Effects of nuclear weapons

An understanding of the technical details—thermal radiation, shock or blast wave, nuclear radiation—makes for more effective participation in the debate.

Leo Sartori

The intensity of public debate on issues involving nuclear weapons and strategic policy is currently at an all-time high. This is surely a welcome development. Although the issues are largely political, they cannot be addressed without some knowledge of the properties of nuclear weapons and of the destruction that their use could bring about. It is our particular responsibility as technically trained citizens to be informed of the basic facts concerning nuclear weapons and to help our fellow citizens understand them so that they can contribute more effectively to the debate. It is my hope that this article—a presentation of the fundamental principles governing nuclear explosions and their effects—will be useful to those interested in carrying out this responsibility for education on nuclear war.

I begin by summarizing the nature of the three major components of a nuclear explosion—thermal radiation, shock wave and nuclear radiation—and by describing how the effects of these components depend on the yield of the weapon, its height of burst and the distance from the point of detonation. I follow this with a description of the destruction that we could expect if nuclear weapons were actually employed in each of three contexts frequently discussed: a single weapon detonated over a major city, a large-scale "counterforce" exchange limited to strategic targets, and, finally, the extreme case—an all-out nuclear war.

Direct information on nuclear-wea-

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0031-9228 / 83 / 0300 32-09 / $01.00

Hiroshima, photographed by Americans from the USS Appalachian, 27 November 1945. (US Navy photograph.) Figure 1

pons effects comes from study of the two explosions that actually took place in a combat setting—the bombs dropped on Hiroshima and Nagasaki in 1945 (see figure 1)—and from numerous tests conducted since then. All testing by the United States and the Soviet Union since 1963 has been underground, atmospheric tests having been banned by treaty.

Prediction of nuclear-weapons effects is difficult because the weapons have changed a great deal since 1945. Present-day weapons have yields one to two orders of magnitude greater than the ones dropped on Japan. A thermonuclear weapon has never been used in combat, nor has a ballistic missile ever been tested with a live warhead. Moreover, most scenarios for nuclear war entail the use of nuclear weapons on a scale far beyond that of an individual explosion. It is obviously impossible to predict the outcome of such exchanges with high confidence. One has to make many assumptions about how technical systems would work under conditions in which they have never been tested, and, perhaps more important, about how human beings would react to a disaster of unprecedented proportions. The best one can do in making models is to try to include as many dimensions of the problem as possible, make the most informed guesses as to the values of the relevant parameters, and attach large probable errors to the results. In the case of all-out nuclear war, the scale of destruction is so great that the specific numbers almost don't matter. The only firm conclusion one can draw—that humankind must find a way to prevent this disaster from coming about—is independent of any model.

Most of my data on weapons effects come from the authoritative source, *The Effects of Nuclear Weapons*, by Samuel Glasstone and Phillip J. Dolan.[1] The results of government studies on nuclear war scenarios appear in another valuable publication, *The Effects of Nuclear War*, by the Office of Technology Assessment.[2]

Thermal radiation

Some 70 to 80 percent of the energy yield of a nuclear weapon is emitted as thermal radiation within about a microsecond of the explosion. Because the temperature during this phase is in the tens of millions of degrees, the primary radiation is principally soft x rays. Unless the burst is at a very high altitude, the x rays are largely absorbed within a few feet, heating the surrounding air to form a fireball. As the fireball expands, about half its thermal energy goes into a shock wave; the rest is ultimately reradiated at much lower temperatures, mostly between 6000 K and 7000 K. The duration of the thermal pulse increases with yield from about 1 second for a 10-kiloton burst to 10 seconds for explosions of about 1 megaton.

As the thermal pulse propagates, it undergoes geometrical spreading and is attenuated by absorption and scattering. We can write the integrated thermal flux Q as

$$Q = f\tau Y/4\pi D^2$$

where Y is the yield, D is the slant range, or distance from the point of detonation, and τ is a transmission factor whose value depends on atmospheric conditions as well as on the slant range. (The attenuation is generally not a simple exponential.) The thermal energy fraction f is the fraction of the total yield that remains as thermal energy in the fireball after the shock wave forms. For airbursts, f is between 0.35 and 0.40, and for contact surface bursts it is about 0.18. Because 1 kiloton of TNT releases 10^{12} calories, we can write the integrated thermal flux in hybrid units as

$$Q \simeq 3000(f\tau Y/D^2)\ \mathrm{cal/cm^2}$$

with Y in megatons and D in miles. On a clear day the attenuation is quite gradual: Typical transmission factors for low-altitude bursts are 60%–70% at 5 miles, and 5%–10% at 40 miles. At high altitudes the absorption is even weaker. In haze or fog, thermal radiation is more strongly absorbed. Figure 2 shows the radiant exposures as a function of slant range and yield for low-altitude bursts on a clear day.

The harmful effects of thermal radiation on people are of two kinds: "flash" burns, caused by radiation striking exposed skin directly, and secondary, or "contact" burns, caused either by ignited clothing or by a general fire started by the radiation. The severity of a flash burn depends on the duration of the exposure and on the individual's skin pigmentation. Five to six calories per square centimeter received in ten seconds will cause second-degree burns, and 8–10 cal/cm^2 will cause third-degree burns. As figure 2 shows, such exposures would be experienced on a clear day out to 7 or 8 miles from a one-megaton burst. Even someone indoors near a window would be in danger. The pulse from a high-yield burst lasts long enough, however, to enable people indoors or with nearby shelter to take cover and thus reduce their exposure. Ignition of clothing, which requires 20–25 cal/cm^2, would occur to about 5 miles from ground zero. A person whose eyes were actually focused on the fireball would suffer serious retinal burning that could cause permanent blindness.

Because any opaque material is an effective shield against thermal radiation, people not in the direct path of the thermal pulse would be safe from flash burns. However, the danger of fire would be high over a large area. Wood-frame houses are not likely to be set afire directly; in tests, such structures charred heavily and emitted dense smoke but did not burn. Ten calories per cm^2 in ten seconds suffices to ignite light combustibles such as paper or dry leaves; ignition of household items like overstuffed chairs or beds requires 20–30 cal/cm^2. Interior fires, once started, are more likely to be sustained than outdoor ones. The strong wind associated with the blast wave, which arrives a few seconds after the thermal pulse, might extinguish some fires; test evidence on this effect is inconclusive. On the other hand, the blast wave is likely to start many fires by breaking gas lines, by overturning stoves and furnaces, or by causing electrical short circuits.

