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Catastrophic Releases of Radioactivity

The gravest conceivable accident to a nuclear reactor is far less destructive than the detonation of a nuclear weapon, even if it is imagined that the weapon causes harm only by radiation

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A large population could be exposed to a dangerous amount of radioactivity in a number of ways. Such an event would be the inevitable consequence of even the most limited nuclear war. It could happen if an accident to a nuclear reactor caused its containing vessel to burst and allowed material from the core of the reactor to escape into the atmosphere. The inadvertent release from a reactor of water or gases bearing radioactive nuclei would create the danger of an exposure of lesser magnitude. Still another possibility is an accident during the manufacture, transportation, reprocessing or storage of radioactive material for nuclear reactors or nuclear weapons.

There are large differences in the amounts of radioactivity that could be released in such events, and so each possibility must be considered separately. We shall therefore describe the radioactivity that would probably be released in each of three events. The first is the detonation of a thermonuclear weapon at ground level. The second is the melting of the core of a nuclear reactor and the bursting of its containment vessel, with a resulting escape of radioactivity. The third is the explosion of a thermonuclear warhead on a nuclear reactor.

We want to emphasize that we shall not include in these comparisons the blast and the heat that constitute the prompt, explosive effect of a thermonuclear weapon. We shall examine and compare only the delayed effects brought on by the release of radioactivity. It emerges nonetheless that the detonation of a nuclear weapon is far more to be feared than any accident to a reactor. Moreover, the detonation of a weapon on a reactor is many times more damaging than the detonation of a weapon on the ground. The nuclear attack turns the reactor into a devastating radiological weapon.

A thermonuclear weapon is usually made up of three parts. The first part is in essence a trigger whose most important component is a few kilograms of plutonium. The fissioning of the plutonium nuclei gives rise to the heat that is needed to set off a thermonuclear explosion.

The second part is the thermonuclear explosive: a mixture of deuterium and tritium, the heavy isotopes of hydrogen. The thermonuclear fusion of a deuterium nucleus (which has one proton and one neutron) with a tritium nucleus (one proton and two neutrons) yields a helium nucleus (two protons and two neutrons). The extra neutron is emitted at high velocity and a quantity of energy is released as heat. The products of this reaction do not have long-lasting radioactivity.

The third part of the weapon is a mantle of uranium that surrounds the layer of deuterium and tritium. The nuclei of uranium atoms fission when they are bombarded by the neutrons emitted in the course of thermonuclear fusion. The fragments of the fissioned nuclei are a source of copious radioactivity. In a three-part thermonuclear weapon about half of the energy released comes from thermonuclear fusion and half from the fissioning of the uranium.

The heat generated by the detonation of a thermonuclear weapon vaporizes the weapon itself almost instantly, and so the nuclear reactions stop. Most of the nuclei created by the fissioning of the uranium are now in an abnormally energetic state. Their return to a state of lower energy is accompanied by the emission of radiation in the high-energy part of the electromagnetic spectrum, the part made up of X rays and gamma rays. This radiation heats the surrounding air, forming a shock wave that heats additional layers of air. The result is a luminous fireball. For a weapon that has an explosive yield of one megaton (the equivalent in energy of a million tons of chemical explosive) the fireball rises at a rate approaching 400 feet per second to an altitude of approximately 60,000 feet. A one-megaton yield is typical of a warhead on an intercontinental ballistic missile in the arsenal of the U.S.S.R.

The updraft generated by the rising fireball lifts large quantities of soil and debris. A one-megaton explosion at ground level can excavate a crater as much as 400 feet deep and 1,200 feet in diameter. As the fireball cools, the radioactive nuclei created by the explosion condense onto particles of dirt, which over a period of time return to the earth as radioactive fallout.

