comparison for particular counties that have their own individual characteristics with respect to smoking and other risk factors for cancer.

The analysis treats each set consisting of a study county (or counties) and the associated controls as a stratum in which all departures from overall US rates are the same. This cannot, however, be exactly true, and the data are therefore affected by variation arising from extraneous factors. The technical term *statistically significant* refers only to the probability that a difference arose from mere chance and has nothing to do with biological as opposed to mathematical significance. Although many RRs are significantly different from 1.00, values such as 0.98 or 1.03 have little meaning or biological relevance. The fact that thousands of RRs have been computed and tested for significance must be taken into account in assessing the meaning of the RRs that achieve statistical significance.

The survey has other limitations, including the following:

- Data were available only for counties. Some counties with nuclear facilities also contain large cities distant from the plants. Local effects associated with the plants might be impossible to detect using county death rates because of the dilution resulting from the inclusion of the city populations. Similar problems, however, affect the health districts in the United Kingdom used by Roman et al[25] in their studies of Harwell, Aldermaston, and Burghfield, and by Cook-Mozaffari et al[11,26] in their subsequent survey of cancer mortality around all nuclear facilities (and potential facilities) in England and Wales.
- This study relied mainly on mortality data. Incidence data were available only for counties associated with four facilities. Mortality data, however, are not optimal for monitoring such cancers as those of the thyroid or the female breast, or childhood leukaemia, for which improved therapy has markedly lowered death rates in recent years while not affecting incidence. On the other hand, the British survey

that stimulated the present investigation did identify significant excess mortality from childhood leukaemia.

- The kind of cancer responsible for death was taken from physicians' statements on death certificates. However, in the absence of an autopsy, it can be difficult to decide whether a cancer of the lung or of the liver is primary or metastatic. The quality of medical care available undoubtedly varies from county to county and may affect the accuracy of cause-of-death certification and the comparability of county data.
- Although the DOE facilities have operated for more than 30 years, most of the commercial power plants came into service only in 1970 or later. Because of the long latent period for most radiogenic cancers, only during the first few years of operation would it have been possible for plant emissions to induce cancers (other than leukaemia) that would be detectable in the years prior to 1985.
- This was an "ecological" survey in which the exposures of individuals are not known. Persons who lived in particular counties at the time of death may not have been long-term residents. Some residents will have moved elsewhere and died in another part of the county. Some residents of counties that have a nuclear facility may live far from the plant, not be at any risk, and their experience may dilute that of residents living closer to the plant.

Conclusion

Despite the limitations inherent in an ecological study of cancer mortality in counties with and without nuclear facilities, the methods used have been applied effectively in the past to identify environmental carcinogens. For example, based on findings from the "cancer maps" constructed from county mortality statistics by the National Cancer Institute, counties with shipyard industries were found to have elevated lung cancer death rates, particularly among men. Subsequent case-control studies in the high-risk areas linked the excess lung cancer deaths to asbestos exposures.[27]

If conventional estimates of the cancer risks attributable to radiation are accepted, exposures from the monitored emissions from nuclear facilities in the United States, typically less that 3 millirem per year, to the maximally exposed individual,[28] were too small to result in detectable harm. Such levels are, in fact, much smaller than the population exposures from natural background radiation, which amount to about 100 millirem per year, excluding lung doses from radon. A similar situation existed in the United Kingdom. However, excess childhood leukaemias were still identified in the areas around the Sellafield and Dounreay reprocessing plants and the Aldermaston and Burghfield weapons facilities.[20,25] It has not been shown, however, that those excesses were caused by radioactive emissions from the plants. A recent case-control study of leukaemia cases that occurred near the Sellafield plant concluded that a possible causative factor might be paternal occupational exposure to radiation prior to conception.[29] It has also been hypothesized that the clusters in the United Kingdom might have an infective, possibly viral, explanation.[30]

