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Abstract

The present paper summarizes the initial data on the fallout levels in Europe and the United States produced by the Chernobyl nuclear reactor accident, in order to estimate what the potential effects on human health are likely to be, and what kind of studies should be undertaken to test these predictions. The reported concentrations in the diet were 100 to 1000 times greater than any observed in Europe during the height of atmospheric bomb-testing. Existing epidemiological data on leukemia, cancer, fetal and infant mortality changes following the arrival of fallout are reviewed, together with the most recent laboratory studies on the free-radical dominated effect of very low dose-rate radiation, which explains the unexpectedly large effects of protracted exposures to fallout compared with short exposures to medical X-rays or direct radiation from an atomic bomb detonation. Estimates are that between 150,000 to 600,000 additional cancer cases in Europe alone may result from the disaster. (Int J Biosocial Res., 8(1); 7-36, 1986.)

Introduction

The explosion of the nuclear reactor at Chernobyl, U.S.S.R., in the early morning hours of Saturday, April 26, 1986, led to the widespread contamination of large parts of the Soviet Union and Europe with radioactive fission products, comparable in amount to the total radioactivity released by the detonation of some 200 to 400 Hiroshima-sized weapons. This is roughly the equivalent of some 10 years of atmospheric testing of atomic bombs at the Nevada test-site in the south-western corner of the United States at the highest annual rate that occurred in 1957, all compressed into a single tragic event.

For decades there has been a world-wide debate as to whether the testing of nuclear weapons and accidental releases from nuclear reactors and other facilities has had a detectable affect on human health. The answer bears directly on the question as to just how serious the consequences of the accident in Chernobyl is likely to be, and thus on the future of all commercial nuclear power generation. It also has important implications for what the effects of a nuclear war might be on populations not in the immediate target areas who

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would be exposed to the drifting clouds of fallout hundreds or even thousands of miles away. It is the purpose of the present paper to summarize what is already known about the fallout from Chernobyl, and to suggest what should be studied in the aftermath of the accident. Because the observed levels of iodine-131 all over Europe were some 100-1000 times larger than those observed during any previous period of nuclear bomb testing, such studies will permit a clear resolution of the controversy that has existed over the health effects of low dose, low dose-rate exposures from environmental sources. Accordingly, the present paper will summarize what has already been learned from existing epidemiological investigations and the latest laboratory studies of the biological mechanisms involved in the action of low-level radiation, particularly on the physical and mental health of the newborn.

THE FALLOUT FROM CHERNOBYL

Although there still is a considerable degree of uncertainty as to exactly how much radioactivity escaped from the reactor in Chernobyl, there already exists a large body of environmental measurements of the resulting levels of radioactivity in the air, the rainwater, the vegetation and the milk in Europe, Asia and North America from which doses to various critical organs can be calculated. This data was collected by radiation monitoring systems established in many countries to measure nuclear weapons test fallout and releases from nuclear facilities, and reported to the U.S. Environmental Protection Agency (EPA) which published a series of reports available to the public.[1] The amount of detail varies widely from country to country, the most complete information published so far relating to concentrations of iodine-131 in the air, on the ground and in the milk, with much less complete data on concentration in rainwater, drinking water, vegetation and the soil. For a few countries, spectral analysis of the gamma-ray emitting isotopes provides information on the relative amounts of various radioactive materials contained in the air such as cesium-137 and cesium-134, as well as other forms of short-lived iodine, In addition, external gamma radiation rates are available over a period of a few weeks for many cities and towns especially in Austria and Finland that serve as a valuable check on the time-history of the event, and which allow a comparison with what is know about the fallout from the bomb tests of the 1950's and early 60's. Additional details on radiation levels in Germany have been gathered and published by the Institute for Energy and Environmental Research in Heidelberg.[2]

An analysis of the available data carried out at the Lawrence Livermore Laboratories [3] and reported in *Science* by Colin Norman [4] arrives at the conclusion that probably as much as 40 million curies of iodine-131 were released, corresponding to half the total inventory contained in the reactor. This is a very large amount, equal to the fission products produced in the detonation of some 200 to 400 bombs of the Hiroshima and Nagasaki size, each of which is believed to have had the equivalent energy release of 10 to 20,000 tons of TNT, or the equivalent of a 5 megaton weapon. These estimates are made based on the following: a 1,000 megawatt reactor, such as the Chernobyl reactor, has the equivalent of 800 to 1,000 Hiroshima comparable bombs worth of radioactivity, if it has been operational for six months to one year. If 50 percent of the reactor's fission products are released, it can be estimated that 200-400 Hiroshima-like bombs would be released. However, what actual fraction of the radioactive Iodine-131 and other fission products were actually released from the Chernobyl reactor is not known.

At Chernobyl, a powerful hydrogen expolosion that burst through a heavy concrete structure surrounding the large graphite core containing tubes of uranium apparently led to the ejection of radioactive fission products high into the atmosphere.[3] The fact that the explosion lifted the debris so high into the air may be the reason why there were not many more immediate deaths from acute radiation exposure in the population of the nearby towns. Winds from the Black Sea to the south carried the initial cloud of debris to the north-west over Byelorussia, Eastern Poland, Lithuania and across the Baltic to the east coast of Sweden, where it was detected at 9 a.m. on Monday, April 28 at the Forsmark Nuclear Power Plant, 60 miles north of Stockholm. The explosion was followed by a fire that burned for many days, continuing to release large amounts of radioactivity as the winds shifted so as to carry the clouds of radioactive debris towards the west and south, where it reached Austria on April 29 and Turkey at the eastern end of the Mediterranean on May 1.

Heavy rains brought down extremely large amounts of radioactivity to the ground in Austria, so that one sample of rainwater in Vienna registered 1.7 million picocuries [pCi] of iodine-131 per liter on April 30, the highest reported by the EPA anywhere after the accident [5], while the milk reached 50,000 pCi in a single liter that day. [One pCi is one trillionth of a curie, or 10^{-12} curies, and one curie is an amount of activity equal to that of one gram of radium, corresponding to 37 billion disintegrations per second].

To appreciate the enormous magnitude of the activity measured in Vienna, a daily intake of only 100 pCi was regarded as cause for serious concern at the time of the bomb-testing in the atmosphere, since the consumption of this amount for a year, a total of 36,500 pCi, was estimated by the Federal Radiation Council [FRC] to result in a maximum dose of 1,500 millirads [mr] to the thyroid of an infant 1 year old accepted as allowable at that time.[6]

However, a study at the University of Michigan published in 1959 by Beierwaltes [7] showed that the small fetal thyroid concentrates iodine-131 by as much as ten times more than the infant thyroid, giving a radiation dose some ten times larger, or some 100 times greater than that for the still larger adult thyroid. Therefore, the thyroid of a fetus can receive as much as 0.4 mr from a single picocurie of iodine-131 ingested, or 40 mr for the maximum permissible concentration of 100 pCi in a liter of milk according to the FRC standards. These doses must be compared with that received from normal background radiation in a year, which is of the order of 80-100 mr per year or 0.25 mr per day, roughly one third from naturally occurring radioisotopes in the body, one third from external sources in the ground, and another third from cosmic rays. Another useful comparison that brings these doses into perspective is that a typical X-ray of the chest and neck of an infant taken with modern X-ray equipment and fast film gives the thyroid only 1-2 mr.

Fortunately, dilution of the rainwater reduced the drinking water concentration to only 100 - 1700 pCi/1, but the milk had reached levels as high as 50,000 pCi/1 on the same day because cows graze typically over 10 square meters of pasture per day, and the ground was covered with as much as 900,000 pCi of I-131 per square meter, varying widely because of differences in the local rainfall and sloping of the ground. Nevertheless, fetal thyroid doses as large as 20,000 mr would be expected to have occurred from the consumption of a single liter of milk by a pregnant woman in Vienna on April 30.