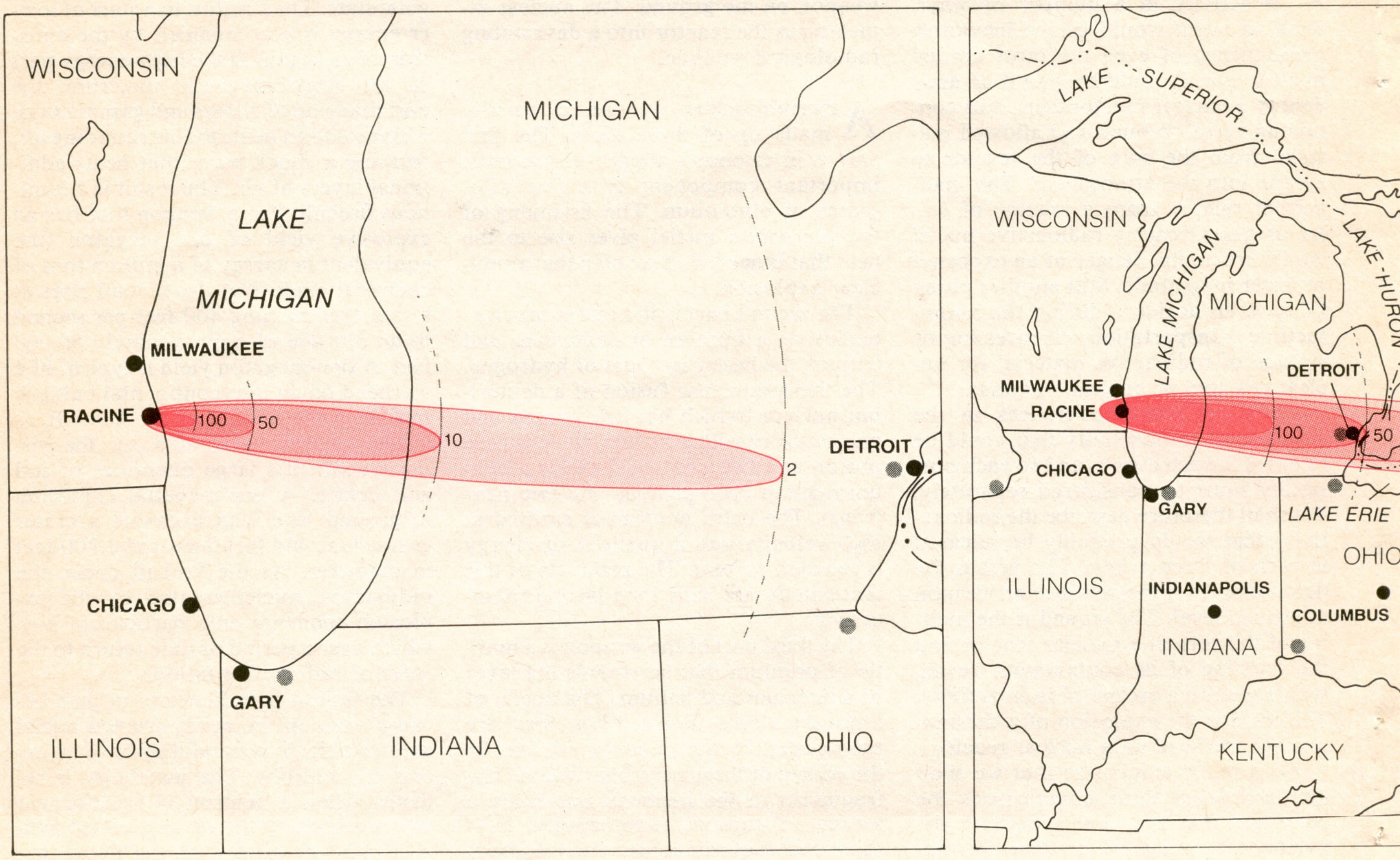
The fallout is radioactive in part because some of the newly created nuclei are unstable: in general they have an excess of neutrons. The instability is relieved when a neutron is transformed into a proton by the process called beta decay; in the course of the decay the nucleus expels an electron, which in this context is called a beta ray. Such transformations can again leave the nucleus in an excited state, from which it returns to a lower energy level by emitting electromagnetic radiation, mainly gamma rays. The fallout particles continue to emit beta and gamma rays for many decades after the explosion. These emissions come at random times. Given a quantity of radioactive nuclei, one can predict only the average number of emissions in any given interval. With the passing of time the number of nuclei in an excited or an unstable state decreases, and so the intensity of the radioactivity diminishes.

Several units of measure are employed to describe an amount of radioactivity or the amount of energy the radioactivity can deposit in living tissue. The standard unit for radioactivity itself is the curie, which is defined as 3.7×10^{10} emissions per second. The definition makes no reference to the kind of radiation or to the energy it carries. The unit for the deposition of energy by radioactivity is the rad, which is defined as the absorption of 100 ergs by a gram of matter such as living tissue. Another unit is the roentgen, which pertains exclusively to gamma rays and X rays. Exposure to one roentgen of gamma rays is equivalent to the absorption of about 94 ergs by a gram of tissue. Hence the rad and the roentgen are almost equal.

Because none of these units describes the amount of biological damage caused by the radiation, still another unit of measure is needed. The unit is the rem, an abbreviation of roentgen equivalent man. A dose of radiation measured in rem takes into account the fact that different kinds of radiation may have quite different effects on a living organism, even if they deposit the same amount of energy and cause damage by the same general mechanism, namely the ionization of atoms in intracellular molecules. The differences in damage reflect such characteristics of the radiation as the distance to which it penetrates in a given tissue. A dose in rem is equal to a dose in rads multiplied by a factor called the relative biological effectiveness (RBE) of the particular form of the radiation. For beta and gamma rays the RBE is approximately 1. In the discussion that follows, therefore, a dose in rads will be considered equal to a dose in rem. A sense of the size of the dosages we shall consider can be gained by comparing them with the following pair of examples: a chest X ray entails a dose of some .01 rem, absorbed in a fraction of a second; the natural background radiation at sea level amounts to about .075 rem per year.

