Nuclear War and Climatic Catastrophe: Some Policy Implications

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NUCLEAR WAR AND CLIMATIC CATASTROPHE: SOME POLICY IMPLICATIONS

It is not even impossible to imagine that the effects of an atomic war fought with greatly perfected weapons and pushed by the utmost determination will endanger the survival of man.

Edward Teller
Bulletin of the Atomic Scientists, February 1947

The extreme danger to mankind inherent in the proposal by [Edward Teller and others to develop thermonuclear weapons] wholly outweighs any military advantage.

J. Robert Oppenheimer, *et al.*
Report of the General Advisory Committee, AEC
October 1949

The fact that no limits exist to the destructiveness of this weapon makes its very existence and the knowledge of its construction a danger to humanity. . . . It is . . . an evil thing.

Enrico Fermi and I. I. Rabi
Addendum, *ibid.*

A very large nuclear war would be a calamity of indescribable proportions and absolutely unpredictable consequences, with the uncertainties tending toward the worse. . . . All-out nuclear war would mean the destruction of contemporary civilization, throw man back centuries, cause the deaths of hundreds of millions or billions of people, and, with a certain degree of probability, would cause man to be destroyed as a biological species . . .

Andrei Sakharov
Foreign Affairs, Summer 1983

Apocalyptic predictions require, to be taken seriously, higher standards of evidence than do assertions on other matters

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where the stakes are not as great. Since the immediate effects of even a single thermonuclear weapon explosion are so devastating, it is natural to assume—even without considering detailed mechanisms—that the more or less simultaneous explosion of ten thousand such weapons all over the Northern Hemisphere might have unpredictable and catastrophic consequences.

And yet, while it is widely accepted that a full nuclear war might mean the end of civilization at least in the Northern Hemisphere, claims that nuclear war might imply a reversion of the human population to prehistoric levels, or even the extinction of the human species, have, among some policymakers at least, been dismissed as alarmist or, worse, irrelevant. Popular works that stress this theme, such as Nevil Shute's *On the Beach,* and Jonathan Schell's *The Fate of the Earth,* have been labeled disreputable. The apocalyptic claims are rejected as unproved and unlikely, and it is judged unwise to frighten the public with doomsday talk when nuclear weapons are needed, we are told, to preserve the peace. But, as the above quotations illustrate, comparably dire warnings have been made by respectable scientists with diverse political inclinations, including many of the American and Soviet physicists who conceived, devised and constructed the world nuclear arsenals.

Part of the resistance to serious consideration of such apocalyptic pronouncements is their necessarily theoretical basis. Understanding the long-term consequences of nuclear war is not a problem amenable to experimental verification—at least not more than once. Another part of the resistance is psychological. Most people—recognizing nuclear war as a grave and terrifying prospect, and nuclear policy as immersed in technical complexities, official secrecy and bureaucratic inertia—tend to practice what psychiatrists call denial: putting the agonizing problem out of our heads, since there seems nothing we can do about it. Even policymakers must feel this temptation from time to time. But for policymakers there is another concern: if it turns out that nuclear war could end our civilization or our species, such a finding might be considered a retroactive rebuke to those responsible, actively or passively, in the past or in the present, for the global nuclear arms race.

The stakes are too high for us to permit any such factors to influence our assessment of the consequences of nuclear war. If nuclear war now seems significantly more catastrophic than has generally been believed in the military and policy communities, then serious consideration of the resulting implications is urgently called for.

It is in that spirit that this article seeks, first, to present a short summary, in lay terms, of the climatic and biological consequences of nuclear war that emerge from extensive scientific studies conducted over the past two years, the essential conclusions of which have now been endorsed by a large number of scientists. These findings were presented in detail at a special conference in Cambridge, Mass., involving almost 100 scientists on April 22–26, 1983, and were publicly announced at a conference in Washington, D.C., on October 31 and November 1, 1983. They have been reported in summary form in the press, and a detailed statement of the findings and their bases will be published in *Science*.[1] The present summary is designed particularly for the lay reader.

Following this summary, I explore the possible strategic and policy implications of the new findings.* They point to one apparently inescapable conclusion: the necessity of moving as rapidly as possible to reduce the global nuclear arsenals below levels that could conceivably cause the kind of climatic catastrophe and cascading biological devastation predicted by the new studies. Such a reduction would have to be to a small percentage of the present global strategic arsenals.

II

The central point of the new findings is that the long-term consequences of a nuclear war could constitute a global climatic catastrophe.

The immediate consequences of a single thermonuclear weapon explosion are well known and well documented—fireball radiation,

[1] R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack and Carl Sagan [TTAPS], "Global Atmospheric Consequences of Nuclear War," *Science*, in press; P. R. Ehrlich, M. A. Harwell, Peter H. Raven, Carl Sagan, G. M. Woodwell, *et al.*, "The Long-Term Biological Consequences of Nuclear War," *Science*, in press.

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This article would not have been possible without the high scientific competence and dedication of my co-authors on the TTAPS study, Richard P. Turco, Owen B. Toon, Thomas P. Ackerman, and James B. Pollack, and my 19 coauthors of the accompanying scientific paper on the long-term biological consequences of nuclear war. Finally, I wish to thank my Soviet colleagues, V. V. Alexandrov, E. I. Chazov, G. S. Golitsyn, and E. P. Velikhov among others, for organizing independent confirmations of the probable existence of a post-nuclear-war climatic catastrophe, and for helping to generate a different kind of climate—one of mutual concern and cooperation that is essential if we are to emerge safely from the trap that our two nations have jointly set for ourselves, our civilization, and our species.

prompt neutrons and gamma rays, blast, and fires.[2] The Hiroshima bomb that killed between 100,000 and 200,000 people was a fission device of about 12 kilotons yield (the explosive equivalent of 12,000 tons of TNT). A modern thermonuclear warhead uses a device something like the Hiroshima bomb as the trigger—the "match" to light the fusion reaction. A typical thermonuclear weapon now has a yield of about 500 kilotons (or 0.5 megatons, a megaton being the explosive equivalent of a million tons of TNT). There are many weapons in the 9 to 20 megaton range in the strategic arsenals of the United States and the Soviet Union today. The highest-yield weapon ever exploded is 58 megatons.

Strategic nuclear weapons are those designed for delivery by ground-based or submarine-launched missiles, or by bombers, to targets in the adversary's homeland. Many weapons with yields roughly equal to that of the Hiroshima bomb are today assigned to "tactical" or "theater" military missions, or are designated "munitions" and relegated to ground-to-air and air-to-air missiles, torpedoes, depth charges and artillery. While strategic weapons often have higher yields than tactical weapons, this is not always the case.[3] Modern tactical or theater missiles (e.g., Pershing II, SS-20) and air support weapons (e.g., those carried by F-15 or MiG-23 aircraft) have sufficient range to make the distinction between "strategic" and "tactical" or "theater" weapons increasingly artificial. Both categories of weapons can be delivered by land-based missiles, sea-based missiles, and aircraft; and by intermediate-range as well as intercontinental delivery systems. Nevertheless, by the usual accounting, there are around 18,000 strategic thermonuclear weapons (warheads) and the equivalent number of fission triggers in the American and Soviet strategic arsenals, with an aggregate yield of about 10,000 megatons.

The total number of nuclear weapons (strategic plus theater and tactical) in the arsenals of the two nations is close to 50,000, with an aggregate yield near 15,000 megatons. For convenience, we here collapse the distinction between strategic and theater weapons, and adopt, under the rubric "strategic," an aggregate yield of 13,000 megatons. The nuclear weapons of the rest of the world—

[2] Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear War*, 3rd ed., Washington: Department of Defense, 1977.

[3] The "tactical" Pershing I, for example, is listed as carrying warheads with yields as high as 400 kilotons, while the "strategic" Poseidon C-3 is listed with a yield of only 40 kilotons. *World Armaments and Disarmament, SIPRI Yearbook 1982*, Stockholm International Peace Research Institute, London: Taylor and Francis, 1982; J. Record, *U.S. Nuclear Weapons in Europe*, Washington: Brookings Institution, 1974.

mainly Britain, France and China—amount to many hundred warheads and a few hundred megatons of additional aggregate yield.

No one knows, of course, how many warheads with what aggregate yield would be detonated in a nuclear war. Because of attacks on strategic aircraft and missiles, and because of technological failures, it is clear that less than the entire world arsenal would be detonated. On the other hand, it is generally accepted, even among most military planners, that a "small" nuclear war would be almost impossible to contain before it escalated to include much of the world arsenals.[4] (Precipitating factors include command and control malfunctions, communications failures, the necessity for instantaneous decisions on the fates of millions, fear, panic and other aspects of real nuclear war fought by real people.) For this reason alone, any serious attempt to examine the possible consequences of nuclear war must place major emphasis on large-scale exchanges in the five-to-seven-thousand-megaton range, and many studies have done so.[5] Many of the effects described below, however, can be triggered by much smaller wars.