It is therefore apparent that the internal dose from the diet and drinking water to the critical thyroid gland of the rapidly growing fetus completely dwarfs the external does from radioactivity deposited on the ground as measured with a Geiger counter or other detector sensitive only to the penetrating high energy gamma radiation. In Vienna, this was only of the order of 30 microrads per hour, or 0.72 mr per day, some 4 times the natural background of 0.19 mr per day, and 27,000 times less than the fetal thyroid dose from the consumption of a single liter of milk. Since the activity in the milk decreases only slowly from day to day following the peak that typically occurs a few days after arrival of the fallout, the cumulative amount ingested in the following months when the milk is not withdrawn or the cows are not placed on stored feed is about 12 times the peak intake [8], or 600,000 pCi in Vienna, if 50,000 was indeed the peak concentration. Thus, the total dose to the thyroid of a fetus in Vienna following the accident could have been as large as 240,000 mr if the mother had continued to consume the local milk, a dose comparable to those received by the children in the Marshall Islands who were accidentally exposed to the fallout of a large hydrogen bomb test on March 1, 1954 carried out at Bikini.[9]

The dominant role of dietary intake in the health effect of fallout is therefore clearly brought out by this data, especially when heavy rainfalls occur at the same time when a cloud of fallout moves overhead, something that was first recognized in the case of the rainout in Albany-Troy, New York from a 43,000 ton [TNT] weapon detonated at the Nevada test-site in April of 1953. [10-13] Furthermore, the enormous toxicity of internally deposited radioactivity compared to ordinary chemical toxins is brought out by the fact that the studies of Stewart [14] and others since then have shown that only about 100 mr to a fetus during the first trimester of intrauterine development doubles the risk of developing leukemia or cancer. This is a dose equal to that delivered to the fetal thyroid by a mere 250 pCi of I-131 taken in by the mother, corresponding to the disintegration of only 550 atoms of iodine per minute. The reason for this great toxicity is that each electron emitted by a radioactive nucleus of iodine-131 or other beta-particle emitter possesses a few million electron-volts of energy, sufficient to disrupt millions of organic molecules in living cells. As a result, radioactive isotopes that concentrate in specific organs, such as iodine-131 in the thyroid, strontium-90 in the bone and bone-marrow, are millions of times more damaging per unit mass than ordinary chemical toxins such as lead or teratogens such as thalidomide.[15]

At the same time, the fallout cloud reached Italy, where the milk climbed to still higher levels of iodine-131, reaching 87,000 pCi per liter of cow's milk in Santa Teresa by May 2, and 320,000 pCi per liter in sheep's milk, the highest concentration reported anywhere in Europe. If milk at this concentration was in fact consumed by a pregnant woman, the fetal thyroid dose from a single liter would have been 128,000 mr, the equivalent of some 60,000 chest x-rays to the thyroid.

By Monday, May 5, heavy fallout was recorded all across West-Germany. The highest concentrations were observed in eastern Bavaria, closest to Austria, where 2,700,000 pCi iodine-131 were measured per square meter on the ground, together with 300,000 pCi/m^2 of cesium-137, which has a much longer persistence in the environment than iodine-131, half of the deposited amount remaining 30 years later, compared with a half-life of only 8 days for iodine-131.[16] Milk for cows kept on pasture showed 140,000 pCi/1 near Regensburg, and even for cows fed on stored forage, the milk contained 500 pCi/1 [16], probably as a result of the ingestion of contaminated water and inhalation of the activity in the air. The meat in samples of beef collected in southern Germany published by the government of Baden-Wurtenberg showed concentrations of iodine-131 of 2,970 pCi per kilogram and 14,310 pCi per kilogram of long-lived cesium-137.[2] Thus, meat consumption during periods of heavy fallout is a very important pathway for many radioactive trace elements, particularly cesium isotopes.

The importance of inhalation as a pathway for radioactivity in the body during such an accident is brought out by the large air-concentrations measured even as far away as Munich on the 6th day after the accident. As reported by the EPA, the air in Munich, some 800 miles from Chernobyl, contained 932 pCi per cubic meter that day. Since the typical adult inhales some 10-30 cubic meters in the course of a day depending on his physical activity, a total of 9,320 to 27,960 pCi would be inhaled. For the case of iodine-131 that dominated at the time, this means as large a does as 11,184 mr to the thyroid of a fetus if inhaled by a pregnant woman in a single day. This also shows how important a timely warning of such an accident is, since staying indoors, closing the windows, breathing through a wet cloth, and lying down to reduce the air-intake can greatly reduce the amount of radioactivity inhaled. But it also brings out the fact that even if the cows are fed stored hay, and people are warned not to drink the milk, the radioactivity in the air alone can be a serious threat to human health, especially for the developing fetus and young child.

Based on available measurements of cesium-137 on the ground in southern Germany, namely 270,000 to 810,000 pCi per square meter, the Institute for Energy and Environmental Research in Heidelberg concluded that the accident resulted in a total deposition of this isotope in that part of Germany some 2 to 6 times larger than from all the 30 last years of nuclear weapons testing.[2] They also estimate that the future cumulative dose to the average adult in Germany due to the long-lived cesium-137 and strontium-90 over the next 50 years will be about 680 mr to the bone, 330 mr to the liver, and about 200 mr to the whole body.

The fact that distance by itself does not necessarily offer protection in the case of a serious nucleau accident or release from the detonation of a nuclear weapon is brought out by the fact that the air concentrations reported were even larger in some areas of northern Germany and Belgium than either in Vienna or Munich closer to Chernobyl. Thus, the EPA Radiation Date Summary gives 2,422 pCi per cubic meter total air beta activity for the island of Norderney in the North-Sea, and 1,620 pCi per cubic meter measured in Brussels on May 2. The highest air concentration was reported in Oskarsham, Sweden, on the Baltic coast 150 miles south of Stockholm, where the reading was 5,130 pCi per cubic meter, leading to an average intake of 102,600 pCi in one day at 20 cubic meters per day.

By the 9th day after the accident, or by Monday, May 5, one branch of the fallout cloud had reached all the way across France to Spain and North Africa.[3] The initial cloud that had moved northwest to Sweden had continued to move across Greenland and reached the North American continent. A third arm of the fallout that had started towards the south had reached southern Arabia, Iran, and Afghanistan, and a fourth arm had moved east across Siberia to Mongolia and China.

That day, the rainwater in Portland, Oregon showed 46 pCi/1 of rainwater, as did the rainwater in Olympia and Richland, Washington. It rose gradually in the Northwest of the U.S., peaking on the twelfth day of May in Spokane, Washington, with a reading of 6,620 pCi/1, and milk concentration of 130 pCi/1 reported by the Oregon Health Department for Pendleton, Oregon. Radioactivity was first recorded on the East Coast of the U.S. in Vermont and upstate New York near Albany on May 7th, reaching 1660 pCi/1 in Montpelier, Vermont for rainwater by Sunday, May 11, two weeks after the accident occurred. Air concentrations reached 0.15 to 1.6 pCi per cubic meter in twelve locations in the U.S., 100 to 1000 times less than the highest levels in Europe, but hundreds of times greater than the normal concentrations of "particulate" radioactivity in the air, a term that refers to iodine-131, cesium-137 and strontium-90 which are found in the form of dust particles, as contrasted with radioactive gases such as krypton-85 and xenon-137 emitted both by nuclear facilities and the detonation of nuclear weapons.

During this time, the highest ground deposition of iodine-131 in the U.S. was recorded in Montpelier, Vermont on the 11th day of May at 12,300 pCi per square meter. This was some 100 times less than the 1,000,000 pCi per square meter in Saluggia, Italy a week earlier, which had led to very large levels of radioactivity in fresh vegetables in Italy so that they had to be withdrawn from the market, the concentration being as large as 132,000 pCi in a kilogram of fresh produce such as spinach or lettuce. Thus, although the levels in the U.S. were about 100 times smaller than in Europe, since the combined intake from inhalation, milk and vegetable consumption in some areas reached 1000 to

2000 pCi, doses to the fetal thyroid reached some 400 to 800 mr in the Northwest and Northeast of the U.S. Since, as will be discussed in more detail below, the health effect at very low dose-rates appear to increase more rapidly with dose than at high-dose rates, the effects on the developing fetus may only have been some ten times less than in Europe. The iodine levels observed in the U .S. from the accident at Chernobyl were close to those measured following the rainout of a Chinese nuclear detonation in the range of 20,000 to 200,000 TNT equivalent on September 26, 1976.[8] No advice to avoid the consumption of fresh milk or vegetables were given to pregnant women by government agencies in the U.S., since the observed levels were far below those regarded as dangerous to human health by the Federal Government.

THE QUESTION OF SAFE LEVELS OF RADIOACTIVITY

There was in fact considerable disagreement as to proper criterion for withdrawing contaminated food or milk from the market, since this is clearly a political decision in the absence of any absolutely "safe" threshold for either the effects of radiation on the reproductive cells or in direct "somatic" effects on the human body, such as the induction of cancer, birth defects, spontaneous abortions, infant mortality, and lowered resistance to infectious diseases. In some parts of Germany, the local state health authorities ordered the removal of milk from the market when the concentrations exceeded 500 pCi/1, while in other areas, including the U.S., no action was deemed necessary until the concentrations reached 15,000 pCi/1. The higher limit was adopted in the U.S. as recently as 1982. In 1964-65, an even higher Protective Action Guide level of 70,000 pCi per liter of milk had been adopted [17] without any public hearings, despite the growing scientific evidence that radiation was much more harmful to the developing infant than when the FRC gruidelines were established a few years earlier. As a result, government agencies in the U.S. were able to announce that the observed levels were less than 1% of that permissible, and they they presented no danger to human health, and most European countries lifted restrictions on milk and vegetable consumption at the end of the first week in June, long before milk levels had declined to 100 or even 500 pCi per liter of iodine-131.