The biological effects of radiation vary considerably from one person to another. They depend, for example, on age and health. For this reason it is not possible to cite precise radiation levels at which one could expect to see particular symptoms of radiation sickness, such as loss of hair, vomiting, diarrhea, internal bleeding or lesions in the mouth and throat. Still, it has been established that if the human body is exposed to more than 500 or 600 rem in an interval not much longer than a day or two, survival is almost impossible. If the dose is between 200 and 450 rem, survival is possible but by no means assured, even if medical care is available. All things considered, it seems reasonable to assume that a dose of 400 rem in a day implies a mortality rate of 50 percent or more. Exposure of a population to 100 rem in the same period would cause sickness and some deaths. At this dosage, however, most people could be expected to recover even without medical attention.

In calculating the land area made uninhabitable by a given release of radioactivity we shall take the maximum ac-



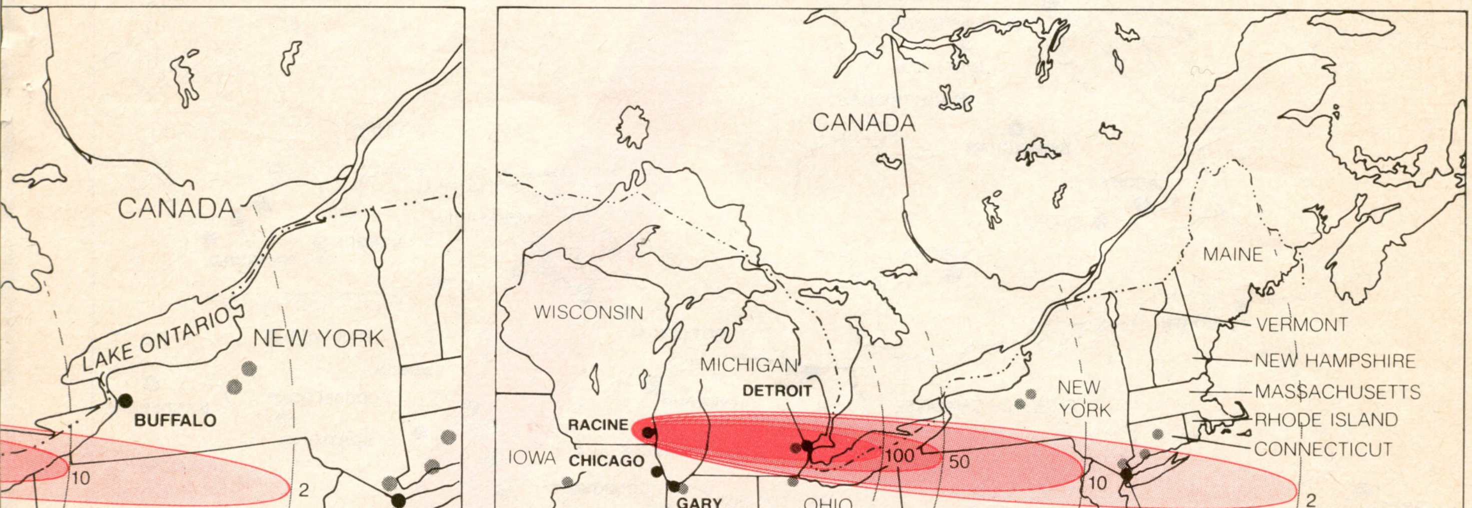
DOSE CONTOURS resulting from three hypothetical releases of radioactivity are compared. The map at the left shows the pattern that develops a week after an accident in which the core of a one-gigawatt nuclear reactor releases a third of its radioactivity. The site of the hypothetical accident is Racine, Wis. The amount of radioactivity released is 100 million times the amount released during the accident at the Three Mile Island Nuclear Generating Station near Harrisburg, Pa., in March, 1979. The map in the middle shows the pattern that develops a week after a one-megaton thermonuclear weapon explodes at ground level in Racine, sparing the reactor but initially releasing a far greater quantity of radioactivity. The map at the right shows the pattern that develops a week after a one-megaton weapon vaporceptable dose to the general public to be 2 rem per year. This dose is more than 10 times the maximum recommended by the U.S. Environmental Protection Agency, and it is more than 20 times the natural background radiation. On the other hand, it is less than the 5 rem per year now considered an upper limit for workers exposed to radiation over a period of years. A standard of 2 rem per year might well be adopted in the aftermath of a peacetime reactor accident. In a nuclear war, however, the public could hardly be excluded from all areas in which the radiation level is 2 rem per year. Indeed, people driven by hunger or other imperatives might be willing (or compelled) to occupy areas in which they would absorb more than 50 rem per year, a dose that causes radiation sickness in more than half of the people exposed. A dose of 50 rem per year also causes occasional fatalities and may cause cancer in some people years after the exposure.