Under certain circumstances, individual fires could merge into a single mass fire that consumes a large area. Such "fire storms" occurred during World War II, in Hiroshima after the atomic attack (but not in Nagasaki) as well as in several German and Japanese cities after massive incendiary bomb raids. If a fire storm does occur, people in underground shelters might be killed by heat, by asphyxiation or by carbon monoxide entering through the ventilation system.

Care of burn victims would be one of the most taxing medical problems in case of nuclear war. Third-degree burns over 25% of a person's body or second-degree burns over 30% generally produce serious shock and are likely to be fatal unless promptly treated. Burn treatment is complicated, requiring specialized facilities and intensive care. In the entire United States there are facilities to treat only a few thousand severe burn cases, fewer than the number likely to result from a single explosion in a populated area.

Blast

Blast is the effect that would generally be counted on to accomplish the military objectives assigned to nuclear weapons in a conflict. (A noteworthy exception is the neutron bomb, which relies on prompt radiation.) The shock or blast wave produced by a nuclear explosion is characterized by a sharp increase in air pressure, accompanied by extremely strong winds. Sudden overpressure crushes objects and collapses structures, while the wind can turn any fairly light object into a lethal projectile.

Under ideal hydrodynamic conditions the shock velocity U in air is given[1] by

$$U = c_0(1 + 6p/7P_0)^{1/2}$$

and the wind velocity u by

$$u = {}^5\!/_7(p/P_0)c_0(1 + 6p/7P_0)^{-1/2}$$

Here p is the peak overpressure, c_0 the ambient velocity of sound ahead of the shock front, and P_0 the ambient pressure. Table 1 gives the relation between the peak overpressure, the peak dynamic pressure of the wind, and the maximum wind velocity, obtained from the last equation. The dynamic pressure is given by $\frac{1}{2}\rho u^2$, where ρ is the density of air.

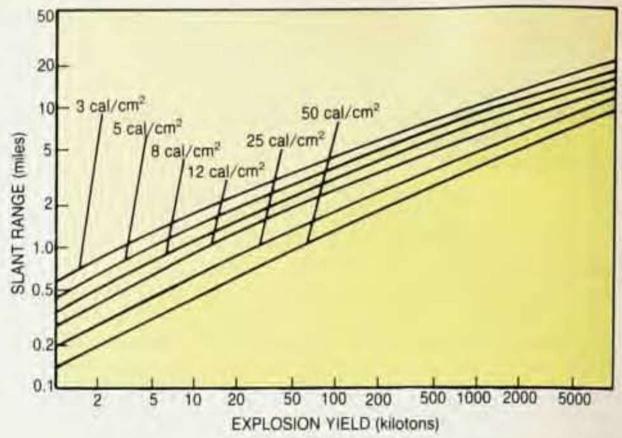
An important hydrodynamic scaling law simplifies the analysis of shock effects: The peak overpressure is a function only of the parameter z, defined as $Y^{1/3}/D$. This scaling law has been verified experimentally up to and including the megaton range, for all but very-high-altitude explosions. It follows that the area over which a given overpressure is produced is proportional to $Y^{2/3}$; this quantity is defined as the equivalent megatonnage of the weapon. Notice that the combined equivalent megatonnage of several low-yield weapons is greater than that of a single weapon with the same total yield.

Figure 3 is a log–log plot of overpressure p against $1/z$ for a free-air burst. In the high-overpressure range, p varies approximately as z^3; for low overpressures the fall-off is less steep. A fairly good approximate formula is[3]

$$p = 22.4\ z^3 + 15.8\ z^{3/2}$$

where p is measured in lb/in^2 and z in $\text{megatons}^{1/3}/\text{mile}$.

When the shock wave from an air burst strikes the ground, it is reflected. Because the reflected shock passes through an already shocked region in which density and temperature are higher than ambient, it propagates faster than the primary shock. For certain geometries, the reflected front catches up to the primary and the two fronts merge, creating an overpressure typically twice that of the primary shock alone. The merged fronts are known as the Mach stem and the region in which the phenomenon occurs is called the Mach reflection region. In the "ordinary" reflection region the reflected shock front arrives at a given point after the primary front has already passed, and two distinct pressure peaks are experienced.



Slant ranges for specified radiant exposures on the ground, as a function of yield. These data, valid for airbursts at altitudes up to 15 000 feet, assume 12-mile visibility. (From reference 1.) Figure 2

Because of the Mach effect, the peak overpressure at a given distance from ground zero can be greater for a weapon detonated at a substantial altitude than for a ground burst, even though the slant range is obviously less for the ground burst. This effect is most pronounced in the low- and medium-overpressure regions, that is, fairly far from ground zero. Figure 4 is a contour plot of peak overpressure against altitude and distance from ground zero. Due to the scaling law, the overpressure is a function of the "scaled height of burst" $h/Y^{1/3}$ and the scaled distance from ground zero $d/Y^{1/3}$; a single plot provides the data for any yield. By convention, all lengths are scaled to a 1 kiloton yield. Thus, a 200-foot scaled height of burst corresponds to 200 feet for 1 kiloton, 2000 feet for 1 megaton, and so on.

As the bulges in the curves of figure 4 indicate, for relatively low overpressures there is a well-defined "optimum height of burst" that maximizes the overpressure at a given distance from ground zero or, alternatively, that maximizes the distance to which a specified overpressure extends. For 15 lb/in^2, for example, the "optimal" scaled height of burst is 650 feet. For this height of burst the 15-lb/in^2 contour extends to 1200 scaled feet, as compared to only 800 feet for a contact burst. The area exposed to at least 15 lb/in^2 is more than doubled.

In the high-overpressure region, closer to ground zero, the Mach effect occurs only for very low heights of burst and the peak overpressure is nearly independent of height of burst in the Mach reflection region.

The height of burst likely to be employed depends on the nature of the target. In an attack on an extended "soft" target, such as an airfield or industrial plant, the objective would be to create overpressures of 10–30 lb/in^2 over as large an area as possible. For such an attack, an air burst at a scaled height of 600 to 800 feet would be the indicated choice. On the other hand, a "hard" target, such as an ICBM silo, can withstand overpressures as high as 1000 lb/in^2 or more. (Hardness figures much higher than 1000 lb/in^2 have been cited in recent discussions, principally in connection with the proposed closely-spaced basing mode for the MX missile.) To attack such a target successfully, the weapon must detonate at very close range. Although an optimum height of burst exists in this case, it is quite low, and a burst at this height is only slightly more effective than a ground burst.