Back in 1959, when the U.S. government set up the Federal Radiation Council to resolve the disputes that had arisen during the time of bomb testing over the safe levels of radioactivity between the Public Health Service, the Pentagon and various concerned citizens groups, the level for iodine-131 at which action was to be initiated to reduce the intake by the public was set arbitrarily at a magnitude that would result in a dose of 1,500 mr to the thyroid in the course of a year for the case of a one-year old infant, taken to the most sensitive member of the population. This was simply one-tenth of the thyroid dose deemed acceptable for occupationally exposed adults as adopted by the Atomic Energy Commission on the recommendation of the International Commission on Radiation Protection [ICRP], a group of government and nuclear industry scientists who had been concerned with the problem of the health effects of radiation. Their recommendations were based mainly on what was known about the effect of radium on the workers who painted liminescent dials and often tipped their brushes with their lips, together with observations of individuals exposed to massive doses of radiation in the course of radiation therapy and the initial studies of the survivors of Hiroshima and Nagasaki. Using this information, they calculated "permissible" limits for the amounts of the various fission products that could be permitted to accumulate in various organs of a healthy male adult such that the risk of dying of from accidents in the workplace in other industries. The purely arbitrary factor of one-tenth of this as acceptable for exposures to the general population was originally suggested by the ICRP and generally adopted by most countries to calculate the allowable concentrations of radioactive substances in the air, the milk and the drinking water for the general public as a result of weapons tests or the operation of nuclear power plants and other facilities.

But, unfortunately at that time, there was almost no information on the action of very low levels of radiation from distant fallout on human health such as occurred in the course of nuclear weapons testing during the 1950's, particularly on the fetus. Based on the high does exposures to the direct radiation from the bomb or in therapeutic medical exposures of adults which involved hundreds to thousands of rads, or 100,000 to 1,000,000 millirads, there should have been no detectable effects at all. Many scientists believed that there was a safe "threshold" level, possibly as large as 50,000 mr, below which no deleterious effects would occur, especially since immediate death appeared to show such a threshold at about 100,000 mr to the whole body, with half of the exposed individuals dying at a dose of some 300-500,000 mr.[13]

Others cited the evidence from animal studies that it takes doses of the order of 100,000 mr to double the rate of mutations to argue that exposure of the general population to 500 mr would be acceptable for individuals living near the test-site in Nevada or near the fence of a nuclear power plant. They also cited initial data on individuals who survived in Hiroshima and Nagasaki that it takes comparably large doses of the order of 100,000 mr to double the risk of cancer, in agreement with the theory that cancer occurs as a result of a mutation essentially similar to what which leads to inherited defects in the offspring.[18,19]

One of the strongest arguments that doses of the order of 100 mr are not likely to be significant for human health was the fact that normal background radiation that gave everyone doses of this order every year for generations did not seem to have prevented human beings from evolving and living on this planet with only a very small number of individuals being born with gross birth defects, although a few studies had shown indications that natural background radiation could explain some geographical differences in congenital defects and cancer rates.[13,15] An apparently equally strong argument to support this conclusion came from the widespread belief that ordinary diagnostic x-rays that gave doses in the same low range of 5 to 200 mr per film had apparently had no detectable effects since x-rays were discovered in 1895.

Childhood Leukemia and Cancer

The first indication that the risk of small doses of radiation might have been seriously underestimated did not begin to emerge until the large-scale epidemiological studies of Dr. Alice Stewart at Oxford University first published in 1958.[14] Dr. Stewart discovered that children exposed to only a few diagnostic X-rays during intrauterine development had almost twice the risk of developing leukemia and other cancers before age 10 than children not exposed. Since typical pelvic X-rays gave the fetus doses of the order of 300 to 500 mr, this meant that doses as small as 1,000 to 1,500 mr could double the normal rate of childhood cancers when given in the last months of pregnancy. This was some 50 to 100 times smaller than for the doubling of genetic effects and cancer in adults and mature animals on which all the existing permissible radiation doses to the general population had been based.

However, this was not to be the end of the reasons for the growing concern. By 1970, Stewart had completed a study of some 16 million children born in England and Wales, and she was able to find enough cases to allow her to study the relative sensitivity of the fetus at different stages of development.[20] She discovered that for those fetuses irradiated in the first three months of pregnancy, the risk was some 10 times greater than for the majority who were irradiated just before birth. Translated into the dose needed to double the normal risk, this turned out to be only about 100 mr, or some 1,000 times smaller than the doubling dose for genetic damage and cancer in adults.

The implications of Stewart's findings, which have since been widely substantiated, both for the effects of fallout and the operation of nuclear reactors were clearly devastating, since for the exising permissible dose of 500 mr to the whole body of a pregnant woman living near the test site in Nevada or the fence of a nuclear power plant, there could be as much as a five-fold increase in the normal risk that her child would develop leukemia or cancer before age ten. Some critics associated with the Atomic Energy commission and the nuclear industry suggested that perhaps protracted exposures from fallout would be less damaging than short x-ray exposures, since repair processes might lessen the risk of developing leukemia or cancer during a longer period of exposure. But a series of studies that examined large populations exposed to fallout from nuclear tests and nuclear facilities since then have not supported this hope.

The first such study showed that fallout that had rained out heavily over Albany-Troy, New York in April of 1953 from a 43,000 ton TNT equivalent bomb test named "Simon", some 2,300 miles away from the point of detonation. The localized deposition, similar to that observed in Europe after Chernobyl, led to an estimated 100 mr external gamma exposure and a thyroid dose of the order of 20,000 mr to infants consuming milk was followed by a four-fold increase in the childhood leukemia rate beginning some 4 to 5 years later.[11,13] A second study of childhood leukemia and cancer in Japan following the arrival of fallout from the Hiroshima and Nagasaka bomb detonations and the subsequent fallout from U.S. and U.S.S.R. tests [21] based on the extensive data gathered by Segi *et al* at Tohoku University in Japan [22] showed a six-fold rise in a series of steps. Again, each rise followed a known test-series by about 5 years, the same delay between radiation exposure and peak of leukemia incidence as observed for the Hiroshima and Nagasaki survivors as well as for infants exposed to diagnostic x-rays *in utero*, declining again some 5 years after the last U.S.-U.S.S.R. atmospheric test series. [See Figure 1]

Two detailed epidemiological studies of leukemia incidence near the Nevada test site in the "downwind" area of Utah also showed significant rises following the onset of testing in Nevada in 1951 [23,24], with a greater rise occurring in the area closest to the site of the tests. It therefore appears that the effect of fallout on the developing fetus and young infant shows no reduction in risk for protracted environmental exposure as compared with a short x-ray exposure, suggesting that the normal defenses against cancer cells and repair mechanisms for radiation damage are not yet fully developed in the fetus and the newborn infant.

Fetal and Infant Mortality

As serious as these findings are, shortly after their discovery evidence began to emerge that leukemia only represents the tip of the iceberg with regard to the effects of low-level fallout on the infant in the mother's womb. Not only did childhood leukemia rates go up in the Albany-Troy area where heavy fallout had come down following the "Simon" bomb-test in April of 1953, but the rate of fetal deaths or spontaneous abortions also showed an abnormally high value.[11-13] Instead of declining steadily as it had for the previous decade, it suddenly stopped decreasing. For New York State as a whole, it reached a minimum around 1955 and then rose again, especially sharply after the rainout of the last large series of atmospheric tests in 1963, after which it declined once more.

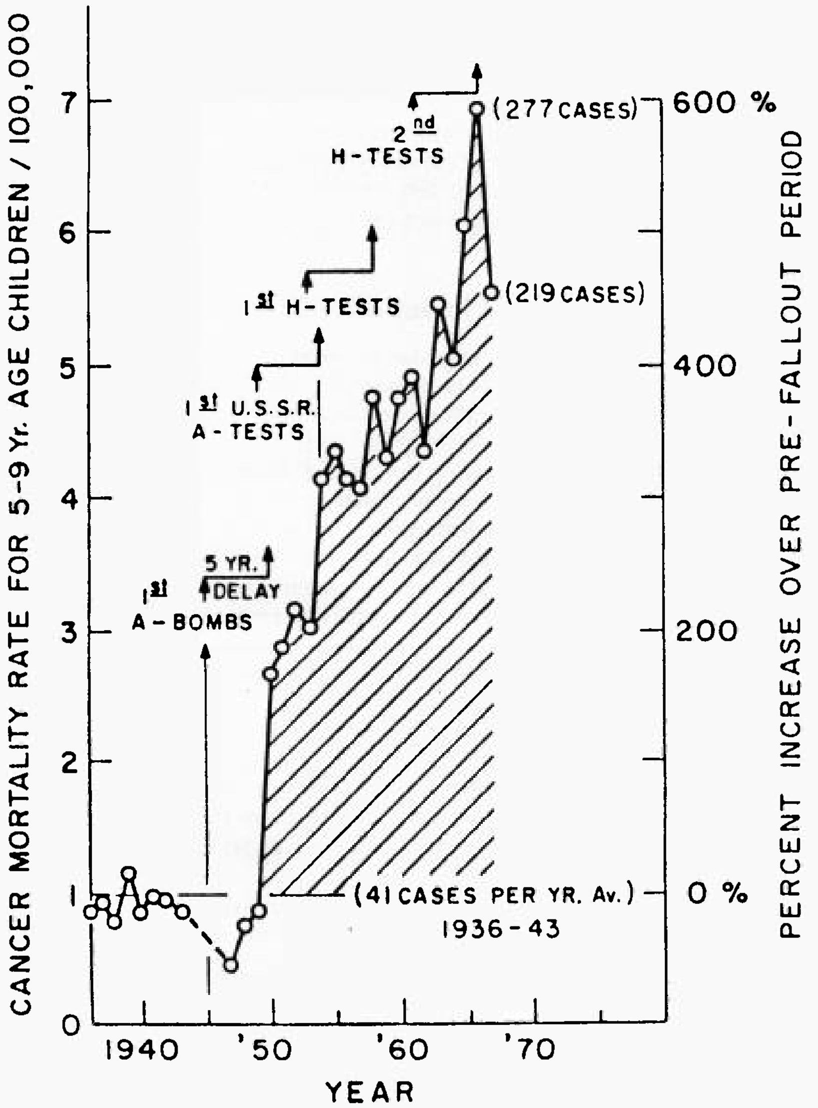
Not only fetal deaths, but also infant mortality showed this pattern, not just for New York but for the U.S. as a whole. And a more detailed examination of state-by-state changes revealed that for 6 states for which milk measurements of radioactivity were available back to 1957, the rise above the normally expected rate was highly correlated with the amount of fallout as indicated by the amount of strontium-90 averaged over the previous 4 years, which is a measure of the amount of strontium-90 in the bone of the mother due to the build-up and excretion of strontium-90.[11]