We now turn to the consequences of the release of radioactivity by a one-megaton thermonuclear weapon detonated at ground level. Most of the resulting radioactive fallout returns to the earth downwind from the explosion, and as much as 70 percent of the fallout takes the form of relatively large particles that return to the earth within a day. The intensity of the radioactivity decreases with distance from the site of the explosion. For one thing, the cloud of debris loses dust particles as it drifts with the wind. In addition the total radioactivity diminishes as the radioactive nuclei decay.

If the wind is steady, the pattern of accumulated dose of radioactivity (in rem) is a set of nested cigar-shaped contours. Each contour denotes a particular dose and all points within the contour are points where the dose is greater. We shall assume a wind speed of 15 miles per hour. In that case the lethal zone—the area circumscribed by the contour line denoting an exposure to 400 rem in 24 hours—amounts to roughly 400 square miles. The number of fatalities in the lethal zone would depend largely on the population density. In the U.S., for example, the population density ranges from 100,000 per square mile in metropolitan areas during business hours to fewer than five per square mile. The radiation from the detonation of a single warhead could therefore kill from a few hundred to several million people. The total would depend not only on the site of the explosion but also on the time of day, the weather conditions, the efficacy of any warning issued and the available protection from radiation.

Those who escape death in the lethal zone would be unable to return to the zone for a long time because the ground would be contaminated by radioactive particles. The survivors would have to wait until the effects of radioactive decay and the settling of the contaminants into the ground by way of rain and snow reduced the radioactivity to an acceptable level. At a maximum acceptable dose of 2 rem per year some 1,200 square miles of land would remain unfit for human use for a year. Larger areas would be affected for a shorter time. The disruption of society would be immense. For example, more than 20,000 square miles would be uninhabitable for a month. Plainly this could dislocate many hundreds of thousands of people.

In an attack involving several weapons the cumulative radioactivity would almost certainly deny to the surviv-



izes the core of a one-gigawatt reactor. Radioactivity from both the reactor and the weapon is spread over the landscape. In each case the prevailing wind is from the west at 15 miles per hour. The plume of debris could drift, however, in a number of directions (*gray circles*). Doses are given in rem per year. One rem represents the amount of radiation that deposits 100 ergs in a gram of tissue. The natural background radiation at sea level is approximately .075 rem per year. The exposure of a population to 2 rem in the course of a year might increase the long-term incidence of cancer. An exposure to 50 rem in a year would cause instances of radiation sickness. Gray dots mark places where a commercial nuclear reactor has been built or is being built within 25 miles of a city with population of more than 100,000.

ing population the use of contaminated workplaces and farms that had escaped destruction in the explosions. Even if the survivors were willing to occupy areas in which they were exposed to doses far greater than 2 rem per year, they would still be unable to use large tracts of land. Each one-megaton weapon creates a zone of 1,500 square miles in which the dose of radiation remains at least 50 rem per year for a month.

In contrast to a nuclear weapon, a nuclear reactor cannot explode. The reactor liberates energy by means of nuclear fission, but even in a reactor that is entirely out of control the rate at which energy is released is more than 10^{12} times slower than it is in a nuclear weapon. Moreover, the energy released in the reactor is absorbed initially by the mass of the core, which is hundreds of times greater than the mass of a nuclear weapon. As a result the temperature of the core even in a runaway reactor rises only slowly.

If the temperature of the core became too great, the fuel elements would melt and the core would fall apart before a chain reaction could generate an explosive amount of energy. A breach of the reactor's containment vessel could then result in a release of radioactivity. In one conceivable accident the total loss of coolant to the fuel rods in the core allows the rods to overheat and melt. The molten material then makes contact with water and a steam explosion tears open the containment vessel, with an ensuing release of radioactive material. In

ATTACK ON A SINGLE REACTOR with a single nuclear weapon could devastate a substantial part of Europe. Here a hypothetical attack has been made on a one-gigawatt nuclear reactor at Neckarwestheim in West Germany. The weapon has an explosive yield of one megaton. The prevailing wind is southeasterly with a speed of 15 miles per hour. A month after the attack the zone in which the dose is 10 rem per year (*light color*) might extend well into the U.K. A year after the attack the 10-rem zone (*dark color*) still includes much of the industrial capacity of West Germany. Gray dots mark the locations of commercial nuclear reactors in West Germany and France.

another conceivable accident the overheating of the core generates hydrogen or other flammable gases, which mix with atmospheric oxygen and then ignite and explode. Again the containment vessel is breached and radioactivity escapes.

In order to compare the hazard posed by a release of radioactivity from a reactor with the release caused by a nuclear weapon, we shall examine the consequences of such a worst-case accident, in which the containment vessel is ruptured. It should be pointed out that the probability of such an event is calculated to be many orders of magnitude smaller than the probability of a lesser accident, such as the one at the Three Mile Island Nuclear Generating Station near Harrisburg, Pa., in March, 1979.