As an example, consider a 1-megaton weapon with a 600-foot circular error probable (a measure of the delivery vehicle's median miss distance) directed against a target able to withstand overpressures of 2000 lb/in^2. A burst at the optimum height, about 1000 feet, gives a 93% probability of destroying the target, compared to 89% for a ground burst.[4]

Because the overpressure at the target drops off quite steeply with height of burst above the optimum, a small fuzing error could lead to substantial degradation in effectiveness. This consideration favors a lower-altitude burst. On the other hand, if two or more weapons are aimed at the same target the attacker would wish to avoid raising large amounts of dust that could cause "fratricide," the destruction or impairment of a warhead by the effects of a prior explosion. To avoid fratricide, the burst must be as high as possible.

Table 2 summarizes the effects of various overpressures on common types of structures, and gives the distance to which each overpressure would be produced by a one-megaton weapon detonated at 6000 feet. The analogous distances for any other yield are easily obtained with the help of the scaling law.

The human body can withstand quite high overpressures without sustaining serious injury. The chief dangers from sudden compression are hemorrhage and possible rupture of abdominal and thoracic walls. The lungs are particularly prone to hemorrhage and edema; their threshold for injury is 12 lb/in^2 and severe damage occurs at 25 lb/in^2. Lethal effects begin at about 40 lb/in^2. The principal danger to people from blast, however, is indirect—it comes from the collapse of buildings, from flying glass and other fragments, and from winds strong enough to hurl people against hard surfaces.

Of all the effects of a nuclear explosion, blast is the most difficult to protect against. Underground facilities such as subway stations provide adequate protection. A home blast shelter requires special construction and is more expensive than a fallout shelter. Most blast shelters are designed to protect against overpressures of 40 lb/in^2 or less. There is little point in trying to do better, because an airburst near the optimum height of burst exposes little or no area to more than 40 lb/in^2. Against a ground burst, the incremental protection provided by a shelter able to withstand 60 lb/in^2, say, would be slight and the incremental cost considerable. Naturally, people would have to have advance warning to make any use of a blast shelter.

Nuclear radiation

The important nuclear radiations associated with nuclear explosions are neutrons, gamma rays, and to a much smaller extent, beta particles. Essentially all the neutrons and most of the gammas are produced in fission and fusion reactions during the explosion proper. The capture of neutrons in the weapon debris and in the surrounding air, earth or water produces additional gamma rays and a large variety of radioisotopes, which make up the radioactive fallout.

The harmful biological effects of nuclear radiation are attributable to damaging ionization produced in the cell bodies of exposed organisms. The mean free paths for both gamma rays and neutrons in animal tissue are on the order of 20 cm—just in the range that causes maximum harm to the organism. If the mean free path were a few millimeters or less, the radiation would be absorbed in the surface layers of the skin and would not reach vital organs; if it were several meters or more, most of the radiation would simply pass through the organism without interacting. As it is, both neutrons and gamma rays are strongly absorbed throughout the body, affecting all organs.

Radiation dosage is measured in *rads*; one rad is defined as the deposition of 100 ergs of ionizing radiation per gram of material. Because equal amounts of energy from different kinds of radiation do not necessarily have the same biological effects, it is necessary to define for each radiation and each effect a parameter called the "relative biological effectiveness." The RBE is the ratio of the absorbed dose of gamma radiation at a specified reference energy to the absorbed dose of the radiation in question that produces the same effect. The biological dose in *rems* is the energy dose in rads, multiplied by the relative biological effectiveness.

The relative biological effectiveness of gamma rays is unity, by definition, at the reference energy, and is only slightly energy-dependent. The RBE of neutrons varies both with energy and with type of injury. For the energy spectrum of nuclear weapons, however, the relative biological effectiveness of the neutrons that cause acute radiation injury is close to unity; hence one may use rems and rads interchangeably in most instances with little error. (The RBE of neutrons for certain injuries, such as cataracts, leukemia and genetic damage, is substantially greater than one.)

Table 3 summarizes the medical effects of radiation on human beings as a function of the total, or whole-body, dose received. As the table indicates, serious illness begins to appear at about 200 rems exposure, and above 600 rems the effects are fatal to most people.

It is useful to distinguish between initial or prompt radiation, which is released in the first minute or so after the explosion, and residual radiation, which is due entirely to induced radioactivity. The initial radiation produces huge doses at close range: The prompt gamma-ray dose one kilometer from a one-megaton burst is on the order of a million rads. The gamma rays and neutrons are, however, strongly attenuated by interactions with air molecules as they propagate. Their mean free paths in sea-level air are a few hundred meters. As a result, even for a weapon of several megatons, the prompt dose a few kilometers from the point of detonation is already below the harmful range. Although the prompt exposure in the immediate vicinity of an explosion is many times the lethal dose, its impact is blunted by the fact that most individuals exposed to so great a dose are likely to have been already killed by the effects of blast and fire.

The characteristics of the residual radiation depend on how much of the explosive yield is due to fission and, most sensitively, on whether or not the fireball touches the ground. Fission reactions form more than 300 different radioactive isotopes, whereas fusion produces negligible activity. Hence, the higher the fission yield the more radioactivity is produced directly in the explosion.

Dangers of fallout. In an air burst, the residual radioactivity comes primarily from fission products, with some coming from weapon residues activated by neutron capture. A surface burst, on the other hand, produces radioisotopes copiously as neutrons are captured by a variety of nuclei in the earth. Much rock and soil vaporized by the intense heat become part of the fireball. As the fireball cools, the vaporized matter condenses into particles in which radioactive nuclei are imbedded. Radioactive nuclei lodge also on particles of dirt and dust sucked up by strong afterwinds as the fireball rises. The contaminated particles eventually descend to Earth, a phenomenon commonly known as fallout.

Other things being equal, there is much more fallout if the fireball touches the ground than if it doesn't. The height of burst below which significant fallout is generated is given[1] by the following approximate formula, in which Y is the yield in megatons

$$h = 2900\,Y^{0.4}\ \text{feet}$$

The probable error here is $\pm 30\%$; Glasstone warns[1] that one should not assume that a burst above this altitude will necessarily result in negligible fallout.

The radioactive nuclei in the fallout decay, each isotope according to its own halflife, emitting both beta and gamma radiation. The gamma rays can produce whole-body doses high enough to cause acute radiation sickness; this is the principal hazard from fallout. Beta rays have a range of only a few millimeters in body tissue and cannot penetrate the skin; they are absorbed by a thin layer of clothing. Fallout particles can, however, cause painful beta burns if they land directly on the skin, and there can be serious consequences if the particles are inhaled or if

Table 1. Shock-front relationships

Peak overpressure (lb/in^2)	Peak dynamic wind pressure (lb/in^2)	Maximum wind velocity (mi/hr)
200	330	2078
150	222	1777
100	123	1415
50	41	934
30	17	669
20	8.1	502
10	2.2	294
5	0.6	163
2	0.1	70

For sea-level air. (Reference 1.)

they find their way into the food chain, ultimately to be ingested and reach sensitive organs. Cancers and genetic abnormalities, the most serious effects of this nature, can be caused by extremely low doses.