Since infant mortality due to all causes was in the neighborhood of 25 per thousands births at the time, compared with only about 1 leukemia death per thousand infants born during the first ten years of life, this represented a much greater health effect than anyone had expected. There had been much concern about the failure of infant mortality to decline as rapidly as it had in the past and as it continued to do in many other countries, but no explanation had been found for this disturbing trend. It was suggested by some that perhaps the

Figure 1.

Cancer Mortality Rate For 5-9 Yr. Old Males In All Of Japan

(From M. Segi *et al.*, Japan Cancer Society)



decline of infant mortality had simply gone down as low as it was possible to go in the U.S., but as shown in Figure 2, this turned out not to be the case. Instead, after fallout levels in the milk and diet had started to decline again in the late 60's, infant mortality in the U.S. did, in fact, resume its previous decline, reaching less than half the value observed during the period of heavy atmospheric fallout. A similar, though less pronounced effect was observed in Europe, where fallout levels were lower than in the U.S.[25], further strengthening the hypothesis that it was low-dose radiation that was responsible for these otherwise unexplained changes in infant mortality.

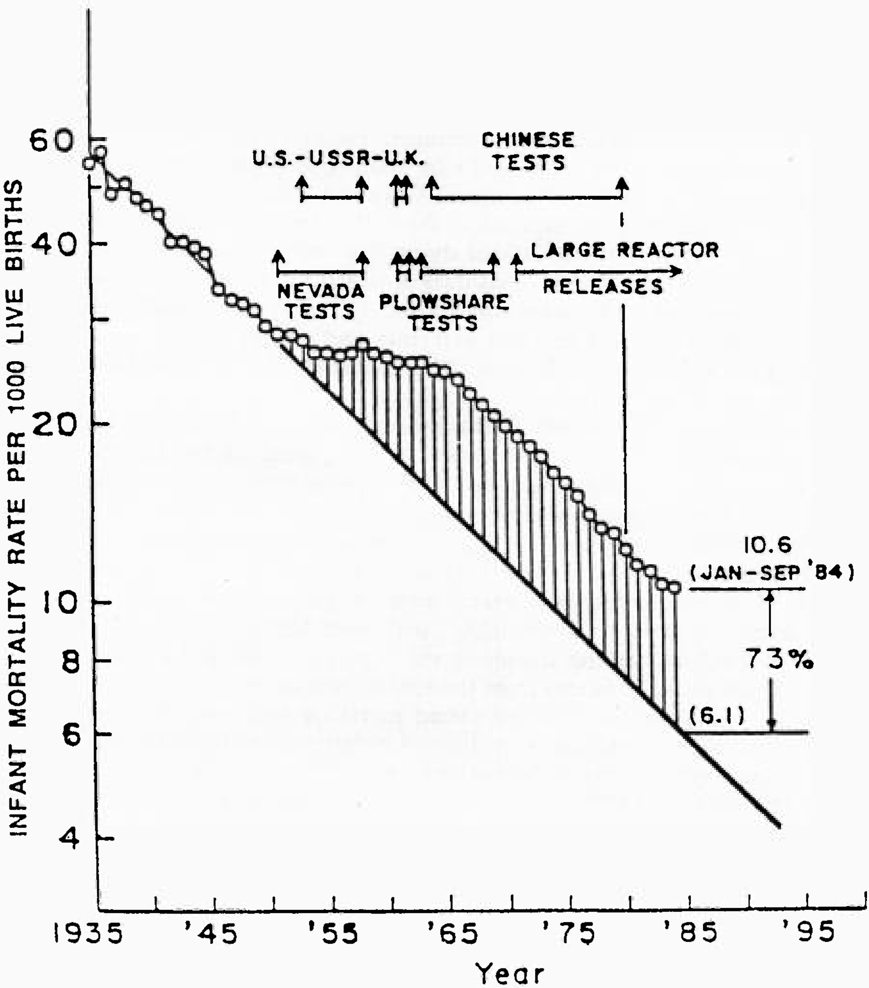
Still further support for this hypothesis was published by Diamond and his associates at Johns Hopkins University in 1973 [26], where a large-scale prospective epidemiological study of mothers who had received abdominal X-rays in the course of necessary diagnostic examinations during pregnancy had been undertaken. Not only did the study confirm Stewart's finding of an increased risk of leukemia and other cancers at the low doses associated with diagnostic X-rays, but especially in the case of white children, there was an even greater increase in deaths due to respiratory problems and infections. Altogether, for all causes of death combined, the mortality rate in the first ten years of life was 18.3 per 1,000 births for the exposed group and only 9.8 for those who had not received diagnostic X-ray radiation *in utero*. Furthermore, those who happened to be exposed in the earlier part of pregnancy showed a much greater increase in the risk of dying that those who were X-rayed just before birth. Thus, there now exists data obtained under conditions where the exact radiation dose to the fetus was accurately known, and which shows that total mortality rates and not just leukemia and cancer can be significantly increased by radiation doses typically associated with normal background radiation and distant fallout.

More recently, Pisello and Piccioni carried out a study-of early fetal mortality (gestational age under 20 weeks) in three areas of the U.S. for which complete data was available both on the number of fetal deaths and live births reported, as well as levels of radioactivity in the milk during the period 1958 to 1969, namely New York City; Hinds County, Mississippi; and Chittenden County, Vermont. Using a linear regression analysis, they found a high correlation between the changing yearly levels of strontium-90 in the milk, and the changes in early fetal mortality, with correlation coefficients between 0.773 and 0.903, explaining the ten to thirty percent rises and declines coinciding with the peaks of fallout from the 1961-63 test series.

Similar rises and declines of infant mortality following changes in the reported releases of radioactivity from a number of nuclear reactors in the United States were found by Sternglass [13,25], including after the accident at Three Mile Island [13,27], where only some 14 curies of radioactivity were estimated to have been released, but the radioactivity stayed at ground-level instead of being carried high into the atmosphere by an explosion.

Figure 2.

U.S. Infant Mortality Rate Per 1000 Live Births (0-1yr)



In the case of the Dresden Nuclear Power Station near Chicago, Illinois, a study of birthweight revealed that a peak of underweight births occurred in the nearby counties that did not take place in the control counties upwind to the west.[25] This finding explains an otherwise puzzling rise in births below 2,500 gram weight in the U.S. during the 1950's that leveled off in the mid-60's. This disturbing phenomenon is of continuing great concern to public health officials since it is believed to be the single greatest cause of the excessively high infant mortality in the U.S. today [28], compared to such other western countries as Denmark, Iceland, and Norway [29], which have no commercial nuclear reactors. Since nuclear reactors are normally allowed to discharge iodine-131 in quantities up to tens of curies per year [30] that are calculated not to result in thyroid doses to infants in excess of the upper limit of 1,500 mr set by existing ICRP and FRC standards for permissible doses from nuclear testing or other releases, it appears that functional damage to thyroid hormone production essential to the normal growth and development of the fetus may be one of the causes of the persisting low birth weight in the U.S. This would also explain the recent rise in congenital defects at birth gathered by the U.S. Center for Disease Control (CDC) in recent years [31], since prematurity and underweight births are known to be associated with an increased frequency of congenital anomalies, especially of the heart. This situation arose because only cancer mortality of adults and not effects on the fetal thyroid or infant mortality was considered in the setting of the existing radiation standards in the late 1950's, before the findings of Stewart [20], Diamond [26], Beierwaltes [7] and others on the great sensitivity of the fetus and the high concentration in the fetal thyroid were known.