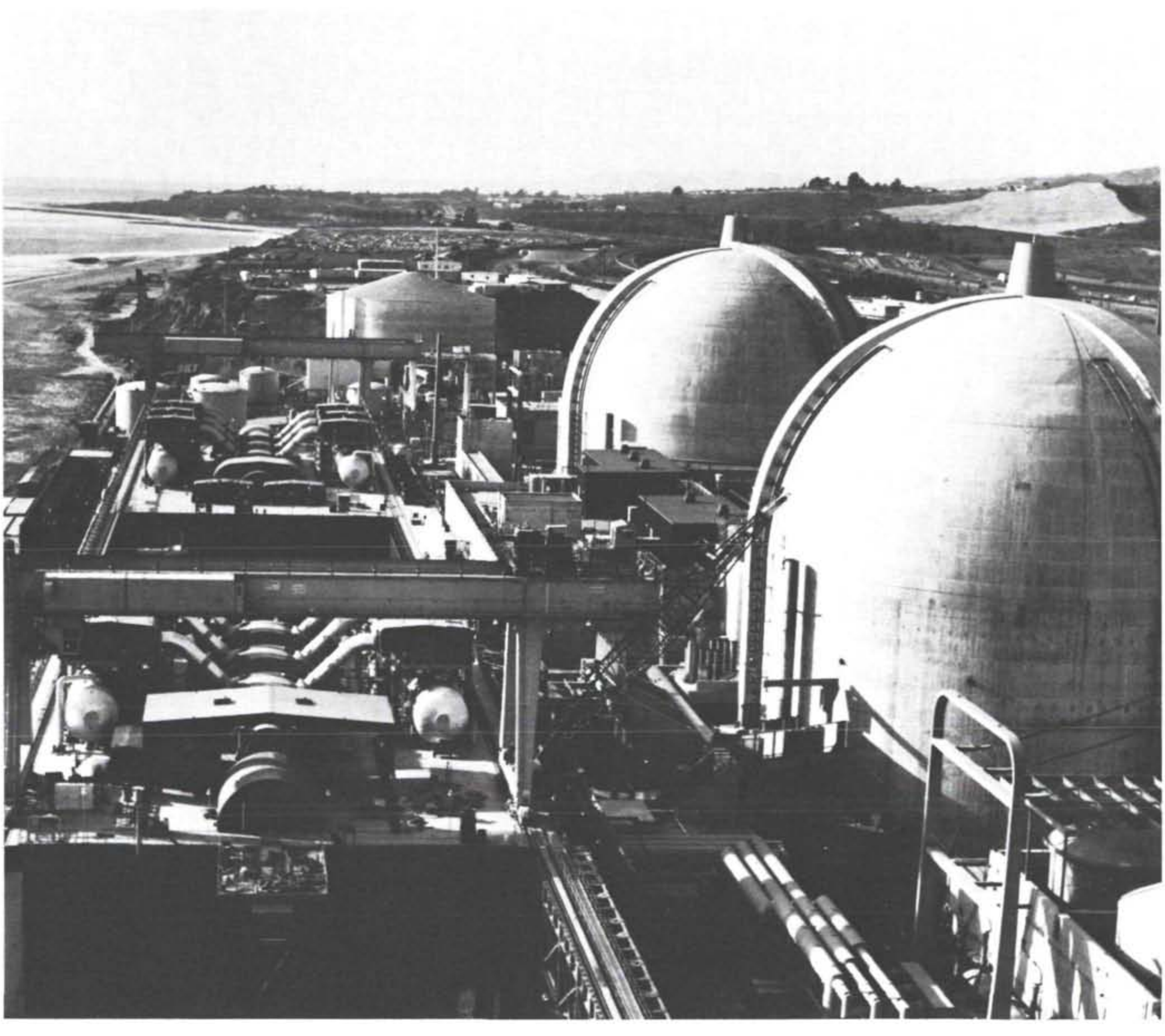
The fact that significant differences were found in our survey for the period *before* facilities went into service illustrates the need for caution before interpreting all differences after start-up as evidence of adverse health effects attributable to operation of the facilities. Help in interpretation is also available from the knowledge about radiation carcinogenesis that has been accumulated during the past 50 years, and especially the last 15 years.[22] Although radiation-induced leukaemia may occur as soon as 2 years after exposure, other cancers such as those of the breast and lung develop more slowly and are unlikely to be identified in mortality data for 10 years or more after radiation exposures. Only with the passage of some years after the first operation of a facility can it be expected that residents of the surrounding area could accumulate sufficient exposure to ionizing radiation or any other potentially harmful discharges to induce a detectable increase in mortality due to malignant neoplasms.

No statistically significant increases in deaths from childhood leukaemia were found. Only in the incidence data available for the Millstone nuclear power plant in Connecticut did the leukaemia rate in children appear to be significantly increased. The increase, however, antedated the operation of Millstone. In 1972, the Centers for Disease Control investigated a cluster of childhood leukaemia and lymphoma in the town of Waterford, where Millstone is located. Six of the 11 cases, however, had onset of disease prior to October 1970, when the Millstone-1 reactor first became operational. In this survey, the SRR for childhood leukaemia was found to be elevated before and after the start-up of Millstone, from 1961 through 1984. The possibility seems remote, therefore, that there was any connection between the leukaemias and the operation of the Millstone plant.

This survey has not shown that the operations at any of the 62 nuclear facilities have caused excess childhood leukaemia in their vicinity. Cook-Mozaffari et al[26] found that, in England and Wales, there were excesses of childhood leukaemia and Hodgkin's disease in areas that had been proposed for nuclear facilities that had not been built or were built only later, which implies that such areas are sometimes marked by unidentified risk factors other than those directly associated with the nuclear installations themselves. Although public concerns have been raised with respect to Fernald, Rocky Flats, Hanford, Three Mile Island, and others, this survey has not detected excess mortality due to leukaemia or other cancers that might have been caused by radioactive emissions from any DOE facility or commercial nuclear electric power plant.

In the combined data for all facilities, the RR of mortality from childhood leukaemia after plant start-up was 1.03, while before start-up it was larger, 1.08. For leukaemia mortality at all ages, the RRs were 0.98 after start-up and 1.02 before. Thus, this survey did not detect any general association between residence in a county with a nuclear facility and death attributable to leukaemia or, in fact, any other form of cancer. As mentioned above, however, the presence in some counties of large populations at considerable distances could dilute any effects that might be present in small areas around the facilities.

We cannot conclude that nuclear facilities have not caused any cancer deaths in persons living near them. It can be concluded, however, that if nuclear facilities posed a risk to neighbouring populations, that risk was too small to be detected by a survey such as this one.



The San Onofre nuclear plant in Southern California, USA, was one of 62 nuclear facilities in the US survey. (Credit: Southern California Edison Co.)

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