After the deposition of fallout particles has ceased, the activity at a given location declines quite slowly, as the sum of exponentials with many different half-lives. A $t^{-1.2}$ dependence provides a good empirical fit to the measured activity for t between about a half hour and six months; the subsequent decline is somewhat steeper. About 80% of the total dose is received in the first day, and about 90% during the first week. The remaining 10%, however, is distributed over a long time; in a high-exposure area the activity can remain at a dangerous level for many weeks or even months.

The shape, extent and location of the fallout pattern from a single surface burst are determined primarily by the height of the troposphere, the distribution of winds and the occurrence of rain or snow. The size of the fallout particles also affects their rate of deposition. The particles range in diameter from less than a micron to several millimeters. The larger ones begin falling back to Earth even before the radioactive cloud has reached its maximum height, so they are all deposited locally. The smallest particles may remain suspended in the atmosphere for long periods and may be carried great distances by winds. Although the radioactivity is very much diluted, low-level effects of long-lived isotopes can extend worldwide.

Figure 5 is a contour map of the total fallout from a surface burst of one-megaton yield, 50% of which is due to fission. Calculated with the assumptions of a steady 15 mph wind and no precipitation, the distribution is sharply peaked in the downwind direction. Under these conditions, a region roughly a thousand square miles in area would be subjected to a total dose over 900 rems, and an area some four times greater would receive more than 100 rems. With shifting winds the distribution would be less asymmetric, but the qualitative features of the fallout pattern would be similar.

Because all matter absorbs nuclear radiation, anything between an individual and the source reduces the dose received. A rough rule of thumb is that a foot of concrete or 18 inches of earth reduces the intensity of gamma rays by a factor of ten; the effect on neutrons is similar, although neutron absorption is somewhat more complicated. Unlike a blast shelter, a fallout shelter does not require special construction; even an ordinary basement provides considerable protection. With earth piled over windows and against walls, radiation may be reduced by a factor of about 20.

Effects of a single explosion

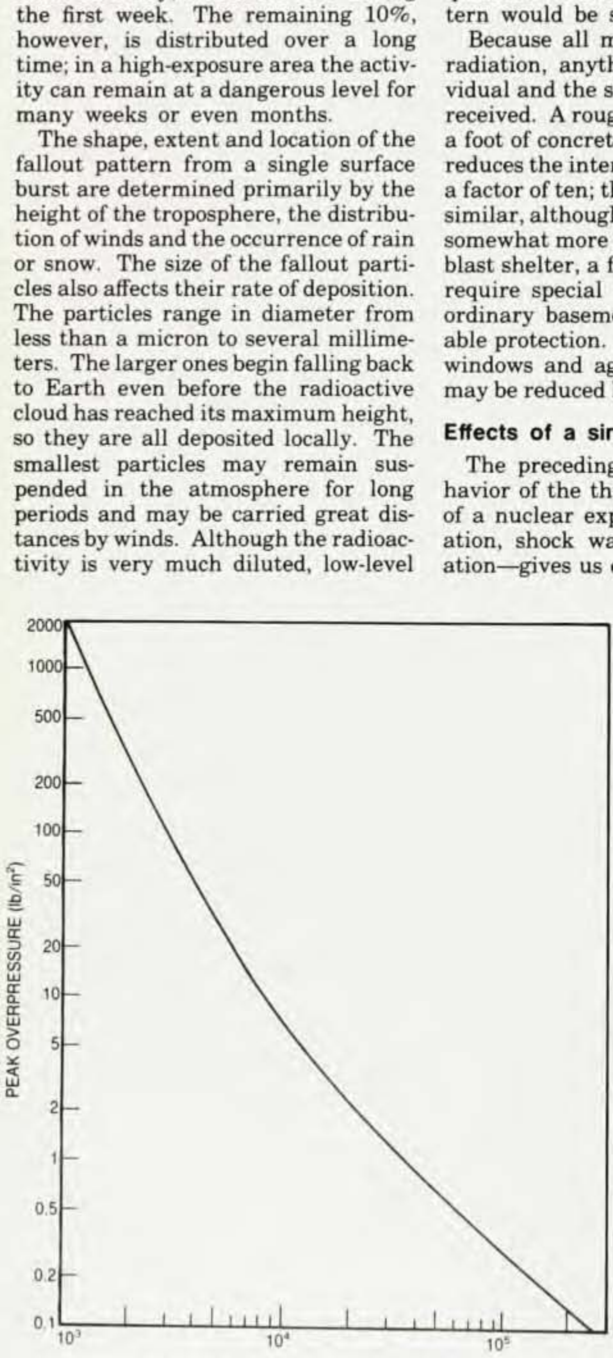
The preceding summary of the behavior of the three major components of a nuclear explosion—thermal radiation, shock wave and nuclear radiation—gives us enough information to estimate the extent of destruction that would occur if a single large nuclear weapon were detonated over a major city. For concreteness we consider a one-megaton weapon exploded at 6000 feet.

According to table 2, the overpressure would exceed 10 lb/in^2 within a circle of 2.7-mile radius centered on ground zero. Virtually every structure in this region would be destroyed and there would be almost no survivors except for people in blast shelters. In a ring between 2.7 and 4 miles from ground zero, overpressures ranging between 5 and 10 lb/in^2 would destroy individual residences, leaving only some foundations and basements. Stronger commercial buildings might remain standing, but with walls blown out, while some industrial buildings might remain nearly functional. Debris would pile in the streets to depths up to several feet. About half the people in this ring would be killed, mostly as the result of buildings collapsing on them. Almost all the survivors would be injured.

In the ring with 2–5 lb/in^2 peak overpressure—4 to 7 miles from ground zero—there would be extensive building damage and many injuries, although the number of immediate fatalities would be small. The danger of fires would be most severe in this region, because fires are more likely to ignite and spread if buildings are left standing than if they are demolished. According to the Office of Technology Assessment,[2] perhaps five percent of the buildings in this region would ignite initially, and it is highly likely that the fire would spread where the separation between buildings is less than 50 feet. Fires would continue to spread for at least 24 hours, and with little opportunity for fire-fighting, perhaps half the buildings would ultimately be consumed.

Finally, in a ring extending to ten miles from ground zero, overpressures of 1–2 lb/in^2 would cause only light damage to commercial structures and moderate damage to residences. Fatalities would be few, but about 25% percent of the residents would be injured.