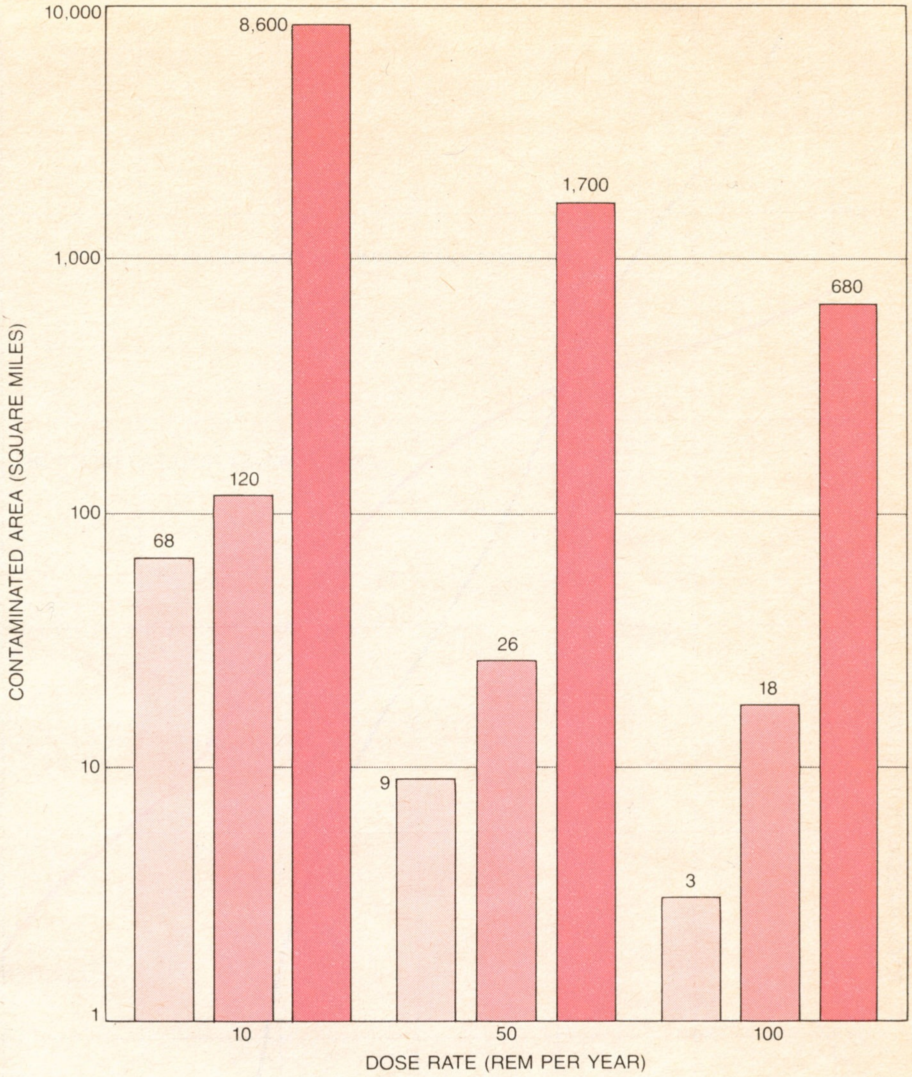
The amount of radioactive material that would escape from a reactor and the composition of the material would depend on the exact nature of the accident and on the time that had passed since the reactor was last refueled. The dispersal of the radioactivity would depend on the shape of the plume of debris released by the accident and on the local weather conditions. Two general conclusions emerge. First, the rate at which radioactivity is released by a thermonuclear weapon is initially far greater than the rate of release by a reactor accident. The radioactivity from the weapon, however, includes a much larger proportion of isotopes whose radioactivity is short-lived. Second, comparatively little heat is released by the reactor accident. As a result the plume of debris remains at low altitude, and it deposits its radioactivity rather promptly. This tends to limit the size of the contaminated area. In sum, the area of land contaminated by the reactor accident is far smaller, but the land stays contaminated longer.

We shall consider a one-gigawatt (1,000 megawatt) nuclear reactor in which a third of the fuel is replaced each year. We shall assume that an explosion breaches the containment vessel and releases into the atmosphere a third of the reactor's content of radioactive nuclei. An hour after the release the radioactivity of the escaped material would be roughly 1.5 billion curies. The detonation of a one-megaton thermonuclear weapon would result in radioactivity 1,000 times greater. The accident at Three Mile Island released 100 million times less. (It released 17 curies of radioactive iodine.)