The adversary's strategic airfields, missile silos, naval bases, submarines at sea, weapons manufacturing and storage locales, civilian and military command and control centers, attack assessment and early warning facilities, and the like are probable targets ("counterforce attack"). While it is often stated that cities are not targeted "per se," many of the above targets are very near or colocated with cities, especially in Europe. In addition, there is an industrial targeting category ("countervalue attack"). Modern nuclear doctrines require that "war-supporting" facilities be attacked. Many of these facilities are necessarily industrial in nature and engage a work force of considerable size. They are almost always situated near major transportation centers, so that raw materials and finished products can be efficiently transported to other industrial sectors, or to forces in the field. Thus, such facilities are, almost by definition, cities, or near or within cities. Other "war-supporting" targets may include the transportation systems themselves (roads, canals, rivers, railways, civilian airfields, etc.), petroleum refineries, storage sites and pipelines, hydroelectric plants, radio and television trans-

[4] See, e.g., D. Ball, Adelphi Paper 169, London: International Institute for Strategic Studies, 1981; P. Bracken and M. Shubik, in *Technology in Society*, Vol. 4, 1982, p. 155.

[5] National Academy of Sciences/National Research Council, *Long-term Worldwide Effects of Multiple Nuclear Weapons Detonations*, Washington: National Academy of Sciences, 1975; Office of Technology Assessment, *The Effects of Nuclear War*, Washington, 1979; J. Peterson (Ed.), *Nuclear War: The Aftermath*, special issue *Ambio*, Vol. 11, Nos. 2–3, Royal Swedish Academy of Sciences, 1982; R. P. Turco, *et al.*, *loc. cit.* footnote 1; S. Bergstrom, *et al.*, *Effects of Nuclear War on Health and Health Services*, Rome: World Health Organization, Publication No. A36.12, 1983; National Academy of Sciences, new 1983 study in press.

mitters and the like. A major countervalue attack therefore might involve almost all large cities in the United States and the Soviet Union, and possibly most of the large cities in the Northern Hemisphere.[6] There are fewer than 2,500 cities in the world with populations over 100,000 inhabitants, so the devastation of all such cities is well within the means of the world nuclear arsenals.

Recent estimates of the immediate deaths from blast, prompt radiation, and fires in a major exchange in which cities were targeted range from several hundred million to 1.1 billion people—the latter estimate is in a World Health Organization study in which targets were assumed not to be restricted entirely to NATO and Warsaw Pact countries.[7] Serious injuries requiring immediate medical attention (which would be largely unavailable) would be suffered by a comparably large number of people, perhaps an additional 1.1 billion.[8] Thus it is possible that something approaching half the human population on the planet would be killed or seriously injured by the direct effects of the nuclear war. Social disruption; the unavailability of electricity, fuel, transportation, food deliveries, communications and other civil services; the absence of medical care; the decline in sanitation measures; rampant disease and severe psychiatric disorders would doubtless collectively claim a significant number of further victims. But a range of additional effects—some unexpected, some inadequately treated in earlier studies, some uncovered only recently—now make the picture much more somber still.

Because of current limitations on missile accuracy, the destruction of missile silos, command and control facilities, and other hardened sites requires nuclear weapons of fairly high yield exploded as groundbursts or as low airbursts. High-yield groundbursts will vaporize, melt and pulverize the surface at the target area and propel large quantities of condensates and fine dust into the upper troposphere and stratosphere. The particles are chiefly entrained in the rising fireball; some ride up the stem of the mushroom cloud. Most military targets, however, are not very hard. The destruction of cities can be accomplished, as demonstrated at Hiroshima and Nagasaki, by lower-yield explosions less than a kilometer above the surface. Low-yield airbursts over cities or near forests will tend to produce massive fires, some of them over areas of 100,000 square kilometers or more. City fires generate enormous quantities of black oily smoke which rise at least into the upper part of the lower

[6] See, e.g., J. Peterson, *op. cit.* footnote 5.
[7] S. Bergstrom, *op. cit.* footnote 5.
[8] *Ibid.*

atmosphere, or troposphere. If firestorms occur, the smoke column rises vigorously, like the draft in a fireplace, and may carry some of the soot into the lower part of the upper atmosphere, or stratosphere. The smoke from forest and grassland fires would initially be restricted to the lower troposphere.

The fission of the (generally plutonium) trigger in every thermonuclear weapon and the reactions in the (generally uranium-238) casing added as a fission yield "booster" produce a witch's brew of radioactive products, which are also entrained in the cloud. Each such product, or radioisotope, has a characteristic "half-life" (defined as the time to decay to half its original level of radioactivity). Most of the radioisotopes have very short half-lives and decay in hours to days. Particles injected into the stratosphere, mainly by high-yield explosions, fall out very slowly—characteristically in about a year, by which time most of the fission products, even when concentrated, will have decayed to much safer levels. Particles injected into the troposphere by low-yield explosions and fires fall out more rapidly—by gravitational settling, rainout, convection, and other processes—before the radioactivity has decayed to moderately safe levels. Thus rapid fallout of tropospheric radioactive debris tends to produce larger doses of ionizing radiation than does the slower fallout of radioactive particles from the stratosphere.

Nuclear explosions of more than one-megaton yield generate a radiant fireball that rises through the troposphere into the stratosphere. The fireballs from weapons with yields between 100 kilotons and one megaton will partially extend into the stratosphere. The high temperatures in the fireball chemically ignite some of the nitrogen in the air, producing oxides of nitrogen, which in turn chemically attack and destroy the gas ozone in the middle stratosphere. But ozone absorbs the biologically dangerous ultraviolet radiation from the Sun. Thus the partial depletion of the stratospheric ozone layer, or "ozonosphere," by high-yield nuclear explosions will increase the flux of solar ultraviolet radiation at the surface of the Earth (after the soot and dust have settled out). After a nuclear war in which thousands of high-yield weapons are detonated, the increase in biologically dangerous ultraviolet light might be several hundred percent. In the more dangerous shorter wavelengths, larger increases would occur. Nucleic acids and proteins, the fundamental molecules for life on Earth, are especially sensitive to ultraviolet radiation. Thus, an increase of the solar ultraviolet flux at the surface of the Earth is potentially dangerous for life.

These four effects—obscuring smoke in the troposphere, obscuring dust in the stratosphere, the fallout of radioactive debris, and the partial destruction of the ozone layer—constitute the four known principal adverse environmental consequences that occur after a nuclear war is "over." There may be others about which we are still ignorant. The dust and, especially, the dark soot absorb ordinary visible light from the Sun, heating the atmosphere and cooling the Earth's surface.

All four of these effects have been treated in our recent scientific investigation.[9] The study, known from the initials of its authors as TTAPS, for the first time demonstrates that severe and prolonged low temperatures would follow a nuclear war. (The study also explains the fact that no such climatic effects were detected after the detonation of hundreds of megatons during the period of U.S.-Soviet atmospheric testing of nuclear weapons, ended by treaty in 1963: the explosions were sequential over many years, not virtually simultaneous; and, occurring over scrub desert, coral atolls, tundra and wasteland, they set no fires.) The new results have been subjected to detailed scrutiny, and half a dozen confirmatory calculations have now been made. A special panel appointed by the National Academy of Sciences to examine this problem has come to similar conclusions.[10]

Unlike many previous studies, the effects do not seem to be restricted to northern mid-latitudes, where the nuclear exchange would mainly take place. There is now substantial evidence that the heating by sunlight of atmospheric dust and soot over northern mid-latitude targets would profoundly change the global circulation. Fine particles would be transported across the equator in weeks, bringing the cold and the dark to the Southern Hemisphere. (In addition, some studies suggest that over 100 megatons would be dedicated to equatorial and Southern Hemisphere targets, thus generating fine particles locally.)[11] While it would be less cold and less dark at the ground in the Southern Hemisphere than in the Northern, massive climatic and environmental disruptions may be triggered there as well.

In our studies, several dozen different scenarios were chosen, covering a wide range of possible wars, and the range of uncertainty in each key parameter was considered (e.g., to describe how many fine particles are injected into the atmosphere). Five representative cases are shown in Table 1, below, ranging from a small low-yield attack exclusively on cities, utilizing, in yield, only 0.8 percent of the world strategic arsenals, to a massive exchange involving 75

[9] R. P. Turco, *et al.*, *loc. cit.* footnote 1.
[10] National Academy of Sciences, 1983, *loc. cit.* footnote 5.
[11] J. Peterson, *op. cit.* footnote 6.