The total number of casualties would depend on the population density, time of day, atmospheric conditions and numerous other factors that are unpredictable. An Office of Technology Assessment study of an assumed explosion at night over downtown Detroit estimated that blast effects would cause 470 000 immediate deaths and 630 000 injuries. Casualties due to flash burns and fires are even more unpredictable because they are sensitive to weather and to how many people happen to be outdoors. The study found that as few as 1000 or as many as



Pressure amplitude of the shock wave from a free-air burst. The horizontal axis is the distance to the blast, scaled by the yield of the blast. No reflected wave is included here. (Adapted from reference 1.) Figure 3

Table 2. Effects of blast wave from a nuclear explosion

Peak overpressure (lb/in²)	Effects	Distance* to which effects are felt (miles)
20	Multistory reinforced-concrete buildings demolished. 500 mph wind	1.8
10	Most factories and commercial buildings collapsed; small wood and brick residences destroyed. 300 mph wind	2.7
5	Unreinforced brick and wood houses destroyed; heavier construction severely damaged. 160 mph wind	4
2	Moderate damage to houses—wall frame cracked, interior walls knocked down, severe damage to roofs. People injured by flying glass and debris. Wind about 70 mph	7
1	Light damage to commercial structures; moderate damage to residences.	10

*Based on a one-megaton burst at 6000 ft altitude.

190 000 burn fatalities could be expected, depending on the conditions assumed.

Counterforce exchange

Analysts generally consider two types of scenarios for large-scale nuclear exchanges. One is a so-called counterforce exchange, in which each side strikes only the strategic forces of the other—ICBM silos and launch-control facilities, nuclear-submarine bases and strategic-bomber bases. The second scenario is an all-out exchange in which the targets include additional military facilities as well as major urban-industrial targets—factories, oil refineries, communication centers and the like. It is generally assumed that cities and civilian populations would not be targeted *per se*. However, because of the proximity of military and industrial targets to major population centers, most large cities would inevitably be hit. Such an all-out exchange would involve thousands of high-yield warheads.

A pure counterforce exchange would have relatively little direct effect on civilian populations. In fact, because ICBM silos are situated in sparsely populated regions, an attack confined strictly to ICBMs would cause virtually no direct damage to civilians, provided none of the attacking missiles were grossly mistargeted. If submarine bases and strategic airfields were included the toll would be greater, because some of those facilities are close to large cities. But most of the civilian populations would still escape direct attack.

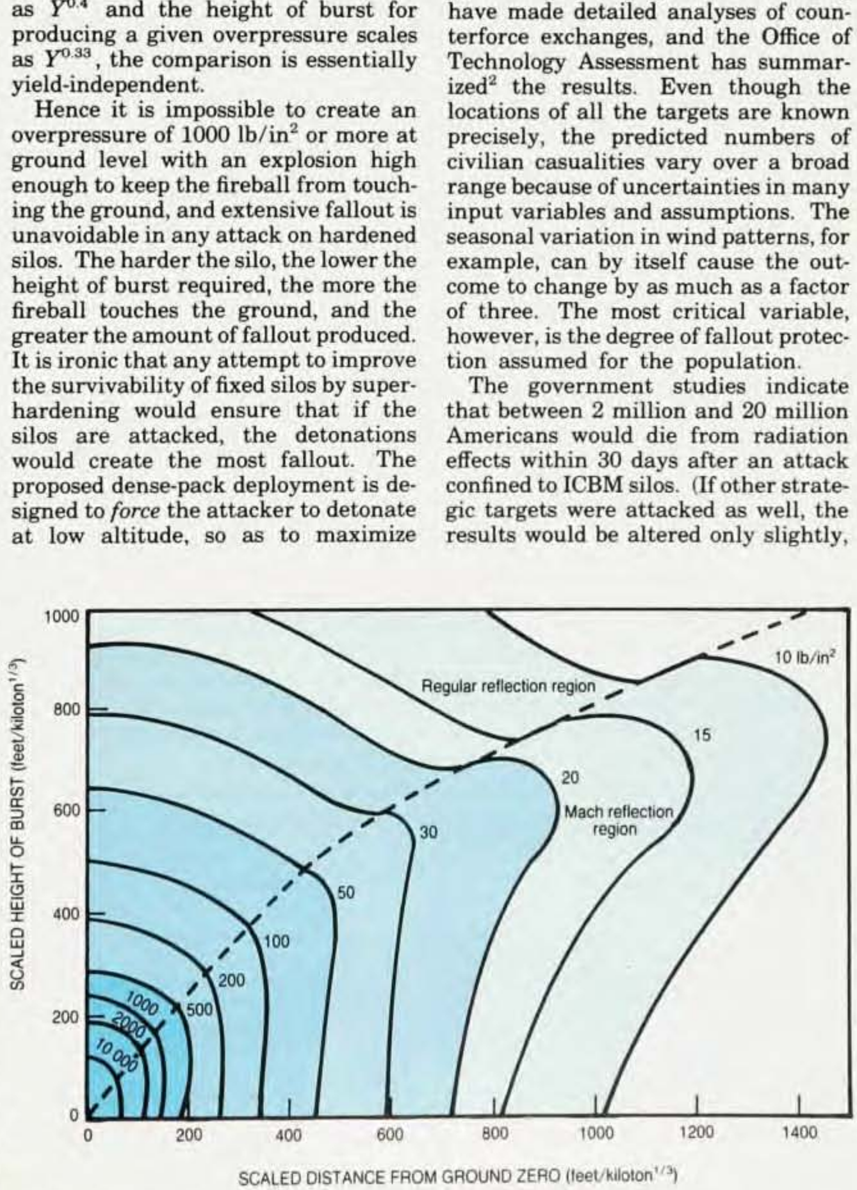
For most of the country, the major impact of a counterforce attack would be due to fallout. As we saw earlier, attacks on hardened silos require low-altitude bursts. According to the equation on page 35, the minimum height of burst to avoid significant fallout in a one-megaton explosion is 2900 feet. But figure 4 shows that to produce 1000 lb/in² overpressure on the ground requires a height of burst less than 2400 feet, even if the detonation is directly overhead. Because the critical height of burst for avoiding high fallout scales as $Y^{0.4}$ and the height of burst for producing a given overpressure scales as $Y^{0.33}$, the comparison is essentially yield-independent.

Hence it is impossible to create an overpressure of 1000 lb/in² or more at ground level with an explosion high enough to keep the fireball from touching the ground, and extensive fallout is unavoidable in any attack on hardened silos. The harder the silo, the lower the height of burst required, the more the fireball touches the ground, and the greater the amount of fallout produced. It is ironic that any attempt to improve the survivability of fixed silos by superhardening would ensure that if the silos are attacked, the detonations would create the most fallout. The proposed dense-pack deployment is designed to *force* the attacker to detonate at low altitude, so as to maximize "fratricide" effects.