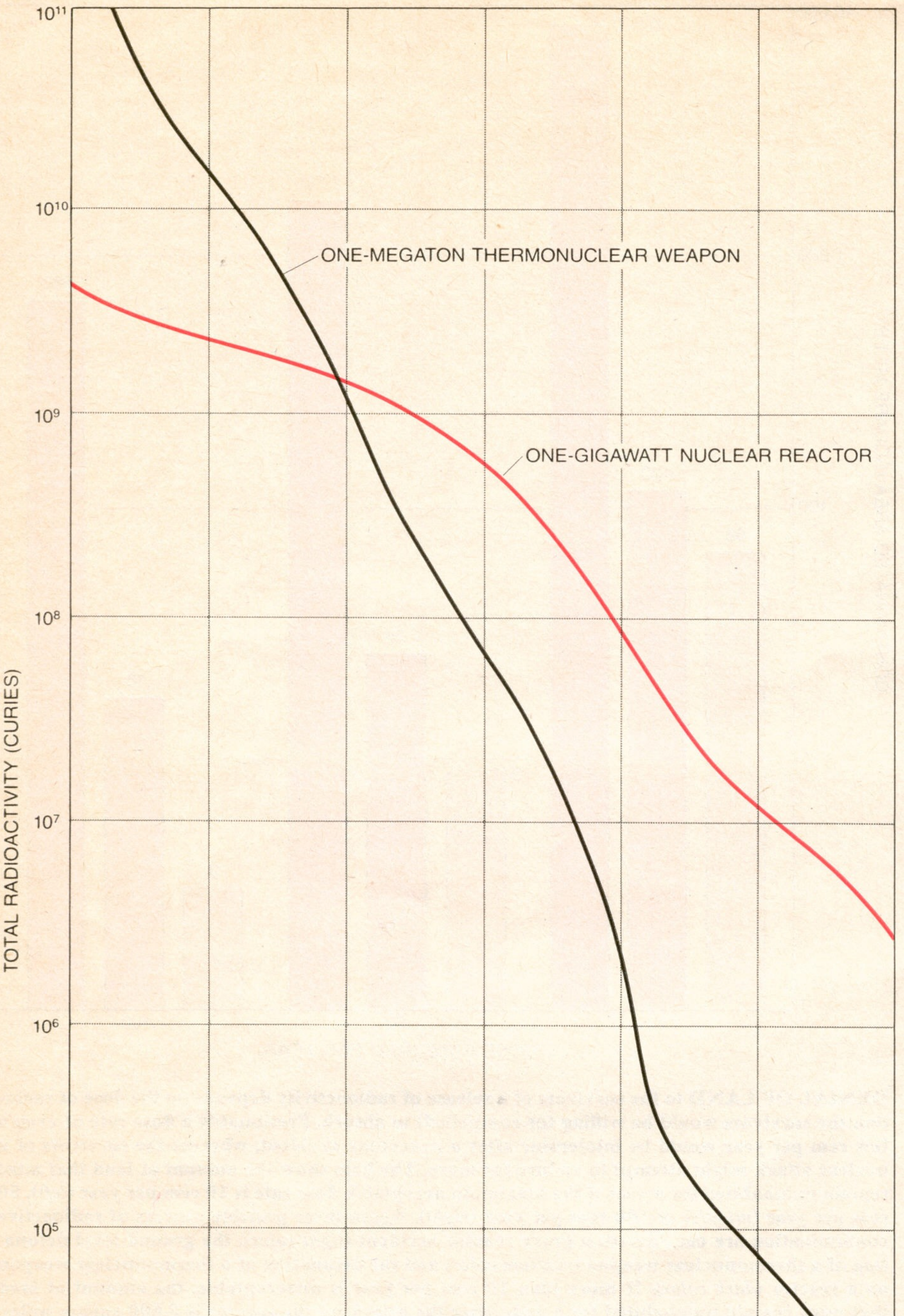
Let the wind speed again be 15 miles per hour. The crucial fact about the outcome of such an accident is that the contaminated area is indeed relatively small. Moreover, the exposure to radiation remains close to a level of 2 rem per year for people in all but a small part of the contaminated area. Specifically, the dose remains 2 rem per year for a month in an area of about 1,800 square miles. (The comparable figure for the detonation of a one-megaton weapon is more than 20,000 square miles.) The lethal zone, where the dose attains a level of 400 rem per day, is less than one square mile. (The lethal zone for the detonation of a one-megaton weapon is 400 square miles.)

The lower dose rate and the smaller size of the contaminated area in the case of a reactor accident suggest that people might be evacuated before they inhaled substantial amounts of radioactive dust. (This is the principal danger after the reactor accident.) It also seems possible that land could be decontaminated. In the case of the nuclear weapon the decontamination of land would be precluded by the far greater deposition of radioactivity.

In comparing the destructive outcome of a reactor accident with that caused by the detonation of a nuclear weapon it is useful to consider briefly the prompt destruction resulting from each event. A reactor meltdown causes no significant damage from blast or heat. A nuclear weapon, on the other hand, causes immediate devastation for five to 10 miles around the site of the explosion. In all likelihood, therefore, the detonation of the weapon would destroy or disrupt emergency and medical facilities. It is reasonable to conclude that if one population were exposed to a dangerous dose of radiation from a nuclear weapon and another population were exposed to the same dose released in a reactor acci-



DENIAL OF LAND to the survivors of a release of radioactivity depends on the dose of radiation the survivors would be willing (or compelled) to absorb. Presumably a dose rate of even a few rem per year would be intolerable after a peacetime accident, whereas the survivors of a nuclear attack might attempt to endure far more. The bars show the amount of land that must remain uninhabited for a year if the maximum acceptable dose rate is 10 rem per year (*left*), 50 rem per year (*middle*) or 100 rem per year (*right*). Again three possible sources of radioactive contamination are considered: a grave reactor accident (*light color*), the ground-level detonation of a thermonuclear weapon (*medium color*) and the detonation of a thermonuclear weapon on a reactor (*dark color*). If more than 10 rem per year is unacceptable, the amount of land that must remain uninhabited for a year after the attack on the reactor is 8,600 square miles.