TABLE 1

NUCLEAR EXCHANGE SCENARIOS

Case	Total Yield (MT)	% Yield Surface Bursts	% Yield Urban or Industrial Targets	Warhead Yield Range (MT)	Total Number of Explosions
1. Baseline Case, countervalue and counterforce[(a)]	5,000	57	20	0.1–10	10,400
11. 3,000 MT nominal, counterforce only[(b)]	3,000	50	0	1 –10	2,250
14. 100 MT nominal, countervalue only[(c)]	100	0	100	0.1	1,000
16. 5000 MT "severe," counterforce only[(b, d)]	5,000	100	0	5 –10	700
17. 10,000 MT "severe," countervalue and counterforce[(c, d)]	10,000	63	15	0.1–10	16,160

a. In the Baseline Case, 12,000 square kilometers of inner cities are burned; on every square centimeter an average of 10 grams of combustibles are burned, and 1.1% of the burned material rises as smoke. Also, 230,000 square kilometers of suburban areas burn, with 1.5 grams consumed at each square centimeter and 3.6% rising as smoke.

b. In this highly conservative case, it is assumed that no smoke emission occurs, that not a blade of grass is burned. Only 25,000 tons of the fine dust is raised into the upper atmosphere for every megaton exploded.

c. In contrast to the Baseline Case, only inner cities burn, but with 10 grams per square centimeter consumed and 3.3% rising as smoke into the high atmosphere.

d. Here, the fine (submicron) dust raised into the upper atmosphere is 150,000 tons per megaton exploded.

percent of the world arsenals. "Nominal" cases assume the most probable parameter choices; "severe" cases assume more adverse parameter choices, but still in the plausible range.

Predicted continental temperatures in the Northern Hemisphere vary after the nuclear war according to the curves shown in Figure 1 on the following page. The high heat-retention capacity of water guarantees that oceanic temperatures will fall at most by a few degrees. Because temperatures are moderated by the adjacent oceans, temperature effects in coastal regions will be less extreme than in continental interiors. The temperatures shown in Figure 1 are average values for Northern Hemisphere land areas.

Even much smaller temperature declines are known to have serious consequences. The explosion of the Tambora volcano in Indonesia in 1815 led to an average global temperature decline of only 1°C, due to the obscuration of sunlight by the fine dust propelled into the stratosphere; yet the hard freezes the following year were so severe that 1816 has been known in Europe and America as "the year without a summer." A 1°C cooling would

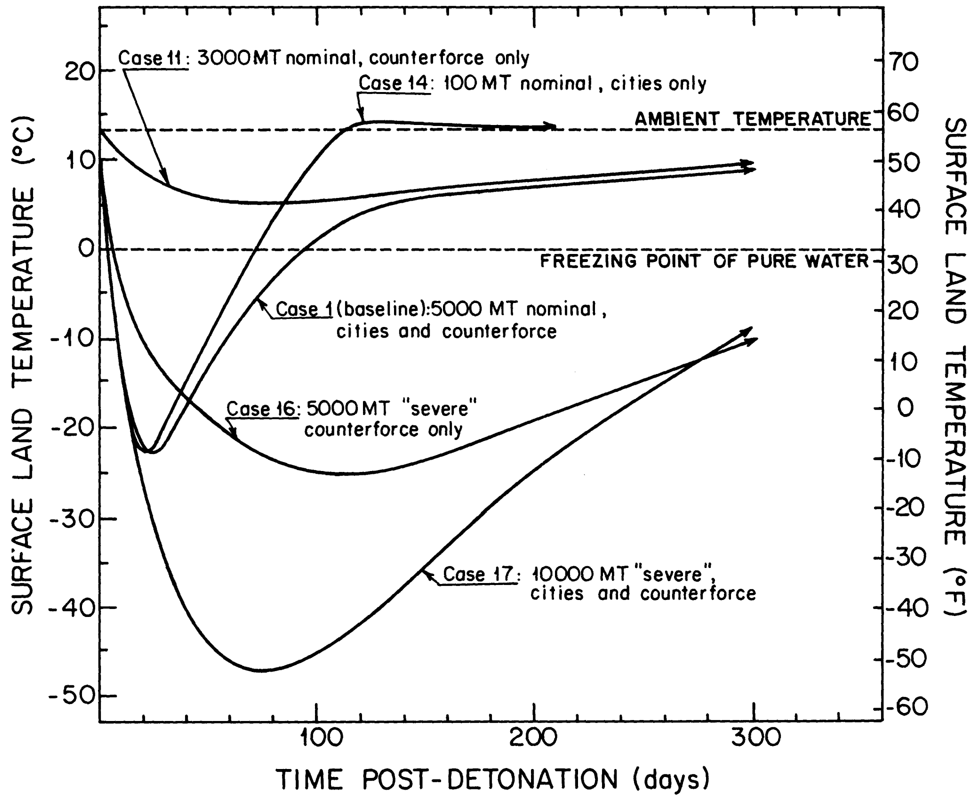


FIGURE 1

TEMPERATURE EFFECTS OF NUCLEAR WAR CASES

NOTE: In this Figure, the average temperature of Northern Hemisphere land areas (away from coastlines) is shown varying with time after the five Cases of nuclear war defined in Table 1. The "ambient" temperature is the average in the Northern Hemisphere over all latitudes and seasons: thus, normal winter temperatures at north temperate latitudes are lower than is shown, and normal tropical temperatures are higher than shown. Cases described as "nominal" assume the most likely values of parameters (such as dust particle size or the frequency of firestorms) that are imperfectly known. Cases marked "severe" represent adverse but not implausible values of these parameters. In Case 14 the curve ends when the temperatures come within a degree of the ambient values. For the four other Cases the curves are shown ending after 300 days, but this is simply because the calculations were not extended further. In these four Cases the curves will continue to the directions they are headed.

nearly eliminate wheat growing in Canada.[12] In the last thousand years, the maximum global or Northern Hemisphere temperature deviations have been around 1°C. In an Ice Age, a typical long-term temperature decline from preexisting conditions is about 10°C. Even the most modest of the cases illustrated in Figure 1 give temporary temperature declines of this order. The Baseline Case is much more adverse. Unlike the situation in an Ice Age, however, the global temperatures after nuclear war plunge rapidly and take only months to a few years to recover, rather than

[12] National Academy of Sciences, 1975, *op. cit.* footnote 5.

thousands of years. No new Ice Age is likely to be induced by a Nuclear Winter.

Because of the obscuration of the Sun, the daytime light levels can fall to a twilit gloom or worse. For more than a week in the northern mid-latitude target zone, it might be much too dark to see, even at midday. In Cases 1 and 14 (Table 1), hemispherically averaged light levels fall to a few percent of normal values, comparable to those at the bottom of a dense overcast. At this illumination, many plants are close to what is called the compensation point, the light level at which photosynthesis can barely keep pace with plant metabolism. In Case 17, illumination, averaged over the entire Northern Hemisphere, falls in daytime to about 0.1 percent of normal, a light level at which plants will not photosynthesize at all. For Cases 1 and especially 17, full recovery to ordinary daylight takes a year or more (Figure 1).

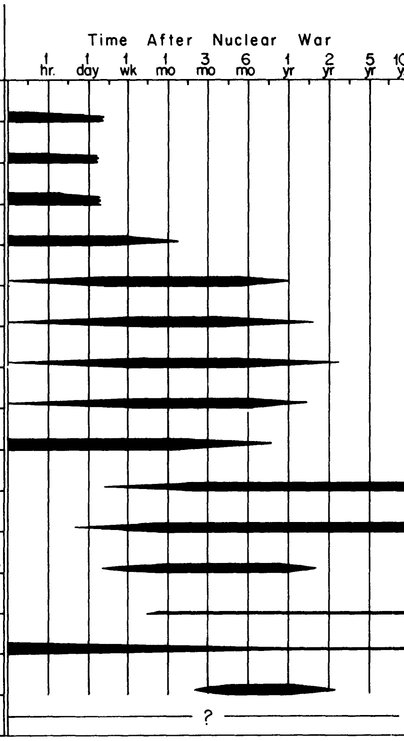
As the fine particles fall out of the atmosphere, carrying radioactivity to the ground, the light levels increase and the surface warms. The depleted ozone layer now permits ultraviolet light to reach the Earth's surface in increased proportions. The relative timing of the multitude of adverse consequences of a nuclear war is shown in Table 2, on the following page.

Perhaps the most striking and unexpected consequence of our study is that even a comparatively small nuclear war can have devastating climatic consequences, provided cities are targeted (see Case 14 in Figure 1; here, the centers of 100 major NATO and Warsaw Pact cities are burning). There is an indication of a very rough threshold at which severe climatic consequences are triggered—around a few hundred nuclear explosions over cities, for smoke generation, or around 2,000 to 3,000 high-yield surface bursts at, e.g., missile silos, for dust generation and ancillary fires. Fine particles can be injected into the atmosphere at increasing rates with only minor effects until these thresholds are crossed. Thereafter, the effects rapidly increase in severity.[13]

As in all calculations of this complexity, there are uncertainties. Some factors tend to work towards more severe or more prolonged effects; others tend to ameliorate the effects.[14] The detailed TTAPS calculations described here are one-dimensional; that is, they assume the fine particles to move vertically by all the appropriate

[13] The climatic threshold for smoke in the troposphere is about 100 million metric tons, injected essentially all at once; for sub-micron fine dust in the stratosphere, about the same.