A Soviet attack against US strategic forces, including two warheads directed at each of the Minuteman and Titan ICBMs, would entail some 2000 explosions, either ground bursts or low-altitude air bursts, in the 1-megaton range. One can estimate the distribution of fallout resulting from such an attack by superposing the fallout patterns for individual bursts. Figure 5 shows the fallout pattern of an individual burst. Inevitably, a substantial fraction of the country would be exposed to high levels of radiation. With the silos concentrated in the West, prevailing westerly winds would drive much of the fallout into densely populated areas in the Midwest and East.

The Department of Defense, the Arms Control and Disarmament Agency and the intelligence community have made detailed analyses of counterforce exchanges, and the Office of Technology Assessment has summarized[2] the results. Even though the locations of all the targets are known precisely, the predicted numbers of civilian casualities vary over a broad range because of uncertainties in many input variables and assumptions. The seasonal variation in wind patterns, for example, can by itself cause the outcome to change by as much as a factor of three. The most critical variable, however, is the degree of fallout protection assumed for the population.

The government studies indicate that between 2 million and 20 million Americans would die from radiation effects within 30 days after an attack confined to ICBM silos. (If other strategic targets were attacked as well, the results would be altered only slightly,



Peak overpressures on the ground for designated heights of burst and distances from ground zero. Lengths are scaled to a 1-kiloton yield. (Adapted from reference 1.) Figure 4 because those targets would probably receive only airbursts.) Moreover, the low end of the range of estimates—fewer than 8–10 million deaths—requires quite optimistic assumptions not likely to be satisfied. The estimated number of injuries is about equal to the number of fatalities. One could also expect extensive radiation damage to crops and livestock. For a US counterforce attack on the Soviet Union the estimated number of casualties is comparable to the above but somewhat smaller, principally because US missile warheads have lower yields than those of the Soviet Union.

These results cast considerable doubt on the validity of an argument that plays a prominent role in the current strategic debate. According to this argument, a Soviet "surgical strike," that is, a strike strictly limited to US ICBMs, could destroy almost all of these missiles while inflicting only light casualties on the civilian population. Although the US would still have a formidable force of surviving bombers and submarine-launched ballistic missiles, a retaliatory strike against Soviet urban-industrial targets would cause heavy civilian casualties and would almost surely elicit a massive Soviet counterstrike in which US cities would be devastated. Fear of such an outcome, it is claimed, would inhibit the US from retaliating. Lacking a strong counterforce capability of its own, the US could make no response to the destruction of its ICBMs. In effect, then, the US deterrent is no longer credible. This is the essence of the "window of vulnerability" argument invoked in support of proposals to increase US counterforce capability and to develop more-survivable basing for US ICBMs.

By conservative estimates, a Soviet "surgical strike" would probably result in at least 7–10 million Americans dead, a comparable number injured, and large-scale disruption of US society, with many millions confined to fallout shelters for weeks. One has to question whether a Soviet leader could confidently assume the US would absorb a blow of such magnitude without retaliating, regardless of the consequences.

All-out exchange

The executive-branch studies referred to above considered also the consequences of a massive all-out exchange. In such an exchange the effects rise to truly catastrophic proportions. Most large cities in both the US and the USSR would be subjected to the kind of devastation that I described earlier (see table 2). All the studies agree that very large numbers of civilians would be killed by blast and thermal effects and that a high percentage of the economic and industrial capacity of both countries would be destroyed, no matter which one struck first.

As in the case of a counterforce exchange, the quantitative results depend on the assumptions concerning the nature of the attacks and the protective postures of the populations, and are subject to large uncertainties. Assuming the US population remains in place and utilizes only locally available shelter, the estimated numbers of prompt fatalities after a Soviet first strike range between about 80 and 170 million. A US retaliatory strike would cause between 50 and 100 million deaths in the USSR.

If we assume that urban populations are evacuated, the estimated casualty levels drop significantly. One Defense Department study predicted 40–55 million prompt fatalities in the United States, while a study by the Defense Civil Preparedness Agency, which assumed substantially greater fallout protection for the evacuees, estimated "only" 20 million deaths. Soviet fatalities after a US retaliation were estimated to be between 23 and 37 million.

The potential saving of significant numbers of lives through civil defense, and particularly through evacuation, has occasioned a heated debate. It is reported that the Soviets devote substantial resources to civil defense preparations, which are said to comprise extensive shelters, hardening and dispersal of industrial facilities, and an evacuation plan. Some have argued that the "civil defense gap" would give the Soviets a decisive advantage in case of nuclear war.

The US public has never taken civil defense very seriously. At present, the Federal Emergency Management Agency is developing a large-scale "crisis relocation" plan, in which host communities in lower-risk areas would be designated to receive evacuees from large cities. There are many obvious problems with such a plan, not least being the feasibility of carrying out such massive evacuations even if the required warning time were available. Many have also questioned the efficacy of Soviet civil defense.

I must emphasize that the casualty figures cited here refer to the first 30 days only, and take no account of the aftermath or the long-term effects. Formidable problems would face the survivors of a large-scale nuclear exchange. Devastated areas could count on little help from the outside, because neighboring communities are likely to have been hit themselves.

For a period of perhaps a month, radiation levels due to fallout would be higher in much of the country, particularly in the eastern half. Figure 6, from a study[5] by the Arms Control and Disarmament Agency, shows the areas that would receive a total dose in excess of 1000 rems. Survivors in those areas would have to spend most of their time in shelters, many of which would be overcrowded. Supplies of food, water and medicine might not be adequate. Maintaining even minimal hygiene and sanitation would be a taxing problem. The level of stress in the shelters is likely to be high. Not knowing how much radiation they had received, peo-

Table 3. Effects of acute radiation on human beings

Dose (rems)	Symptoms	Treatment	Prognosis
0 to 100	Little or no visible sign. Some blood changes are detectable above 25 rems.	No treatment required.	Excellent.
100 to 200	Vomiting, headache, dizziness. Moderate leukopenia (loss of white blood cells).	Hematologic surveillance; reassurance. Hospitalization not required.	Full recovery in a few weeks.
200 to 600	Severe leukopenia; internal bleeding; ulceration; hair loss above 300 rems; infection likely.	Blood transfusions; antibiotics. Hospitalization required.	Guarded. Probability of death near 0 at low end, 90% at high end.
600 to 1000	Same as above but more severe.	Consider bone marrow transplant.	Poor. Probability of death 90–100%. Long convalescent period for survivors.
1000 to 5000	Diarrhea, fever, disturbance of electrolyte balance.	Maintain electrolyte balance.	No chance of recovery, death occurs in 2–14 days.
over 5000	Convulsions, tremor, ataxia.	Sedatives.	Death in 1–2 days or sooner.