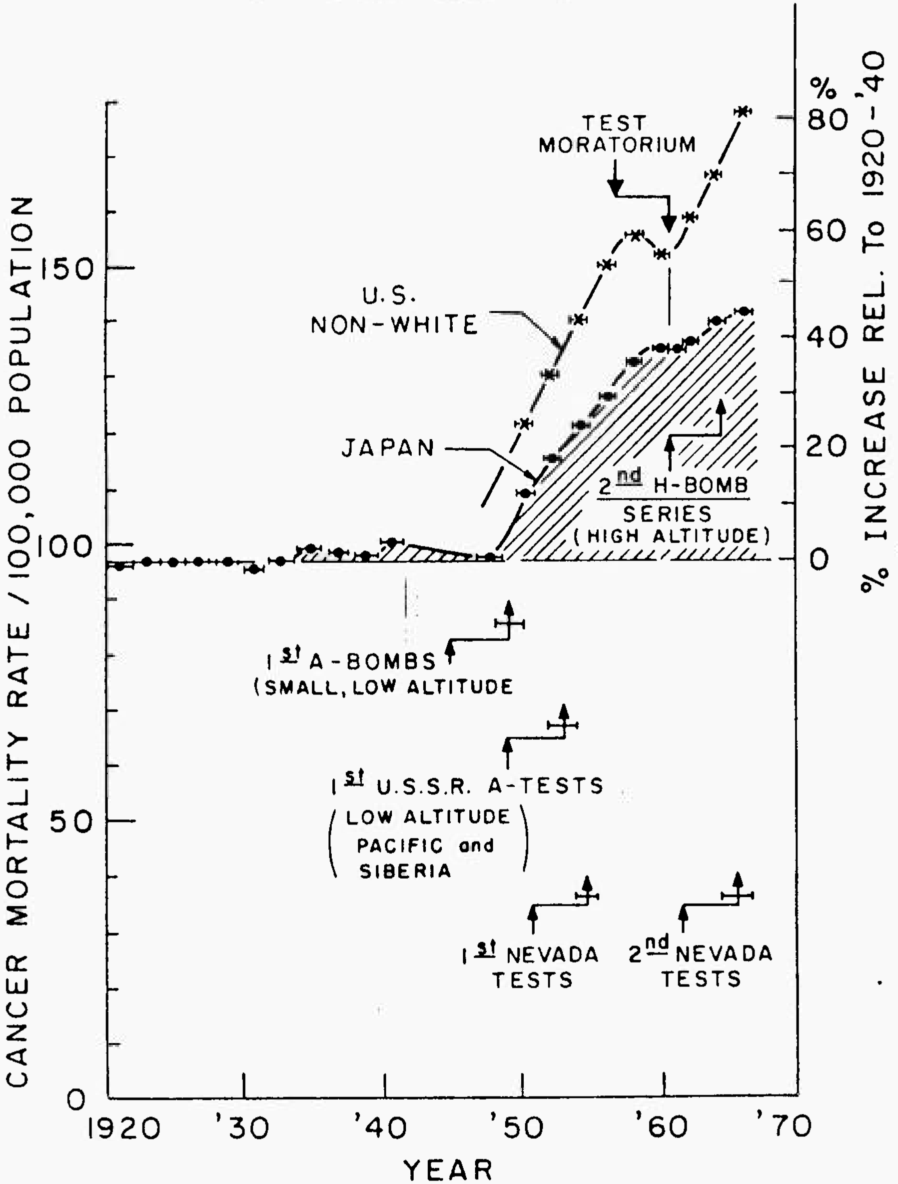
Total Mortality and Cancer at All Ages

Not only childhood cancers and infant mortality due to all causes, but also total mortality at all ages including cancer and deaths from other chronic and infectious diseases was found to have been increased by fallout at about the same time by a number of investigators. Thus, a multivariate study of infant and total mortality by Lave and his associates at Carnegie-Mellon University using data on radioactivity in the milk available for all the fifty states in the U.S. since 1960 showed a positive association with fallout during the period 1961-67 that was strongest for strontium-90 and cesium-137.[32] The study corrected for the effects of air pollution, socio-economic differences, background radiation and many other variables, and concluded that independent of the method of analysis used, fallout was more strongly correlated with mortality than air pollution in 61 metropolitan areas of the U.S.

A study of cancer mortality in Japan and the U.S. for all ages combined [21] based on the worldwide data gathered by Segi [22] and data on cervical cancer collected at Johns Hopkins University showed that sharp rises in cancer rates after World War II in Japan and the U.S. were correlated with the onset of fallout, which stopped some 5 to 7 years after the end of large scale atmospheric testing by the U.S. and the U.S.S.R. For the case of cervical cancer

Figure 3.

Age-Adjusted Cancer Mortality Rate. U.S. and Japanese Males
All Ages, All Sites, Rate Per 100,000
(M. Segi *et al.*, Japan Cancer Society, Nov. 1972)



incidence in Baltimore, the strongest correlation was found with the measured levels of strontium-89, a short-lived isotope of 54 day half-life in the milk, chemically similar to strontium-90, but produced with much greater activity during the fission process.

The sharp rise of total cancer mortality in Japan and for the non-white male population in the U.S. beginning some 5 years after the first nuclear detonations can be seen in Figure 3, based on the data of Segi.[22] It is seen that the cancer rate adjusted for the changing age of the population in Japan was nearly constant at about 96 to 100 per 100,000 population until 1950, when it suddenly rose sharply to nearly 135 by 1960, leveling off some 4 to 6 years after the test moratorium in 1958 to 61. It then resumed its rise briefly 4 to 6 years after the second large atmospheric test series of 1961-62, leveling off once again 4 to 6 years later at a rate of about 140 when fallout levels were declining slowly and only France and China continued to test in the atmosphere. A parallel pattern occurred for the non-white male population in the U.S. plotted here because it includes individuals of Japanese descent, again showing the strikingly sharp rise and brief halt following the test moratorium. Fallout appears to be the principal factor involved in this sudden 40% rise in 10 years, particularly since during the time of rapid industrialization in Japan between 1920 and 1950, with its enormous increase in chemical pollutants, coal burning and smoking, there was no rise greater than 4% in cancer mortality for this period of 30 years.

Cancer rises in the adult population associated with fallout have more recently also been found by Johnson [24] near the atomic test site in Nevada and Utah, with bone-cancer, known to be produced by strontium-90, found to occur at ten times the normally expected value. Leukemia was found at five times the expected rate, and significant excess rates were also found for lymphomas, thyroid cancers, breast cancers, gastrointestinal tract tumors, melanomas, and brain tumors in all age groups. A sub-group with a history of acute fallout effects had a higher incidence of cancer, as would be expected if radiation exposure is the causal factor. Based largely on this study, Federal Judge Bruce L. Jenkins awarded damages to a group of Utah citizens whose family members had developed cancer following the onset of Nevada testing in 1951, on the grounds that the U.S. government agencies carrying out the bomb-tests had been grossly negligent in failing to warn the local population of simple steps that they could have taken to protect themselves and their children.[33]

The Biological Mechanism of Low-Dose Fall-Out

Although the mounting epidemiological evidence for increases in leukemia, cancer, total mortality, fetal mortality, infant mortality due to fallout and releases from nuclear reactors has become very strong in recent years, the question remains as to what the biological mechanism might be that could account for such unexpectedly large and readily detectable effects. Thus it is necessary to explain how leukemia and other cancers among both children and adults could occur at rates that are one hundred to one thousand times higher than predictions based not only on our knowledge of what happened in Hiroshima and Nagasaki, but also on nearly a century of experience with the medical uses of radiation, together with thousands of animal studies in the laboratory on which all present national and international radiation standards are based.

It appears that the key to this puzzle lies in a little-noticed discovery made by a scientist working at the laboratories of the Canadian Atomic Energy Establishment in Pinawa, Manitoba and first reported in the journal *Health Physics* in March of 1972 [34], almost exactly 30 years after the first fission products were created in an experimental graphite moderated reactor in Chicago that was to be the model for the reactor at Chernobyl.

While studying the action of radiation on cell-membranes, Dr. Abram Petkau noticed that occasionally the lipid membrances would rupture after being exposed to high doses of radiation from an X-ray machine. The doses turned out to be of the order of 3,000 rads or 3 million millirads, clearly very large compared to diagnostic medical or background radiation and in general agreement with what other investigators had found in the past. But then he decided to do an experiment that had never been done before. He took a very small amount of radioactive sodium-22 in the chemical form of ordinary salt or sodium chloride and added it to the water in which the cell-membrane was being kept, and determined the dose at which it ruptured. To his astonishment, the membrane broke at the incredibly small dose of 0.7 rads or 700 mr, some 5,000 times less than when exposed to the brief exposure from a medical X-ray machine.

After a series of experiments, he determined that the crucial difference was the length of time over which the radiation exposure occurred, and not the fact that one exposure was due to an external radiation source and the other due to radioactivity dissolved in the water. He found that the more protracted the radiation exposure was, the less total dose it took to break the membrane. A series of further experiments then identified the cause of this unanticipated effect. It turned out to be an indirect chemical action produced by the dissolved oxygen in the water which apparently captured an electron liberated by the absorbed radiation to form a highly toxic or reactive negative ion of oxygen known as the free-radical molecule O_2^-. This negatively charged oxygen molecule is attracted to the electrically polarized cell-membrane, where it initiates a chain reaction that weakens and ultimately destroys the integrity of the membrane. And since the chance of reaching the cell-membrane is greater when there are few other free-radicals present, the efficiency of this process increases as the dose-rate declines. Many detailed studies carried out by Petkau and his co-workers since 1972 showed that this process works all the way down to natural background radiation levels, where in the absence of protective dismutase enzyme, it takes a mere 10 to 20 mr to destroy a cell-membrane.[35] Furthermore, it has been found to work in living systems such as microbes and animals, where the action of dismutase enzymes that apparently evolved at the same time as oxygen-requiring organisms, acts in a protective manner by deactivating the O_2^-; or else oxygen-breathing mammals could never have come into existence.