[14] The slow warming of the Earth due to a CO_2 greenhouse effect attendant to the burning of fossil fuels should not be thought of as tempering the nuclear winter: the greenhouse temperature increments are too small and too slow.



Effect	U.S. / S.U. Population at risk	N.H. Population at risk	S.H. Population at risk	Casualty rate for those at risk	Potential global deaths
Blast	H	M	L	H	M - H
Thermal Radiation	H	M	L	M	M - H
Prompt Ionizing Radiation	L	L	L	H	L - M
Fires	M	M	L	M	M
Toxic Gases	M	M	L	L	L
Dark	H	H	M	L	L
Cold	H	H	H	H	M - H
Frozen Water Supplies	H	H	M	M	M
Fallout Ionizing Radiation	H	H	L - M	M	M - H
Food Shortages	H	H	H	H	H
Medical System Collapse	H	H	M	M	M
Contagious Diseases	M	M	L	H	M
Epidemics and Pandemics	H	H	M	M	M
Psychiatric Disorders	H	H	L	L	L - M
Increased Surface Ultraviolet Light	H	H	M	L	L
Synergisms	?	?	?	?	?

TABLE 2

EFFECTS OF THE BASELINE NUCLEAR WAR

NOTE: This is a schematic representation of the time scale for the effects, which are most severe when the thickness of the horizontal bar is greatest. The columns at the right indicate the degree of risk of the populations of the United States and the Soviet Union, the Northern Hemisphere, and the Southern Hemisphere—with H, M, and L standing for High, Medium, and Low respectively.

laws of physics, but neglect the spreading in latitude and longitude. When soot or dust is moved away from the reference locale, things get better there and worse elsewhere. In addition, fine particles can be transported by weather systems to other locales, where they are carried more rapidly down to the surface. That would ameliorate obscuration not just locally but globally. It is just this transport away from the northern mid-latitudes that involves the equatorial zone and the Southern Hemisphere in the effects of the nuclear war. It would be helpful to perform an accurate three-dimensional calculation on the general atmospheric circulation following a nuclear war. Preliminary estimates suggest that circulation might moderate the low temperatures in the Northern Hemisphere predicted in our calculations by some 30 percent, lessening somewhat the severity of the effects, but still leaving them at catastrophic levels (e.g., a 30°C rather than a 40°C temperature drop). To provide a small margin of safety, we neglect this correction in our subsequent discussion.

There are also effects that tend to make the results much worse: for example, in our calculations we assumed that rainout of fine particles occurred through the entire troposphere. But under realistic circumstances, at least the upper troposphere may be very dry, and any dust or soot carried there initially may take much longer to fall out. There is also a very significant effect deriving from the drastically altered structure of the atmosphere, brought about by the heating of the clouds and the cooling of the surface. This produces a region in which the temperature is approximately constant with altitude in the lower atmosphere and topped by a massive temperature inversion. Particles throughout the atmosphere would then be transported vertically very slowly—as in the present stratosphere. This is a second reason why the lifetime of the clouds of soot and dust may be much longer than we have calculated. If so, the worst of the cold and the dark might be prolonged for considerable periods of time, conceivably for more than a year. We also neglect this effect in subsequent discussion.

Nuclear war scenarios are possible that are much worse than the ones we have presented. For example, if command and control capabilities are lost early in the war—by, say, "decapitation" (an early surprise attack on civilian and military headquarters and communications facilities)—then the war conceivably could be extended for weeks as local commanders make separate and uncoordinated decisions. At least some of the delayed missile launches could be retaliatory strikes against any remaining adversary cities. Generation of an additional smoke pall over a period of weeks or longer following the initiation of the war would extend the magnitude, but especially the duration of the climatic consequences. Or it is possible that more cities and forests would be ignited than we have assumed, or that smoke emissions would be larger, or that a greater fraction of the world arsenals would be committed. Less severe cases are of course possible as well.

These calculations therefore are not, and cannot be, assured prognostications of the full consequences of a nuclear war. Many refinements in them are possible and are being pursued. But there is general agreement on the overall conclusions: in the wake of a nuclear war there is likely to be a period, lasting at least for months, of extreme cold in a radioactive gloom, followed—after the soot and dust fall out—by an extended period of increased ultraviolet light reaching the surface.[15]

We now explore the biological impact of such an assault on the global environment.

III

The immediate human consequences of nuclear explosions range from vaporization of populations near the hypocenter, to blast-generated trauma (from flying glass, falling beams, collapsing skyscrapers and the like), to burns, radiation sickness, shock and severe psychiatric disorders. But our concern here is with longer-term effects.

It is now a commonplace that in the burning of modern tall buildings, more people succumb to toxic gases than to fire. Ignition of many varieties of building materials, insulation and fabrics generates large amounts of such pyrotoxins, including carbon monoxide, cyanides, vinyl chlorides, oxides of nitrogen, ozone, dioxins, and furans. Because of differing practices in the use of such synthetics, the burning of cities in North America and Western Europe will probably generate more pyrotoxins than cities in the Soviet Union, and cities with substantial recent construction more than older, unreconstructed cities. In nuclear war scenarios in which a great many cities are burning, a significant pyrotoxin smog might persist for months. The magnitude of this danger is unknown.

The pyrotoxins, low light levels, radioactive fallout, subsequent ultraviolet light, and especially the cold are together likely to destroy almost all of Northern Hemisphere agriculture, even for the more modest Cases 11 and 14. A 12° to 15°C temperature reduction by itself would eliminate wheat and corn production in the United States, even if all civil systems and agricultural technology were intact.[16] With unavoidable societal disruption, and with the other environmental stresses just mentioned, even a 3,000-megaton "pure" counterforce attack (Case 11) might suffice. Realistically, many fires would be set even in such an attack (see below), and a 3,000-megaton war is likely to wipe out U.S. grain production. This would represent by itself an unprecedented global catastrophe: North American grain is the principal reliable source of export food on the planet, as well as an essential component of U.S. prosperity. Wars just before harvesting of grain and other staples

[15] These results are dependent on important work by a large number of scientists who have previously examined aspects of this subject; many of these workers are acknowledged in the articles cited in footnote 1.

[16] David Pimentel and Mark Sorrells, private communication, 1983.

would be incrementally worse than wars after harvesting. For many scenarios, the effects will extend (see Figure 2) into two or more growing seasons. Widespread fires and subsequent runoff of topsoil are among the many additional deleterious consequences extending for years after the war.

Something like three-quarters of the U.S. population lives in or near cities. In the cities themselves there is, on average, only about one week's supply of food. After a nuclear war it is conceivable that enough of present grain storage might survive to maintain, on some level, the present population for more than a year. But with the breakdown of civil order and transportation systems in the cold, the dark and the fallout, these stores would become largely inaccessible. Vast numbers of survivors would soon starve to death.

In addition, the sub-freezing temperatures imply, in many cases, the unavailability of fresh water. The ground will tend to be frozen to a depth of about a meter—incidentally making it unlikely that the hundreds of millions of dead bodies would be buried, even if the civil organization to do so existed. Fuel stores to melt snow and ice would be in short supply, and ice surfaces and freshly fallen snow would tend to be contaminated by radioactivity and pyrotoxins.

In the presence of excellent medical care, the average value of the acute lethal dose of ionizing radiation for healthy adults is about 450 rads. (As with many other effects, children, the infirm and the elderly tend to be more vulnerable.) Combined with the other assaults on survivors in the postwar environment, and in the probable absence of any significant medical care, the mean lethal acute dose is likely to decline to 350 rads or even lower. For many outdoor scenarios, doses within the fallout plumes that drift hundreds of kilometers downwind of targets are greater than the mean lethal dose. (For a 10,000-megaton war, this is true for more than 30 percent of northern mid-latitude land areas.) Far from targets, intermediate-timescale chronic doses from delayed radioactive fallout may be in excess of 100 rads for the baseline case. These calculations assume no detonations on nuclear reactors or fuel-reprocessing plants, which would increase the dose.

Thus, the combination of acute doses from prompt radioactive fallout, chronic doses from the delayed intermediate-timescale fallout, and internal doses from food and drink are together likely to kill many more by radiation sickness. Because of acute damage to bone marrow, survivors would have significantly increased vulnerability to infectious diseases. Most infants exposed to 100 rads as fetuses in the first two trimesters of pregnancy would suffer mental retardation and/or other serious birth defects. Radiation and some pyrotoxins would later produce neoplastic diseases and genetic damage. Livestock and domesticated animals, with fewer resources, vanishing food supplies and in many cases with greater sensitivity to the stresses of nuclear war than human beings, would also perish in large numbers.

These devastating consequences for humans and for agriculture would not be restricted to the locales in which the war would principally be "fought," but would extend throughout northern mid-latitudes and, with reduced but still significant severity, probably to the tropics and the Southern Hemisphere. The bulk of the world's grain exports originate in northern mid-latitudes. Many nations in the developing as well as the developed world depend on the import of food. Japan, for example, imports 75 percent of its food (and 99 percent of its fuel). Thus, even if there were no climatic and radiation stresses on tropical and Southern Hemisphere societies—many of them already at subsistence levels of nutrition—large numbers of people there would die of starvation.