Adapted from reference 1

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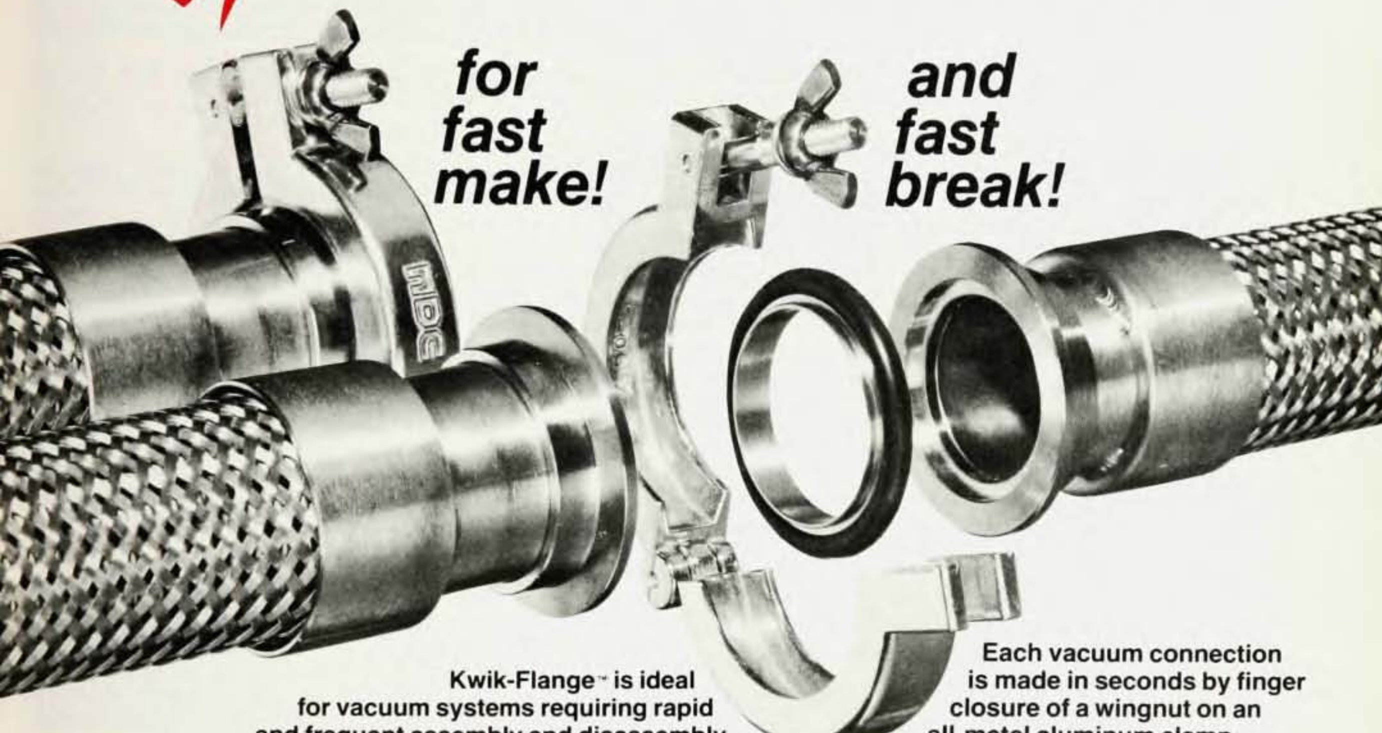

Kwik-Flange™ is ideal for vacuum systems requiring rapid and frequent assembly and disassembly.

Each vacuum connection is made in seconds by finger closure of a wingnut on an all-metal aluminum clamp.

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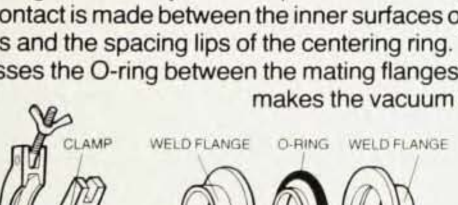
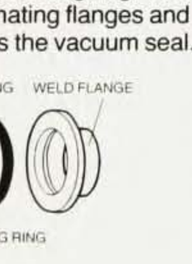
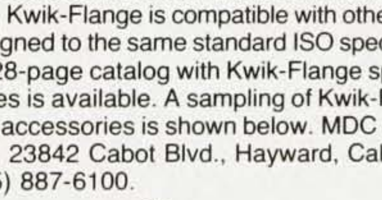


Kwik-Flange fittings are made of type 304 stainless steel; the O-rings are made of Du Pont Viton-A® fluoroelastomer. Assemblies are bakeable to 200°C and usable to 10^{-8} torr. Repeated bakeout can cause deterioration of the O-rings and require their periodic replacement. The fittings are reusable.



Kwik-Flange is a very versatile connection system. Standard fittings and components are available for 1/2", 3/4", 1", 1-1/2", and 2" O.D. tubing. Adapters are available to interface with threaded iron pipe sizes and ultra-high vacuum flanges. Virtually all standard MDC feedthroughs and accessories are available with Kwik-Flange. In addition, Kwik-Flange is compatible with other components designed to the same standard ISO specifications.

A 128-page catalog with Kwik-Flange specifications and prices is available. A sampling of Kwik-Flange fittings and accessories is shown below. MDC Manufacturing, Inc., 23842 Cabot Blvd., Hayward, California 94545, (415) 887-6100.



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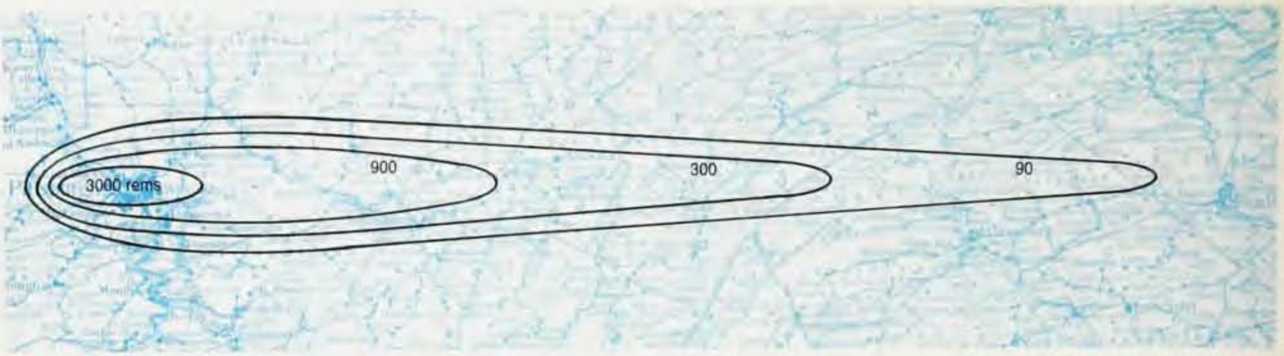


Radiation-dose contour map showing accumulated 7-day exposure following a 1-megaton ground burst. The map assumes a steady wind of 15 mph. The contours indicate the areas receiving 3000, 900, 300 and 90 rems. (Adapted from reference 2.) Figure 5

ple might panic at any symptom of radiation sickness.