Thus, even without a direct hit on the DNA in the nucleus of a cell, or even without any fast charged particles striking the cell at all, it is possible for the indirect action of radiation to destroy or impair normal cell functions, such as the production of critical hormones or the development of the various types of white cells essential for the immune defenses of the body. As a result, very low protracted doses such as those that occur in the case of distant fallout or small releases from nuclear plants can be hundreds or thousands of times more damaging than the same small dose from a short, high dose-rate X-ray.[15]

This explains the absence of serious effects of short diagnostic X-rays such as chest and dental X-rays, generally given in a fraction of a second, or at a rate that is a hundred million times greater than the rate at which the body is exposed to background or fallout radiation over the course of weeks, months, and years. And since the radiation received by the survivors of Hiroshima and Nagasaki from the explosion of the atomic bombs was produced by an intense flash lasting only a matter of seconds, it explains why it took a relatively large dose to double the normal rate of leukemia and cancer.

In the case of high-dose rates, the indirect, free-radical mechanism becomes very inefficient due to the extremely large number of O_2^- molecules created per unit volume deactivating each other. At these high intensities, the direct action of radiation on the DNA in the cell dominates, producing mutations that lead to normal cells going out of control and thus becoming malignant. On the other hand, at very low dose rates, it is the indirect, free radical damage to cell-membranes that dominates, which causes the immune system to be weakened and thus allowing the ever-present cancer cells normally produced by background radiation and other carinogens in the environment to multiply until they damage normal body functions and ultimately leading to a premature death.

Mathematically and in actual laboratory studies, the indirect effect of radiation, being more efficient at low doses given in a certain time interval leads to a dose-response curve that rises more rapidly at small doses, and then levels off at high doses.[15] Such a logarithmic or "superlinear" response, similar to that for most chemical carcinogens that also often act through the production of free-radicals, has two important practical consequences. On the one hand, it leads to a much higher effect at low doses than expected from the "conservative" linear extrapolation from high to low doses, as was used in the establishment of the existing limits on body-burdens for small amounts of radioactivity. On the other hand, the effect at very high doses is not as great as would be expected by a linear extrapolation from very small to very high doses.

Thus, even though the accident at Chernobyl appears to have led to a deposition of long-lived radioactive cesium-137 in Europe of the order of two to six times that from all the years of past bomb tests, it will not lead to a correspondingly greater increase in cancer rates. The precise shape of the dose-

Figure 4.

U.S. Pneumonia and Influenza Mortality (0-1 yr)

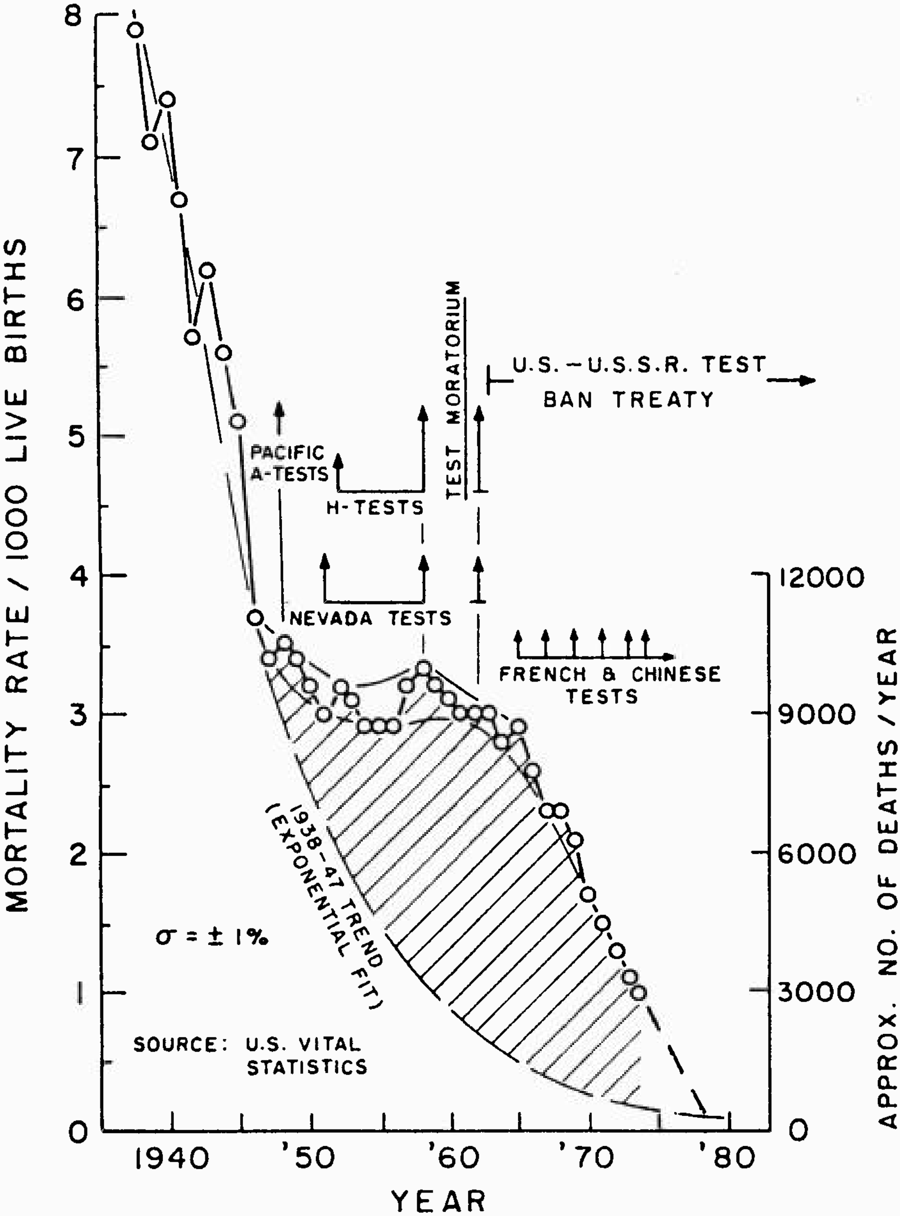
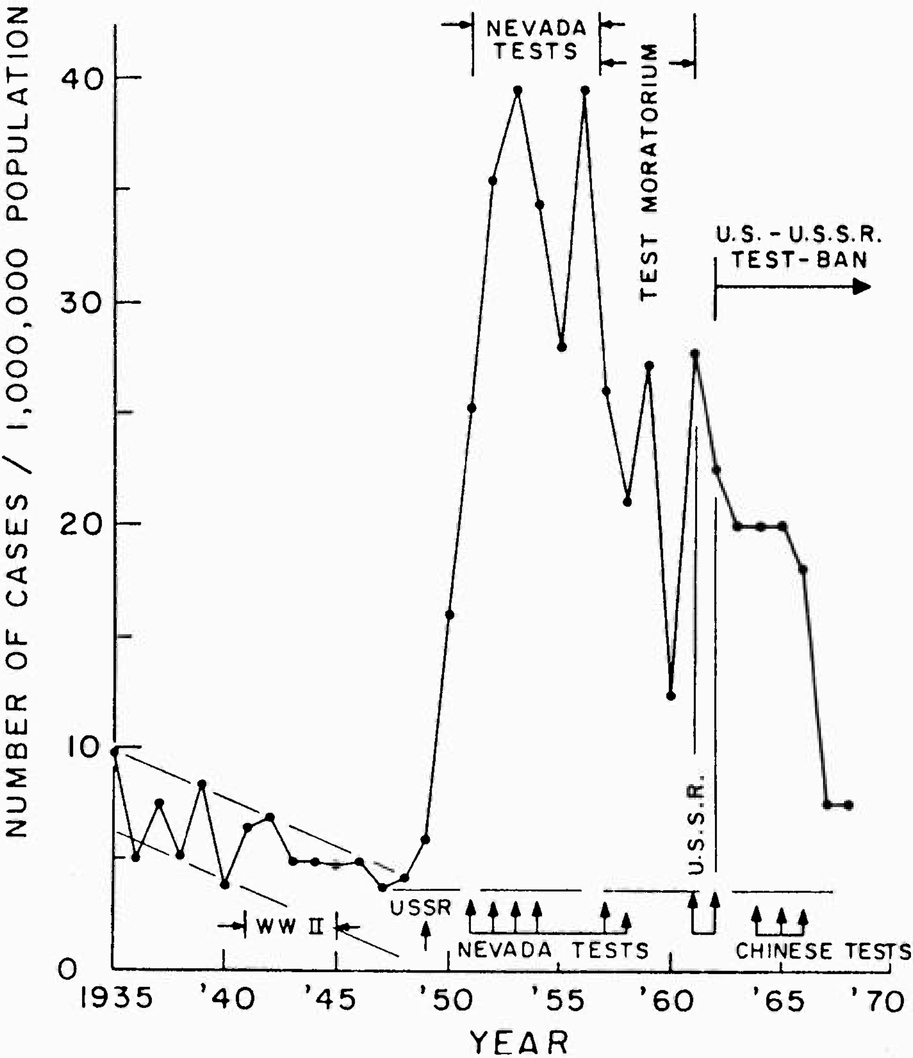


Figure 5.