DECAY OF RADIOACTIVITY released by the detonation of a nuclear weapon differs from the decay of the radioactivity released by a reactor accident because the two inventories of radioactive nuclei have different proportions of various isotopes. After an hour the radioactivity released by the detonation of a one-megaton thermonuclear weapon is 1,000 times greater than the radioactivity that would escape in the worst conceivable peacetime reactor accident. On the other hand, the radioactivity from the reactor takes longer to decay. The unit of radioactivity is the curie. A curie is 3.7×10^{10} emissions per second of various forms of radiation.

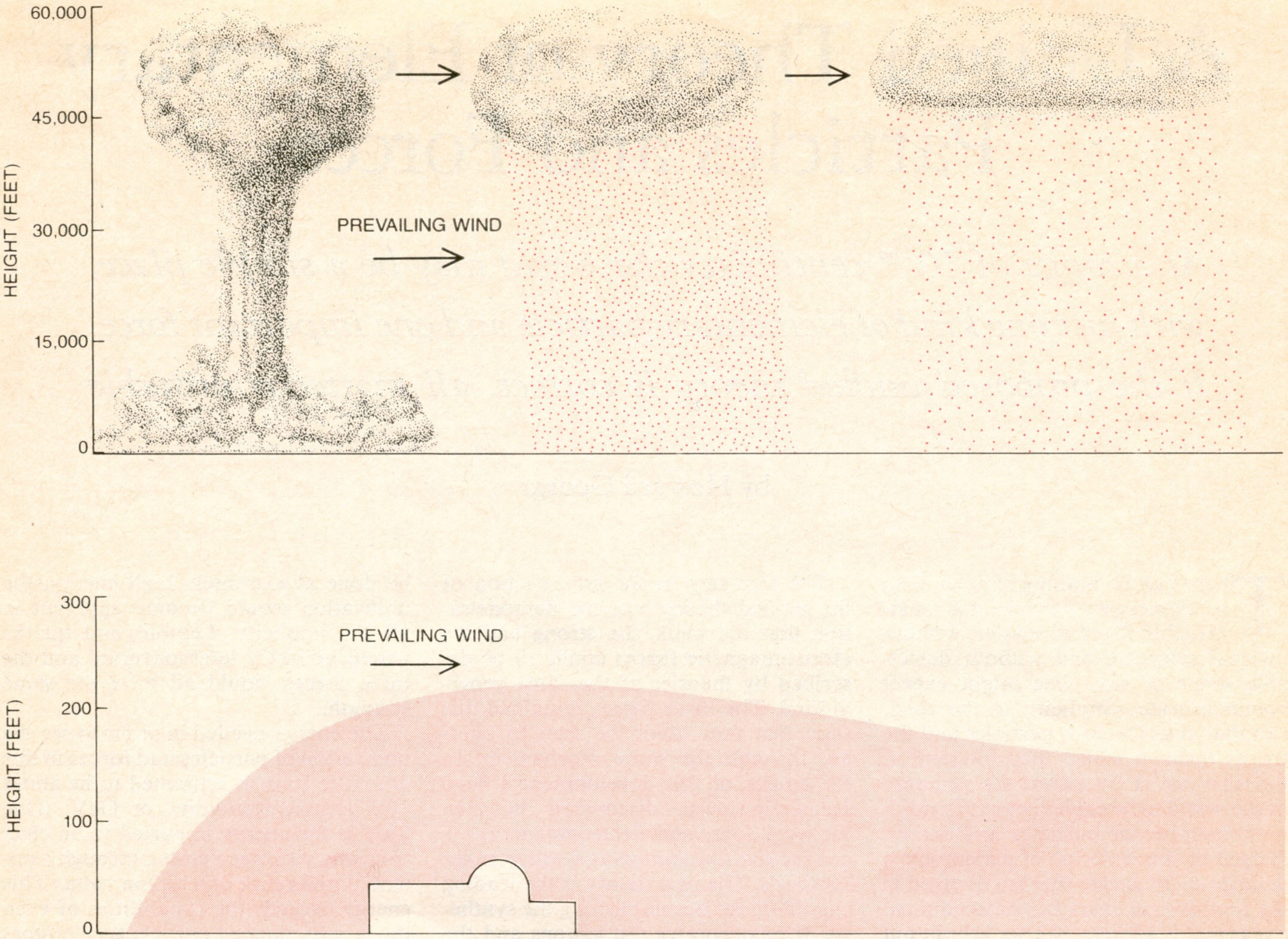
dent, the former population would have many fewer survivors than the latter. The reason is the disruption of the services needed by the victims of radiation exposure.