After radiation levels had subsided sufficiently, people could leave their shelters and begin efforts at recovery. However, they would be working under extreme duress. Millions of people would be homeless. Many essential commodities, including food, could be in short supply. Fallout would have killed much of the nation's livestock. If the attack had come early in the growing season, much of the crop would have been killed by radiation; if it had come at harvest time, the crop could have been lost because of farmers' inability to harvest it.

Doctors have drawn attention[6] to the high danger of infection and communicable diseases during the recovery period. Resistance to infection would be sharply lowered because of radiation, malnutrition and dehydration during the shelter period, and general exposure and hardship. Poor sanitation, lack of refrigeration, and inadequate waste disposal would encourage the spread of disease. Under such conditions epidemic diseases that have long been under control—cholera, plague, typhoid fever—could reemerge as dangerous threats, and hepatitis, salmonellosis, and other diseases of the intestinal tract are likely to become more prevalent and more deadly. Tuberculosis could also increase dramatically.

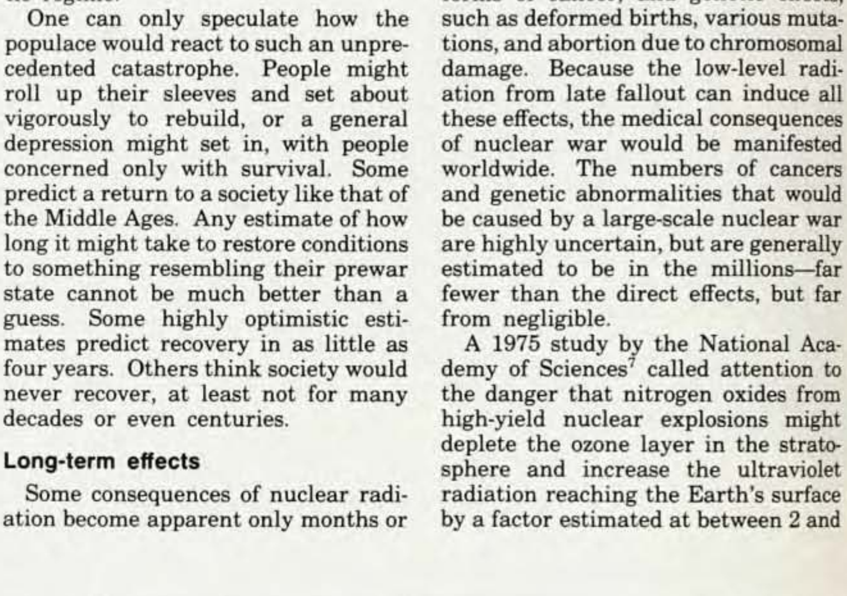
Under such hardships the survivors would have to set about rebuilding and restoring the industrial plant, the communications and transportation networks, and the commercial, medical–scientific, and cultural systems—in short, practically every aspect of the complex US society. Both material and psychological obstacles would confront them. Deficiencies in each component of society would hamper the recovery of the others. The government might be hard put to maintain law and order and to establish and enforce priorities in the recovery effort. Significant changes in the political and social systems might come about. There could be a serious effort to restrict democratic procedures and perhaps even to establish some kind of autocratic regime.

One can only speculate how the populace would react to such an unprecedented catastrophe. People might roll up their sleeves and set about vigorously to rebuild, or a general depression might set in, with people concerned only with survival. Some predict a return to a society like that of the Middle Ages. Any estimate of how long it might take to restore conditions to something resembling their prewar state cannot be much better than a guess. Some highly optimistic estimates predict recovery in as little as four years. Others think society would never recover, at least not for many decades or even centuries.

Long-term effects

Some consequences of nuclear radiation become apparent only months or even years after exposure. These include cataracts, leukemia and other forms of cancer, and genetic effects, such as deformed births, various mutations, and abortion due to chromosomal damage. Because the low-level radiation from late fallout can induce all these effects, the medical consequences of nuclear war would be manifested worldwide. The numbers of cancers and genetic abnormalities that would be caused by a large-scale nuclear war are highly uncertain, but are generally estimated to be in the millions—far fewer than the direct effects, but far from negligible.

A 1975 study by the National Academy of Sciences[7] called attention to the danger that nitrogen oxides from high-yield nuclear explosions might deplete the ozone layer in the stratosphere and increase the ultraviolet radiation reaching the Earth's surface by a factor estimated at between 2 and



Fallout distribution. Map shows areas in the United States that would receive fallout doses of 1000 rems or more in an all-out exchange of strategic nuclear weapons, according to a study by the US Arms Control and Disarmament Agency. Table 3 outlines the effects on human beings. (From reference 5.) Figure 6

100, causing increased skin cancer, severe sunburn, and a variety of potentially harmful ecological effects. The chemistry of the upper atmosphere is complex, and the likely extent of the ozone depletion remains controversial.

Another potential disaster is the deposition of large amounts of smoke in the atmosphere from fires in cities, forests, agricultural lands, and oil and gas fields. A recent study estimates[8] that smoke would reduce the average amount of sunlight reaching the ground in the Northern Hemisphere by a factor of between 2 and 150 for many weeks, perhaps months. This would strongly reduce and perhaps totally eliminate the possibility of growing agricultural crops for an entire season, leading to widespread famine as well as causing a variety of other harmful ecological changes. (See PHYSICS TODAY, October 1982, page 17.)

It is quite possible that there exist other effects of nuclear war, as yet unidentified, that could bring about significant changes, either temporary or irreversible, in the planet's ecology. The ecological system is fragile; it would not take very large changes, for example, to diminish substantially the world food supply. Obviously, one cannot estimate the magnitude of such unknown effects. The likelihood of large but inestimable effects is but another manifestation of the inherent uncertainty in trying to assess the consequences of nuclear war. About the only thing one can predict with certainty is that it would be a disaster of unparalleled dimensions.

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