As agriculture breaks down worldwide (possible initial exceptions might include Argentina, Australia and South Africa if the climatic impact on the Southern Hemisphere proved to be minimal), there will be increasing reliance on natural ecosystems--fruits, tubers, roots, nuts, etc. But wild foodstuffs will also have suffered from the effects of the war. At just the moment that surviving humans turn to the natural environment for the basis of life, that environment would be experiencing a devastation unprecedented in recent geological history.

Two-thirds of all species of plants, animals, and microorganisms on the Earth live within 25° of the equator. Because temperatures tend to vary with the seasons only minimally at tropical latitudes, species there are especially vulnerable to rapid temperature declines. In past major extinction events in the paleontological record, there has been a marked tendency for tropical organisms to show greater vulnerability than organisms living at more temperate latitudes.

The darkness alone may cause a collapse in the aquatic food chain in which sunlight is harvested by phytoplankton, phytoplankton by zooplankton, zooplankton by small fish, small fish by large fish, and, occasionally, large fish by humans. In many nuclear war scenarios, this food chain is likely to collapse at its base for at least a year and is significantly more imperiled in tropical waters. The increase in ultraviolet light available at the surface of the earth approximately a year after the war provides an additional major environmental stress that by itself has been described as having "profound consequences" for aquatic, terrestrial and other ecosystems.[17]

The global ecosystem can be considered an intricately woven fabric composed of threads contributed by the millions of separate species that inhabit the planet and interact with the air, the water and the soil. The system has developed considerable resiliency, so that pulling a single thread is unlikely to unravel the entire fabric. Thus, most ordinary assaults on the biosphere are unlikely to have catastrophic consequences. For example, because of natural small changes in stratospheric ozone abundance, organisms have probably experienced, in the fairly recent geologic past, ten percent fluctuations in the solar near-ultraviolet flux (but not fluctuations by factors of two or more). Similarly, major continental temperature changes of the magnitude and extent addressed here may not have been experienced for tens of thousands and possibly not for millions of years. We have no experimental information, even for aquaria or terraria, on the simultaneous effects of cold, dark, pyrotoxins, ionizing radiation, and ultraviolet light as predicted in the TTAPS study.

Each of these factors, taken separately, may carry serious consequences for the global ecosystem: their interactions may be much more dire still. Extremely worrisome is the possibility of poorly understood or as yet entirely uncontemplated synergisms (where the net consequences of two or more assaults on the environment are much more than the sum of the component parts). For example, more than 100 rads (and possibly more than 200 rads) of external and ingested ionizing radiation is likely to be delivered in a very large nuclear war to all plants, animals and unprotected humans in densely populated regions of northern mid-latitudes. After the soot and dust clear, there can, for such wars, be a 200 to 400 percent increment in the solar ultraviolet flux that reaches the ground, with an increase of many orders of magnitude in the more dangerous shorter-wavelength radiation. Together, these radiation assaults are likely to suppress the immune systems of humans and other species, making them more vulnerable to disease. At the same time, the high ambient-radiation fluxes are likely to produce, through mutation, new varieties of microorganisms, some of which might become pathogenic. The preferential radiation sensitivity of birds and other insect predators would enhance the proliferation of herbivorous and pathogen-carrying insects. Carried by vectors with

[17] C. H. Kruger, R. B. Setlow, *et al.*, *Causes and Effects of Stratospheric Ozone Reduction: An Update*, Washington: National Academy of Sciences, 1982.

high radiation tolerance, it seems possible that epidemics and global pandemics would propagate with no hope of effective mitigation by medical care, even with reduced population sizes and greatly restricted human mobility. Plants, weakened by low temperatures and low light levels, and other animals would likewise be vulnerable to preexisting and newly arisen pathogens.

There are many other conceivable synergisms, all of them still poorly understood because of the complexity of the global ecosystem. Every synergism represents an additional assault, of unknown magnitude, on the global ecosystem and its support functions for humans. What the world would look like after a nuclear war depends in part upon the unknown synergistic interaction of these various adverse effects.

We do not and cannot know that the worst would happen after a nuclear war. Perhaps there is some as yet undiscovered compensating effect or saving grace—although in the past, the overlooked effects in studies of nuclear war have almost always tended toward the worst. But in an uncertain matter of such gravity, it is wise to contemplate the worst, especially when its probability is not extremely small. The summary of the findings of the group of 40 distinguished biologists who met in April 1983 to assess the TTAPS conclusions is worthy of careful consideration:[18]

> Species extinction could be expected for most tropical plants and animals, and for most terrestrial vertebrates of north temperate regions, a large number of plants, and numerous freshwater and some marine organisms. . . . Whether any people would be able to persist for long in the face of highly modified biological communities; novel climates; high levels of radiation; shattered agricultural, social, and economic systems; extraordinary psychological stresses; and a host of other difficulties is open to question. It is clear that the ecosystem effects *alone* resulting from a large-scale thermonuclear war could be enough to destroy the current civilization in at least the Northern Hemisphere. Coupled with the direct casualties of perhaps two billion people, the combined intermediate and long-term effects of nuclear war suggest that eventually there might be no human survivors in the Northern Hemisphere.
>
> Furthermore, the scenario described here is by no means the most severe that could be imagined with present world nuclear arsenals and those contemplated for the near future. In almost any realistic case involving nuclear exchanges between the superpowers, global environmental changes sufficient to cause an extinction event equal to or more severe than that at the close of the Cretaceous when the dinosaurs and many other species died out are likely. In that event, the possibility of the extinction of *Homo sapiens* cannot be excluded.

[18] P. Ehrlich, *et al., loc. cit.* footnote 1.

IV

The foregoing probable consequences of various nuclear war scenarios have implications for doctrine and policy. Some have argued that the difference between the deaths of several hundred million people in a nuclear war (as has been thought until recently to be a reasonable upper limit) and the death of every person on Earth (as now seems possible) is only a matter of one order of magnitude. For me, the difference is considerably greater. Restricting our attention only to those who die as a consequence of the war conceals its full impact.

If we are required to calibrate extinction in numerical terms, I would be sure to include the number of people in future generations who would not be born. A nuclear war imperils all of our descendants, for as long as there will be humans. Even if the population remains static, with an average lifetime of the order of 100 years, over a typical time period for the biological evolution of a successful species (roughly ten million years), we are talking about some 500 trillion people yet to come. By this criterion, the stakes are one million times greater for extinction than for the more modest nuclear wars that kill "only" hundreds of millions of people.

There are many other possible measures of the potential loss—including culture and science, the evolutionary history of the planet, and the significance of the lives of all of our ancestors who contributed to the future of their descendants. Extinction is the undoing of the human enterprise.

For me, the new results on climatic catastrophe raise the stakes of nuclear war enormously. But I recognize that there are those, including some policymakers, who feel that the increased level of fatalities has little impact on policy, but who nevertheless acknowledge that the newly emerging consequences of nuclear war may require changes in specific points of strategic doctrine. I here set down what seem to me some of the more apparent such implications, within the context of present nuclear stockpiles. The idea of a crude threshold, very roughly around 500 to 2,000 warheads, for triggering the climatic catastrophe will be central to some of these considerations. (Such a threshold applies only to something like the present distribution of yields in the strategic arsenals. Drastic conversion to very low-yield arsenals—see below—changes some of the picture dramatically.) I hope others will constructively examine these preliminary thoughts and explore additional implications of the TTAPS results.

1. *First Strike.* The MIRVing of missiles (the introduction of mul-

tiple warheads), improvements in accuracy, and other developments have increased the perceived temptation to launch a devastating first strike against land targets—even though both sides retain a powerful retaliatory force in airborne bombers and submarines at sea. Much current concern and national rhetoric is addressed to the first-strike capability of extant or proposed weapons systems. The mere capability of a first strike creates incentives for a preemptive attack. Launch-on-warning and simultaneous release of all strategic weapons are two of several ominous and destabilizing innovations contrived in response to the fear of a first strike.

The number of U.S. land-based strategic missiles is about 1,050; for the Soviet Union, about 1,400. In addition, each side has at least several dozen dedicated and alternative strategic bomber bases and airstrips, as well as command and control facilities, submarine ports and other prime strategic targets on land. Each target requires—for high probability of its destruction—two or perhaps three attacking warheads. Thus, a convincing first strike against land targets requires at least 2,200 and perhaps as many as 4,500 attacking warheads. Some—for example, to disable bombers that succeed in becoming airborne just before the first strike—would detonate as airbursts. While many missile silos, especially in the United States, are surrounded by farmland and brush, other strategic targets, especially in Europe and Asia, are sufficiently near forests or urban areas for major conflagrations to be set, even in a "pure" counterforce attack. Accordingly, a major first strike would be clearly in the vicinity of, and perhaps well over, the climatic threshold.