Number of Cases Reported Epidemic Encephalitis/1,000,000 Pop. (New York City)



response curve for this range of doses is not known, but it appears to be more of a dependence on the square root of the dose, or even a lesser fractional power function such as the cube-root of the dose, depending on the absolute level from which it starts. Cancer rates for population groups that had very low cancer rates before the accident will tend to rise more than those for which the rate was already relatively high, and the same effect should occur for infant mortality rates. And in both cases, they will be primarily influenced by the diet, with much lower increases for individuals consuming large amounts of ocean-fish as compared to those consuming meat and vegetables more heavily contaminated with long-lived cesium and strontium-90.

Immune System Damage

The hypothesis that it is indirect damage to the immune system that is one of the principal reasons for the unexpectedly large increases in leukemia, cancer, fetal and infant mortality is strongly supported by the pattern of infant mortality changes for the most important infectious diseases such as pneumonia and influenza in the U.S. shown in Figure 4. It is seen that after a decade between 1935 and 1945 before fallout entered the environment, the mortality rate steadily declined as the result of improved socio-economic conditions and medical care. Then, shortly after 1945, mortality rates refused to go down further, until in 1957 , the year of the largest Nevada tests, it actually reversed and started to climb sharply. It halted its rise and began to decline once more during the period of the test-moratorium of 1959-61, after which it briefly halted once more as another large series of atmospheric tests took place in 1961 and 62. Only after the large fallout from these tests showed a gradual reduction in the latter part of the 1960's, when only the Chinese and French continued atmospheric tests, did the mortality rate start to decline once more so that by the mid-seventies it had decreased to less than a thid of its 1957-58 peak.

The effect on the immune system is further supported by the pattern of changes in the incidence of infectious diseases, as shown for the example of epidemic encephalitis in New York City shown in Figure 5. It is seen that after declining steadily between 1935 and 1945, there was a sudden ten-fold rise that coincided with the first atomic tests by the Soviet Union and the onset of tests by the U.S. in Nevada. The incidence sharply declined during the test moratorium in 19958-61, rising again with the large series of nuclear tests that occurred in 1961-62. Finally, with the gradual decrease in fallout after the test-ban, the incidence declined once more to the level they existed before bomb-testing began.

Since within the last few years the crucial role of a weakened immune system in leading to a greater susceptibility to cancers such as lymphomas and Kaposi sarcomas has become dramatically apparent in the case of AIDS victims, it becomes clear that it was a mistake to assume that cancer mortality is solely determined by the chance that a cell in a given organ receiving the radiation exposures is transformed to a malignant state, as assumed in the existing basis for all radiation standards.[18,19] Clearly, any agent that specifically weakens the natural immune defenses such as occurs in the case of strontium-89 and 90 concentrating the bone-marrow can lead to an increased risk not only of myeloid leukemia but of all types of cancers in various organs. Conversely, anything that strengthens the natural immune defenses can lead to the regression of various types of tumors, as has indeed recently led to the most successful treatment of many types of solid tumors at the National Cancer Institute.

Recent laboratory studies have, in fact, demonstrated that bone-seeking isotopes such as strontium-89 and 90, when injected into mice, specifically deactivate a crucial type of white cell that matures in the bone marrow vital to the immune defenses of the body, the so-called Natural Killer (NK) cell.[37] Taken together with the earlier laboratory study showing that very small doses of strontium-90 in the 10 to 100 mr range can produce significant decreases in the bone-marrow cellularity in rodents [38], it appears that perhaps one of the most serious unanticipated effects of fallout is long-term, persistent immune deficiency, acquired during intrauterine development. This condition may remain undetected until expressed many years later when the body is challenged by infectious diseases, such as those that are sexually transmitted and rampant in poor areas of the world, such as central Africa and the Carribean. When in addition the radiation from such isotopes as strontium-89 and 90 in the bone-marrow mutates an existing virus that invades the T-cells of the immune system and kills them in the process of replication [39], the stage is set for a complete collapse of the immune defenses, and resulting death from opportunistic infections or cancer.

As discussed in detail elsewhere [40], the possibility that massive fallout of bone-seeking isotopes was a cofactor in the origin of the AIDS epidemic is strongly supported by the observation that the highest concentrations of strontium-90 in bone as reported by the United Nations Scientific Committee on the Effects of Atomic Radiation [41] among 22 countries studied in 1957 occurred in tropical Central Africa where the AIDS epidemic is believed to have started.

Social Implications

The implications of the discovery of the indirect free-radical mechanism of radiation damage at low doses and dose rates previously thought to be innocuous are clearly extremely far reaching, not only for the likely consequences of the accident at Chernobyl on the people of Russia and Western Europe, but for the entire world.

The danger of fallout can clearly no longer be judged on the basis of our experience with high dose, high dose-rate radiation as encountered in therapeutic medical radiation, animal experiments at high dose-rates, or the effects of the Hiroshima and Nagasaki bombs. At these high does-rates, the indirect mechanism of radiation damage mediated by free-radicals is highly inefficient so that it takes very large doses to damage the cells of the bone marrow, as happened for the firemen and workers at the Chernobyl reactor.

Only at low-dose rates does the crucial role of the indirect action of radiation become apparent. Not only can it weaken the immune defenses of the body at very low total doses, leading to unexpectedly large increases in infectious diseases and cancers, but by subtly damaging the hormonal system of the human body, it can lead to retarded physical and mental development during the crucial period of intrauterine development. This is illustrated in the otherwise unexplained temporal and geographic changes in Scholastic Aptitude Test scores, which declined and rose exactly 17 to 18 years after the onset and ending of large-scale nuclear weapons tests, in direct relation to the measured amounts of iodine-131 in the milk.[42-45]

Such retarded development can have many serious consequences for the health and survival of the newborn. If the lung is not fully matured by the time of birth, the newborn can develop respiratory distress and hyaline membrane disease that greatly increase the risk of neonatal death. Damage to the pituitary glands and gonads of the mother may influence the normal cycle of gestation and birth, leading to immaturity and grossly underweight births. This has been a growing problem in the major metropolitan areas of the U.S. with large nuclear facilities and reactors in their vicinity, especially among the socio-economically deprived, whose diets are often inadequate in crucial calcium. A low calcium diet increases the relative uptake of strontium-89 and 90 released by nuclear reactors in significant quantities, which are at present fixed in accordance with standards based on the relatively low risk of bone cancer mortality of adults from radium ingestion, rather than on the basis of damage to the critical hormone and immune system of the developing fetus.

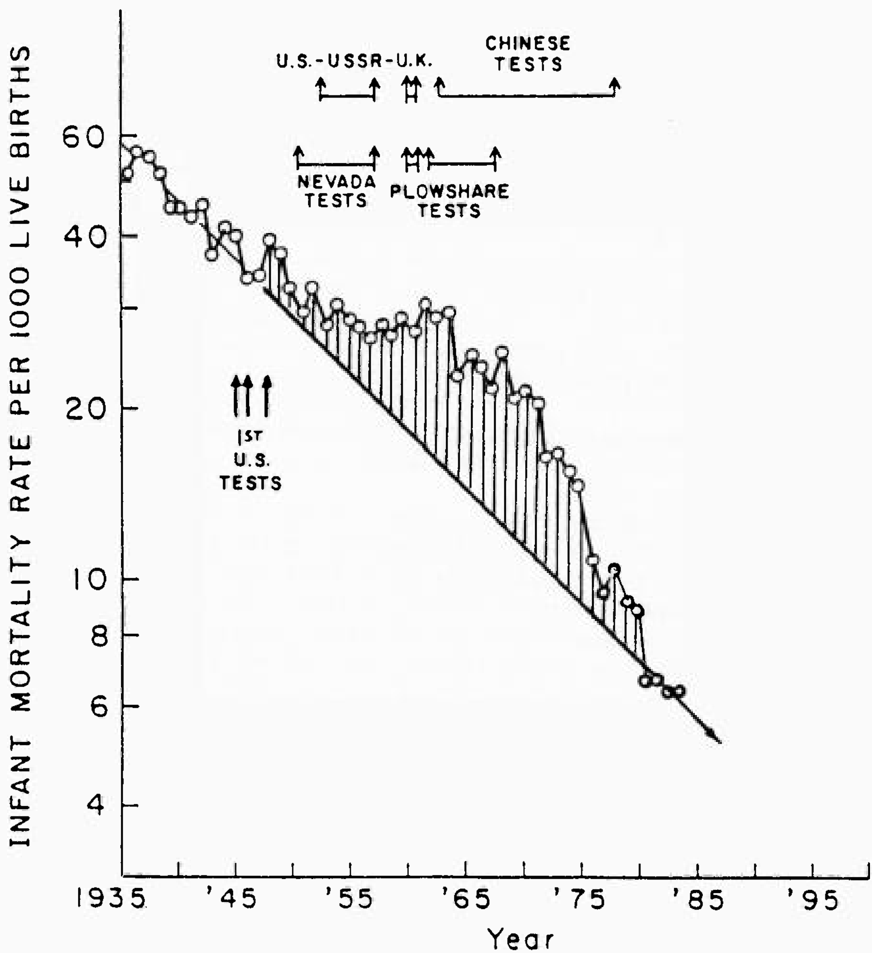
It is well known from studies of women who smoke heavily during pregnancy[46] that underweight infants have a much greater chance of showing brain damage, leading to mental deficit, learning and attention problems, higher rates of drop-out, juvenile delinquency, drug use, crime, homicide, suicide, and a general inability to function adequately in a modern high-technology society.