The probability of the two events we have considered is difficult to assess. Still, there seems to be a belief among both defense analysts and specialists in nuclear power that the probability of the detonation of a nuclear weapon somewhere in the world in the next 10 years is far greater than the probability of the catastrophic meltdown of a nuclear reactor. Among the reasons that might be cited in support of this view are the ever increasing number of nuclear weapons in the arsenals of several nations, the growing truculence that characterizes relations between the U.S. and the U.S.S.R. and the efforts of military planners to shift their nation's strategic policy from that of deterring a nuclear war to that of preparing to fight one.

We now consider the radioactivity that would be released if a one-megaton thermonuclear weapon were detonated on a one-gigawatt nuclear reactor. We shall assume that the radioactive material in the core of the reactor is completely vaporized by the explosion. The radioactivity of the core would then combine with the radioactivity derived from the weapon itself; both would rise with the fireball and return to the earth in the manner characteristic of the fallout from the explosion of a weapon alone.

Since the rate of radioactivity in the reactor is initially much less than the rate of radioactivity given off by the detonation of the weapon, the pattern of contamination in the first week would not differ greatly from the pattern caused by the weapon alone. Because the radioactivity from the reactor is relatively long-lived, however, the time a given area would remain contaminated is significantly greater. In essence, the debris from the weapon would contribute to the contamination a high level of early radioactivity and the debris from the reactor would contribute long-lasting radioactivity. The lethal zone for the detonation of the weapon on the reactor would be more than 500 square miles, an area a third larger than the lethal zone created by the detonation of the weapon alone. The area in which the cumulative dose remained 2 rem per year for a month would be 64,000 square miles, or three times larger. The area in which the dose would remain 2 rem per year for a year is 25,000 square miles, or 20 times larger. An area of 180 square miles would continue for more than a century to expose any occupant to a dose of at least 2 rem per year. Such an area would be a permanent monument to the catastrophe.

Vaporizing the cores of nuclear reac-



PLUME OF DEBRIS caused by the detonation of a nuclear weapon is also different from the plume caused by a reactor accident. The detonation of a one-megaton thermonuclear warhead at ground level (*upper drawing*) creates updrafts that lift the debris of the explosion to an altitude of some 60,000 feet. The debris, which is carried downwind, rains back onto the earth as radioactive fallout. In contrast, the non-nuclear explosion that breaches the containing vessel of the reactor (*lower drawing*) has relatively little energy, and so the released radioactivity is not carried to high altitude. The near absence of a plume reduces the spread of the radioactivity by the prevailing wind.

tors with nuclear weapons is clearly an efficient way to desolate large parts of a nation. Indeed, by waiting for suitable weather conditions, a determined or desperate combatant could devastate a substantial fraction of an opponent's industrial capacity with a single thermonuclear weapon. For example, an attack on a reactor in the Rhine–Neckar River valley could render uninhabitable about a third of West Germany's 96,000-square-mile area for a period of a month or more, even if cumulative doses of radioactivity much higher than 2 rem per year were acceptable to the survivors. The only condition on the attack is that the prevailing wind come from the southeast.

In thinking about such devastation it is well to remember that in central Europe, where the population is dense and the land is intensively exploited, power reactors may lie not far from military installations. The likelihood that a nuclear weapon aimed at a military target would unintentionally destroy a nearby reactor is therefore not negligible. It is also well to remember that storage pools for radioactive wastes are on the same site as the reactor that produces the wastes. The wastes in a typical pool may soon represent an inventory of radioactivity two times greater than that of the reactor core itself. In addition reactors are often constructed in pairs a few hundred feet apart. All things considered, the dose rate following the detonation of a nuclear weapon on a reactor complex could easily be from two to six times higher than what we have calculated.

We can find no public evidence that military planners have carefully considered in any of their scenarios for nuclear war the deliberate or accidental vaporization of the core of a nuclear reactor in a nuclear attack. The best way to minimize the probability of such an event is to avoid all nuclear war. Some helpful steps would be the negotiation of a multinational agreement not to designate nuclear facilities as targets and efforts to ensure that military installations are not situated near civilian reactors.

If a single conclusion is to be drawn from the analysis we have offered, it must be that even a single nuclear weapon would contaminate a much greater area with radioactive fallout than the worst conceivable accident to a nuclear reactor. In view of this the preoccupation of the public with the risks of the generation of electricity by nuclear reactors appears to be misplaced. A catastrophic reactor accident would doubtless cause considerable disruption in its immediate vicinity. It would probably cause long-term medical problems and even some loss of life. Still, the impact of the accident could be moderated, because social, governmental and medical services would be intact and functioning, even in the contaminated area. Moreover, the risks posed by reactors can be minimized by the thoughtful application of technology. A nuclear attack is fundamentally different. The point cannot be overstated: nuclear war poses the ever present danger of suffering and death on a scale unparalleled in human history.