A counterforce first strike is unlikely to be completely effective. Perhaps 10 to 40 percent of the adversary's silos and most of its airborne bombers and submarines at sea will survive, and *its* response may not be against silos, but against cities. Ten percent of a 5,000-warhead strategic arsenal is 500 warheads: distributed over cities, this seems by itself enough to trigger a major climatic catastrophe.

Such a first strike scenario, in which the danger to the aggressor nation depends upon the unpredictable response of the attacked nation, seems risky enough. (The hope for the aggressor nation is that its retained second-strike force, including strategic submarines and unlaunched land-based missiles, will intimidate the adversary into surrender rather than provoke it into retaliation.) But the decision to launch a first strike that is tantamount to national suicide for the aggressor—*even if the attacked nation does not lift a finger to retaliate*—is a different circumstance altogether. If a first strike gains no more than a pyrrhic victory of ten days' duration before the prevailing winds carry the nuclear winter to the aggressor nation, the "attractiveness" of the first strike would seem to be diminished significantly.

A Doomsday Machine is useless if the potential adversary is ignorant of its presence.[19] But since many distinguished scientists, both American and Soviet, have participated vigorously in recent studies of the climatic consequences of nuclear war, since there appears to be no significant disagreement in the conclusions, and since policymakers will doubtless be apprised of these new results, it would appear that a decision to launch a major first strike is now much less rational, and therefore, perhaps, much less probable. The better political leaders understand the nuclear winter, the more secure are such conclusions.

If true, this should have cascading consequences for specific weapons systems. Further, the perceived vulnerability to a first strike has been a major source of stress and fear, and thereby a major spur to the nuclear arms race. Knowledge that a first strike is now less probable might make at least some small contribution to dissipating the poisonous atmosphere of mistrust that currently characterizes Soviet-American relations.

2. *Sub-threshold War.* Devastating nuclear wars that are nevertheless significantly below the threshold for severe climatic consequences certainly seem possible—for example, the destruction of 10 or 20 cities, or 100 silos of a particularly destabilizing missile system. Nevertheless, might some nation be tempted to initiate or engage in a much larger, but still reliably sub-threshold nuclear war? The hope might be that the attacked adversary would be reluctant to retaliate for fear of crossing the threshold.

This is not very different from the hope that a counterforce first strike would not be followed by a retaliatory strike, because of the aggressor's retention of an invulnerable (for example, submarine-based) second-strike force adequate to destroy populations and national economies. It suffers the same deficiency—profound uncertainty about the likely response.

The strategic forces of the United States or the Soviet Union—even if they were all at fixed sites—could not be destroyed in a reliably sub-threshold war: there are too many essential targets. Thus, a sub-threshold first strike powerfully provokes the attacked nation and leaves much of its retaliatory force untouched. It is easy to imagine a nation, having contemplated becoming the object of a

[19] The term "Doomsday Machine" is due to Herman Kahn, *Thinking About the Unthinkable,* New York: Horizon Press, 1962.

sub-threshold first strike, planning to respond in kind, because it judges that failure to do so would itself invite attack. Retaliation could occur immediately against a few key cities—if national leaders were restrained and command and control facilities intact—or massively, months later, after much of the dust and smoke have fallen out, extending the duration but ameliorating the severity of the net climatic effects.

This, however, may not be the case for such nations as Britain, France or China. Because of the marked contiguity of strategic targets and urban areas in Europe, the climatic threshold for attacks on European nuclear powers may be significantly less than for the United States or the Soviet Union. Provided it could be accomplished without triggering a U.S.-Soviet nuclear war, first strikes against all the fixed-site strategic forces of one of these nations might not trigger the climatic catastrophe. Nevertheless, the invulnerable retaliatory capability of these nations—especially the ballistic-missile submarines of Britain and France—makes such a first strike unlikely.

3. *Treaties on Yields and Targeting*. I would not include this possibility, except that it has been mentioned publicly by a leading American nuclear strategist. The proposal has two parts. The first is to ban by treaty all nuclear warheads with yields in excess of 300 or 400 kilotons. The fireballs from warheads of higher yields mainly penetrate into the stratosphere and work to deplete the ozonosphere.

The reconversion of nuclear warheads to lower individual yields would reduce (although not remove) the threat of significantly enhanced ultraviolet radiation at the surface of the Earth, but would in itself have no bearing on the issue of climatic catastrophe, and would increase the intermediate-timescale radioactive fallout. Within the present strategic arsenals, there is no mix of yields that simultaneously minimizes ionizing radiation from fallout and ultraviolet radiation from the Sun.

As delivery system accuracy has progressively improved, there has been a corresponding tendency toward the deployment of lower-yield warheads, although not through any concern about the integrity of the ozonosphere. There is also a trend toward higher fission fractions, implying more radioactive fallout. Limitations on the sizes and therefore, to some extent, on the yields of new warheads are part of recent U.S. arms control proposals. With the bulk of Soviet strategic warheads having yields larger than their U.S. counterparts, however, treaties limiting high yields place greater demands on Soviet than on U.S. compliance. Moreover, to enforce a categorical yield ceiling seems to imply verification problems of some difficulty.

The second part of the proposal is to guarantee by treaty that cities would not be targeted. Then the worst of the climatic effects might be avoided, although the climatic consequences of "pure" counterforce exchanges can still be extremely serious (Figure 1). The encoding of targeting coordinates, however, is in principle done remotely, and involves different coordinates for each warhead. Even if we could imagine international inspection teams descending unannounced on Soviet or American missile silos to inspect the targeting coordinates, an hour later the coordinates could be returned to those appropriate for cities.

Targeting policy is among the most sensitive aspects of nuclear strategy, and maintaining uncertainty about targeting policy is thought to be an essential component of U.S. deterrence. The proposal is unlikely to be received warmly by the U.S. Joint Strategic Targeting Staff or its Soviet counterpart. It is also difficult to understand how those skeptical of the verifiability by reconnaissance satellites of SALT II provisions on the deployment of missiles ten meters long can rest easy about verification of treaties controlling what is encoded in a microchip one millimeter long. Nevertheless, a symbolic, unverifiable targeting treaty, entered into because both sides recognize that it is not in their interest to target cities, might have some merit.

4. *Transition to Low-Yield High-Accuracy Arsenals.* A conceivable response to the prospect of climatic catastrophe might be to continue present trends toward lower-yield and higher-accuracy missiles, perhaps accompanied by development of the technology for warheads to burrow sub-surface before detonating. Payloads have been developed for the Pershing II missile that use radar area-correlators for target recognition and terminal guidance; the targeting probable error is said to be 40 meters.[20] It is evident that a technology is gradually emerging that could permit delivery accuracies of 35 meters or better over intercontinental ranges.

It is evident as well that burrowing technology is also under rapid development.[21] A one-kiloton burst, two to three meters sub-surface, will excavate a crater roughly 60 meters across.[22] Clearly, high-accuracy penetrating warheads in the one-to-ten-kiloton range would be able, with high reliability, to destroy even very hardened silos and underground command posts.

[20] *Aviation Week and Space Technology*, May 15, 1978, p. 225.
[21] *Ibid.*
[22] S. Glasstone and P. J. Dolan, *op. cit.* footnote 2.

Low-yield sub-surface explosions of this sort cannot threaten the ozonosphere. They minimize fires, soot, stratospheric dust and radioactive fallout. Even several thousand simultaneous such detonations might not trigger the nuclear winter. Similar technology might be used for pinpoint attacks on military/industrial targets in urban areas. Thus, the TTAPS results will probably lead to calls for further improvements in high-accuracy earth-burrowing warheads.

There are, I think, a number of difficulties with this proposal, as attractive as it seems in a strictly military context. A world in which the nuclear arsenals were completely converted to a relatively small number of burrowing low-yield warheads would be much safer in terms of the climatic catastrophe. But such warheads are provocative. They are the perfect post-TTAPS first-strike weapon. Their development might well be taken as a serious interest in making a climatically safe but disabling first strike. Greatly expanded deployment of anti-ballistic missiles might be one consequence of their buildup.

Retaliation from surviving silos, aircraft and especially submarines, as discussed above, is likely, whatever the disposition of yields in a first strike. Also, arsenals cannot be converted instantaneously. There would be a very dangerous and protracted transition period in which enough newer weapons are deployed to be destabilizing, and enough older weapons are still in place to trigger the nuclear winter.

However, if the inventories of modern higher-yield (more than ten kiloton) warheads were first brought below threshold, a coordinated U.S.-Soviet deployment of low-yield burrowers might be accomplished in somewhat greater safety. On many launchers, each with a single warhead, they might provide a useful reassurance to defense ministries at some points in the transition process. At any rate, the dramatic reduction of arsenals necessary to go below threshold before large-scale burrower deployment is indistinguishable from major arms reduction for its own sake (see below).

5. *Consequences for the Developing World*. Before the TTAPS calculations were performed, it was possible to argue that the developing world would be severely affected by secondary economic consequences, but not fundamentally destroyed by a northern mid-latitude nuclear war. Now it seems more likely that nations having no part in the conflict—even nations entirely neutral in the global confrontation between the United States and the Soviet Union—might be reduced to prehistoric population levels and economies, or worse. Nations between 70°N and 30°S, nations with marginal economies, nations with large food imports or extensive malnutri-

tion today, and nations with their own strategic targets are particularly at risk.