Radioactive iodine is furthermore known to produce hypothyroidism that is associated with lethargy, and in extreme cases is known to produce various degrees of mental retardation or cretinism. Thus, the greatest danger to the well-being of any society may not be the increase in cancer and other chronic diseases in its older population, but the subtle and gradual deterioration of the physical and mental capabilities of its children when governments insist that nuclear weapons production and the maintenance of a large nuclear industry is the highest priority, necessitating that permissible radiation doses to the workers and the public must be kept high.

That this may already be happening in the United States is suggested by the fact illustrated in Figures 6., and 7., where the decline in infant mortality due to all causes combined has been plotted for two different states. One of these is a state that has no nuclear reactors or other large nuclear facilities in it or near its borders, such as Wyoming. The other is a state downstream from a series of large reactors such as Three Mile Island and Peach Bottom, namely

Figure 6.

Wyoming Infant Mortality Rate Per 1000 Live Births (0-1 yr)



Maryland, which in addition, has the Calvert Cliffs Nuclear Power Station on Chesapeake Bay within its territory.

Inspection of these graphs reveals the same steady decline as for the U.S. as a whole between 1935 and 1950, before large scale atomic testing and construction of nuclear reactors took place. Again, just as for the U.S., there is a sudden halt to the decline during the period of large-scale atmospheric tests, peaking just after the known peak in strontium-90 in the diet in 1964, after which there is an accelerating decline as radiation levels decreased. In the case of Wyoming, infant mortality declined all the way to the projected level expected on the basis of the 1935 to 1950 performance, reaching record lows of close to 6 per thousand live births, as low as reached by European nations having no nuclear power reactors, namely Denmark, Norway and Iceland, starting downward from a peak of 30 at the height of nuclear fallout.

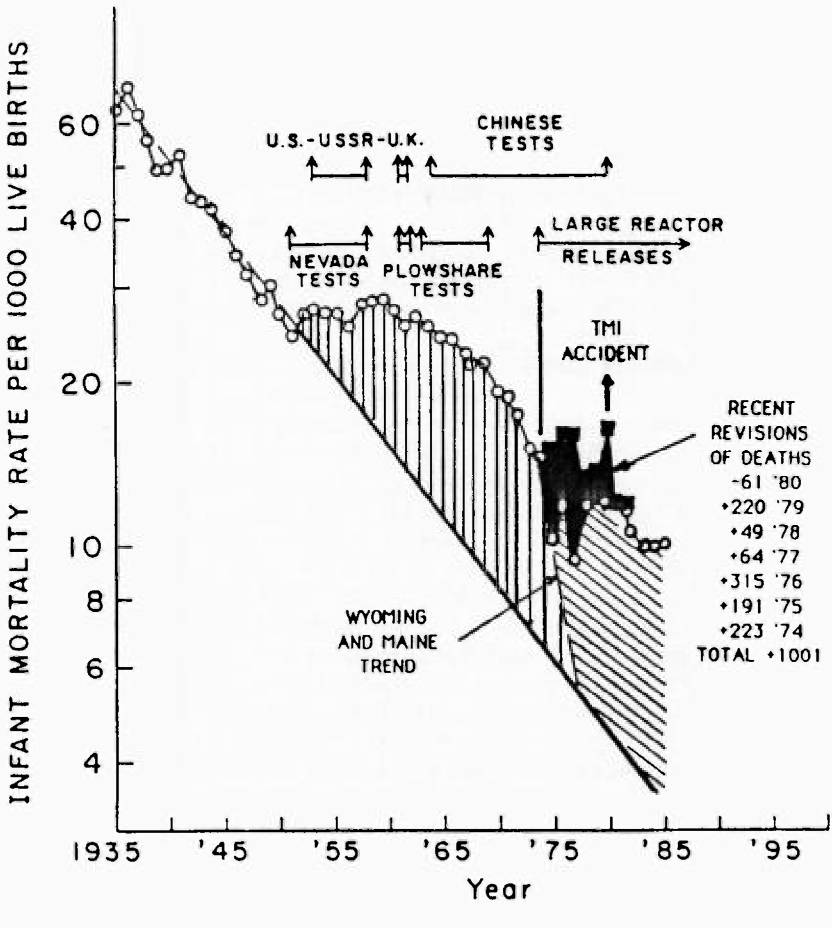
In sharp contrast, whereas Maryland showed the same accelerating decline as Wyoming after the end of large-scale atmospheric testing, the decline suddenly ended in 1974, which is the year that the first of the large nuclear reactors on the Susquehana, namely Three Mile Island Unit 1, went on line near Harrisburg. There follow two peaks in the next few years, the first when the trouble-plagued reactors at Peach Bottom a few miles from the Maryland-Pennsylvania border was placed in operation and started to emit such large quantities of iodine-131 that the NRC threatened to close it down. This was followed by a second peak in 1979-80, when the accident at Three Mile Island Unit 2 and the subsequent venting of radioactive gases from the containment released large quantities of radioactivity into the environment. This peak was followed by a dramatic decline in the following year as both reactors at Three Mile Island were shut down.

However, it is seen that infant mortality remained far above the expected low value that would have been attained at the same time as in Wyoming if the decline that took place between 1964 and 1974 had continued uninterrupted. By 1985, the decline in Maryland is seen to have halted once again as still another large reactor was placed on line on the Susquehana River above Harrisburg. By that time, infant mortality was two and a half times greater than it should have been or close to the rate expected on the basis of the Wyoming decline. This means that in the State of Maryland today, some 6 out of 10 infants that die in the first year of life are probably dying as a result of fallout from nuclear weapons tests and releases from nuclear reactors. And for each infant that dies, there are perhaps ten times as many that are subtly affected by hormonal damage that will impair their normal physical and mental development to various degrees, especially when combined with socio-economic and other environmental factors acting in a synergistic manner.

Indeed, for the United States as a whole, there has been another disturbing slowing down of the normal rate of decline of infant and total mortality in the last few years, similar to that during the period of large atmospheric testing as evident in Figure 7., for the case of infant mortality in Maryland. In view of the evidence that indicates no such slowing down of the normally expected decline

Figure 7.

Maryland Infant Mortality Rate Per 1000 Live Births (0-1 yr)



of infant and total mortality in states like Wyoming that have no large nuclear reactors or other sources of fission products in or near their borders, one is led to the conclusion that the growing releases of fission products into the environment at the existing high permissible levels is the single most important factor involved in the recent failure of both total and infant mortality to decline as it did briefly during the early 1970's, before the large increase it and medical care available to the poor.

Similarly, in the Soviet Union, infant mortality suddenly reversed its long decline and started to climb sharply in the early 1970's when the first nuclear reactors went into operation near the large cities of European Russia.

Conclusion

As for the effect of the Chernobyl accident on the people of Russia and the rest of the world, this will clearly differ enormously depending on the amount of radioactivity received from the spreading arms of fallout. For the case of Germany, the Institute for Energy and Environmental Research arrives at the tentative estimate of 15,000 to 60,000 additional cancer cases that will be produced by the long-term levels of radioactivity on the ground and in the diet over the next 50 years. Since the total population of Europe for the countries in which comparable levels of radioactivity were reported is some ten times greater than that of West Germany, there may be as many as 150,000 to 600,000 cancer cases resulting from the accident.

Since the studies of Lave [32] and others have shown that total mortality, including heart disease, stroke and infectious diseases are also increased by nearly comparable amounts, one arrives at the conclusion that the overall death toll may eventually exceed 1 million. Such a large figure is not inconsistent with early estimates made by Pauling [48] and Sakharov [49] back in 1957-58, who arrived at the conclusion that for every megaton of TNT equivalent release of nuclear detonations anywhere on the globe, there could be anywhere from 1,600 to 60,000 deaths in those living at the time, and a roughly equal number among those that would be born in future generations, or a total of some 3,200 to 120,000 extra deaths from all causes combined. If the estimate made by the Livermore group [3] is correct that as much as 50% of all the volatile fission products escaped from the stricken reactor, then this would correspond roughly to the radioactivity produced did not rise into the stratosphere, where most of the short-lived activity would normally decay before reaching the ground. Thus, the upper limit of Sakharov's and Pauling's estimates is likely to be a lower limit for the total number of deaths, giving a minimum of 600,000 additional deaths due to the accident at Chernobyl.

Only detailed epidemiological studies of changes in mortality rates in Europe and other parts of the world reached by the drifting clouds correlated with local measurements of radiation levels in the diet will be able to give us a more definitive answer. Such studies must be undertaken as soon as possible so that the true danger of a reliance upon nuclear weapons and nuclear power generation can be fully evaluated.

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Biographical Note

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