Thus, the very survival of nations distant from any likely nuclear conflict can now be seen to depend on the prudence and wisdom of the major nuclear powers. India, Brazil, Nigeria or Saudi Arabia could collapse in a nuclear war without a single bomb being dropped on their territories.[23]

Quite apart from any concern about the deflection of world financial, technical and intellectual resources to the nuclear arms race, the prospect of nuclear war now clearly and visibly threatens every nation and every person on the planet. The diplomatic and economic pressure accordingly placed on the five nuclear powers by the other nations of the world, concerned about their own survival, could be at least marginally significant.

6. *Shelters.* The usual sorts of shelters envisioned for civilian populations are ineffective even for the nuclear war consequences known before the TTAPS study. The more ambitious among them include food and water for a week or two, modest heating capabilities, rudimentary sanitary and air filtration facilities and no provisions for the psychological burdens of an extended stay below ground with unknown climatic and ecological consequences propagating overhead. The kinds of shelters suitable for prolonged subfreezing temperatures, high radiation doses, and pyrotoxins would have to be very much more elaborate—quite apart from the question of what good it would be to emerge six or nine months later to an ultraviolet-bathed and biologically depauperate surface, with insect pests proliferating, disease rampant, and the basis of agriculture destroyed.

Appropriate shelters, able to service individual families or family groups for months to a year, are too expensive for most families even in the affluent West. The construction of major government shelters for civilian populations would be enormously expensive as well as in itself potentially destabilizing. The prospect of the climatic catastrophe also heightens the perceived inequity between government leaders and (in some cases) their families, provided elaborate shelters, and the bulk of the civilian population, unable to afford even a minimally adequate shelter.

[23] The distribution of the coldest regions will vary with time and geography. In one recent but still very crude three-dimensional simulation of the nuclear winter, the temperature has, by 40 days after the war, dropped by 15 to more than 40 centigrade degrees over much of the globe, including a vast region extending from Chad to Novosibirsk, from the Caspian Sea to Sri Lanka, embracing India, Pakistan and western China, and having its most severe effects in Afghanistan, Iran and Saudi Arabia. V. V. Alexandrov and G. L. Stenchikov, preprint, Computing Center, U.S.S.R. Academy of Sciences, Moscow, 1983.

But even if it were possible to build perfectly effective shelters for the entire populations of the United States and the Soviet Union, this would in no way address the danger to which the rest of the world would be put. Shelters for the combatant nations under circumstances in which only their citizens are threatened are one thing. Shelters for the combatant nations when gravely threatened noncombatant nations have only rudimentary or nonexistent shelters are a very different matter.

7. *Ballistic-Missile Defense Systems*. It might be argued that the prospect of a climatic catastrophe strengthens whatever arguments there may be for ground-based or space-based ballistic missile defense (BMD) systems, as proposed by President Reagan in his March 23, 1983 "Star Wars" speech. There are grave technical, cost and policy difficulties with such proposals.[24] Even advocates do not envision it being fully operational in less than two or three decades.

Optimistic informed estimates of porosity or "penetrance" (the fraction of attacking missiles successfully detonating at their targets despite the BMD) are no lower than 5 to 30 percent. The present world arsenal of strategic warheads is so much greater than the threshold for climatic catastrophe that, even if 5 to 30 percent of attacking missiles get through in something like a full exchange, the catastrophe could be triggered. And most competent estimates put the porosity—at least for the foreseeable future—at 50 percent to 99 percent. Further, one likely response to an adversary's anticipated deployment of BMD systems would be a proportionate increase in the stockpiles of offensive warheads in compensation.

There are three phases in the trajectories of incoming missiles when they might be attacked: boost phase, midcourse phase, and terminal phase. Boost-phase and midcourse interception would, at best, require an untried technology deployed at scales never before attempted. Only terminal-phase BMDs exist at the present time (anti-ballistic missiles or ABMs), and even they, ineffective as they are, may require ruinous capital investments before they can provide meaningful levels of defense. Developments in terminal-phase maneuverability of attacking warheads are likely to raise the price tag of an effective BMD sharply again. Even in the best of circumstances, offense will be more effective and less costly than defense.

Finally, terminal-phase interception, generally effective only for hard-target defense, is characteristically designed to occur at very

[24] Richard Garwin, testimony before the Subcommittee on International Security and Scientific Affairs of the House Committee on Foreign Affairs, U.S. Congress, November 10. 1983; Hans Bethe, manuscript in preparation.

low altitudes. There would be an advantage to the offense if it fused the incoming missiles so they would explode if attacked ("sympathetic detonation"). In some schemes, the BMD itself involves nuclear warheads exploded near the ground. A fair fraction of hard targets, especially in Europe and the Soviet Union, are within a few tens of kilometers of cities or forests. Thus, the most readily deployable BMD suffers the disability, when it works at all, of generating fires contributory to a climatic catastrophe, quite apart from its porosity.

8. *Other Possibilities.* There are a number of other conceivable responses to the climatic catastrophe, some even more desperate than those discussed above. For example, a nation might relocate its silos and mobile launchers (the latter inviting barrage attack) to cities and forests to guarantee that a barely adequate counterforce first strike by its adversary would trigger a global climatic catastrophe with high confidence. Or nations with small nuclear arsenals or marginal strategic capability might contemplate amassing a threshold arsenal of some 500 to 2,000 deliverable warheads in order to be taken seriously in "great power" politics.

But these and similar contrivances increase the probability of nuclear war or the dangers attendant to nuclear war sufficiently that they are likely to be rejected by the nation contemplating such moves or, failing that, by other nations. Major relocations of strategic weapons systems or the deployment of new strategic arsenals are readily detectable by national technical means.

V

None of the foregoing possible strategic and policy responses to the prospect of a nuclear war-triggered climatic catastrophe seem adequate even for the security of the nuclear powers, much less for the rest of the world. The prospect reinforces, in the short run, the standard arguments for strategic confidence-building, especially between the United States and the Soviet Union; for tempering puerile rhetoric; for resisting the temptation to demonize the adversary; for reducing the likelihood of strategic confrontations arising from accident or miscalculation; for stabilizing old and new weapons systems—for example, by de-MIRVing missiles; for abandoning nuclear-war-fighting strategies and mistrusting the possibility of "containment" of a tactical or limited nuclear war; for considering safe unilateral steps, such as the retiring of some old weapons systems with very high-yield warheads; for improving communications at all levels, especially among general staffs and between heads of governments; and for public declarations of relevant policy changes. The United States might also contemplate ratification of SALT II and of the 1948 U.N. Convention on the Prevention and Punishment of the Crime of Genocide (ratified by 92 nations, including the Soviet Union).

Both nations might consider abandoning apocalyptic threats and doctrines. To the extent that these are not credible, they undermine deterrence; to the extent that they are credible, they set in motion events that tend toward apocalyptic conclusions.

In the long run, the prospect of climatic catastrophe raises real questions about what is meant by national and international security. To me, it seems clear that the species is in grave danger at least until the world arsenals are reduced below the threshold for climatic catastrophe; the nations and the global civilization would remain vulnerable even at lower inventories. It may even be that, now, the only credible arsenal is below threshold. George Kennan's celebrated proposal[25] to reduce the world arsenals initially to 50 percent of their current numbers is recognized as hard enough to implement. But it would be only the first step toward what is now clearly and urgently needed—a more than 90-percent reduction (Kennan proposed an ultimate reduction of more than 84 percent—adequate for strategic deterrence, if that is considered essential, but unlikely to trigger the nuclear winter. Still further reductions could then be contemplated.

The detonation of weapons stockpiles near or above threshold would be, we can now recognize, in contravention of the 1977 Geneva Convention on The Hostile Use of Environmental Modification Techniques, signed by 48 nations and duly ratified by the Soviet Union and the United States.[26] And Article 6 of the 1968 Nuclear Non-Proliferation Treaty requires the United States and the Soviet Union, among other signatory states, "to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament. . . ." I do not imagine that these treaties can, by themselves, play a determining role in producing major reductions in the world strategic arsenals, but they establish some sense of international

[25] George F. Kennan, "The Only Way Out of the Nuclear Nightmare," *Manchester Guardian Weekly*, May 31, 1981. This is Kennan's acceptance speech for the Albert Einstein Peace Prize on May 19, 1981, in Washington, D.C.

[26] Article 1, paragraph 1, states: "Each State Party to this Convention undertakes not to engage in military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage, or injury to another State Party." Paragraph 2 goes on: "Each State Party to this Convention undertakes not to assist, encourage or induce any State, group of States or international organization to engage in activities contrary to the provisions of paragraph 1 . . ."

obligation and can at least expedite urgent bilateral and multilateral consultations.

VI

We have, by slow and imperceptible steps, been constructing a Doomsday Machine. Until recently—and then, only by accident—no one even noticed. And we have distributed its triggers all over the Northern Hemisphere. Every American and Soviet leader since 1945 has made critical decisions regarding nuclear war in total ignorance of the climatic catastrophe. Perhaps this knowledge would have moderated the subsequent course of world events and, especially, the nuclear arms race. Today, at least, we have no excuse for failing to factor the catastrophe into long-term decisions on strategic policy.

Since it is the soot produced by urban fires that is the most sensitive trigger of the climatic catastrophe, and since such fires can be ignited even by low-yield strategic weapons, it appears that the most critical ready index of the world nuclear arsenals, in terms of climatic change, may be the total *number* of strategic warheads. (There is some dependence on yield, to be sure, and future very low-yield, high-accuracy burrowing warheads could destroy strategic targets without triggering the nuclear winter, as discussed above.) For other purposes there are other indices—numbers of submarine-launched warheads, throw-weight (net payload deliverable to target), total megatonnage, etc. From different choices of such indices, different conclusions about strategic parity can be drawn. In the total number of strategic warheads, however, the United States is "ahead" of the Soviet Union and always has been.

Very roughly, the level of the world strategic arsenals necessary to induce the climatic catastrophe seems to be somewhere around 500 to 2,000 warheads—an estimate that may be somewhat high for airbursts over cities, and somewhat low for high-yield groundbursts. The intrinsic uncertainty in this number is itself of strategic importance, and prudent policy would assume a value below the low end of the plausible range.

National or global inventories above this rough threshold move the world arsenals into a region that might be called the "Doomsday Zone." If the world arsenals were well below this rough threshold, no concatenation of computer malfunction, carelessness, unauthorized acts, communications failure, miscalculation and madness in high office could unleash the nuclear winter. When global arsenals are above the threshold, such a catastrophe is at least possible. The further above threshold we are, the more likely it is that a major exchange would trigger the climatic catastrophe.

Traditional belief and childhood experience teach that more weapons buy more security. But since the advent of nuclear weapons and the acquisition of a capacity for "overkill," the possibility has arisen that, past a certain point, more nuclear weapons do not increase national security. I wish here to suggest that, beyond the climatic threshold, an increase in the number of strategic weapons leads to a pronounced *decline* in national (and global) security. National security is not a zero-sum game. Strategic insecurity of one adversary almost always means strategic insecurity for the other. Conventional pre-1945 wisdom, no matter how deeply felt, is not an adequate guide in an age of apocalyptic weapons.

If we are content with world inventories above the threshold, we are saying that it is safe to trust the fate of our global civilization and perhaps our species to all leaders, civilian and military, of all present and future major nuclear powers; and to the command and control efficiency and technical reliability in those nations now and in the indefinite future. For myself, I would far rather have a world in which the climatic catastrophe cannot happen, independent of the vicissitudes of leaders, institutions and machines. This seems to me elementary planetary hygiene, as well as elementary patriotism.

Something like a thousand warheads (or a few hundred megatons) is of the same order as the arsenals that were publicly announced in the 1950s and 1960s as an unmistakable strategic deterrent, and as sufficient to destroy either the United States or the Soviet Union "irrecoverably." Considerably smaller arsenals would, with present improvements in accuracy and reliability, probably suffice. Thus it is possible to contemplate a world in which the global strategic arsenals are below threshold, where mutual deterrence is in effect to discourage the use of those surviving warheads, and where, in the unhappy event that some warheads are detonated, there is little likelihood of the climatic catastrophe.[27]

To achieve so dramatic a decline in the global arsenals will require not only heroic measures by both the United States and the Soviet Union—it will also require consistent action by Britain, France and China, especially when the U.S. and Soviet arsenals are significantly reduced. Currently proposed increments in the arsenals at least of France would bring that nation's warhead inventory near or above threshold. I have already remarked on the strategic instability, in

[27] Since higher-yield tactical warheads can also be used to burn cities, and might do so inadvertently, especially in Europe, provision for their elimination should also eventually be made. But initial attention should be directed to strategic warheads and their delivery systems.

the context of the climatic catastrophe only, of the warhead inventories of these nations. But if major cuts in the U.S. and Soviet arsenals were under way, it is not too much to hope that the other major powers would, after negotiations, follow suit. These considerations also underscore the danger of nuclear weapons proliferation to other nations, especially when the major inventories are in steep decline.

Figure 2, on the following page, illustrates the growth of the American and Soviet strategic inventories from 1945 to the present.[28] To minimize confusion in the Figure, the British, French and Chinese arsenals are not shown; they are, however, as just mentioned, significant on the new scale of climatically dangerous arsenals. We see from the Figure that the United States passed the Doomsday Threshold around 1953, and the Soviet Union not until about 1966. The largest disparity in the arsenals was in 1961 (a difference of some 6,000 warheads). At the present time the disparity is less than it has been in any year since 1955. A published extrapolation of the present strategic arsenals into 1985 is shown as dashed, nearly vertical lines, accommodating new U.S. (Pershing II, cruise, MX and Trident) and Soviet (SS-21, -22, -23) strategic systems. If these extrapolations are valid, the United States and the Soviet Union would have almost identical numbers of inventories by the late 1980s.

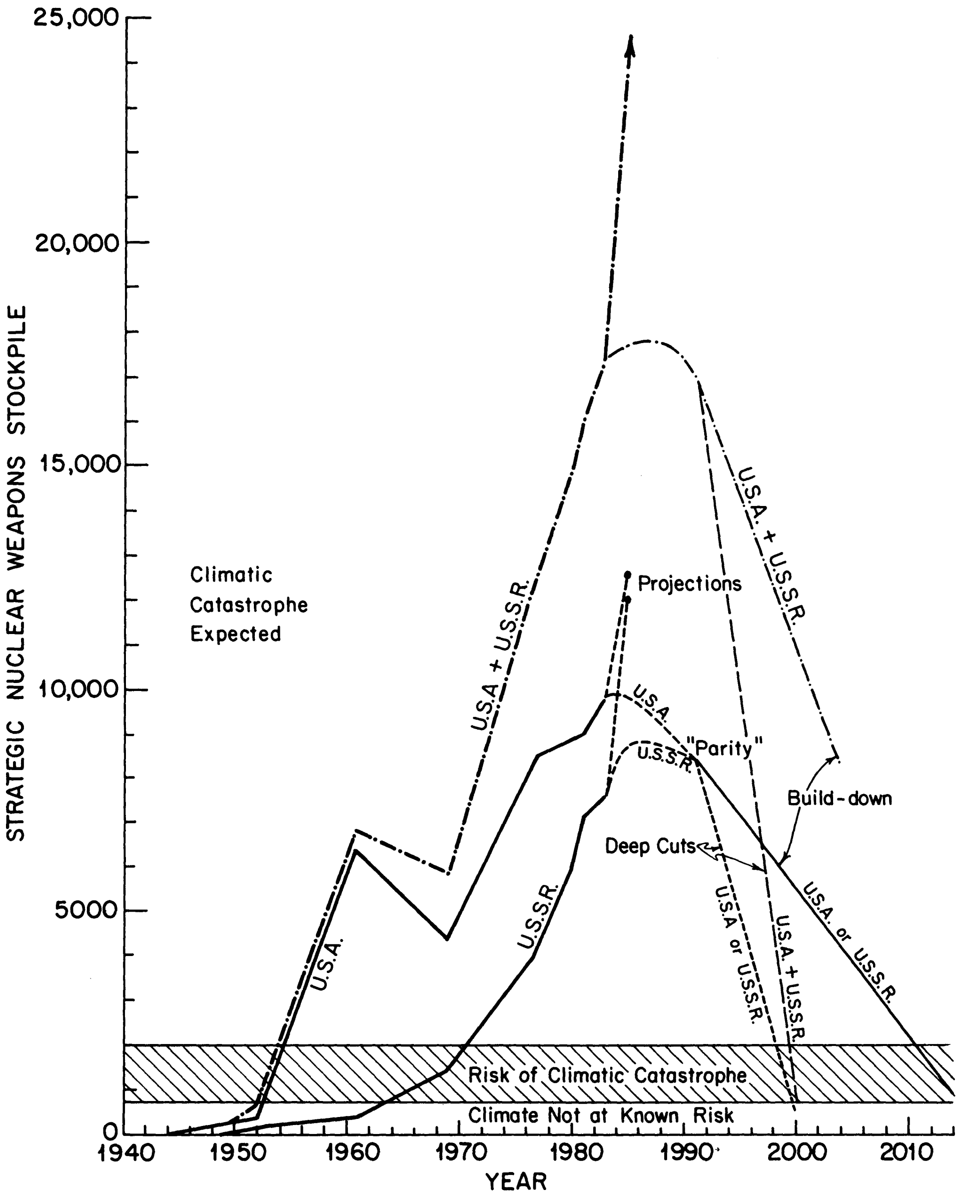
The uppermost (dash-dot) curve in Figure 2 shows the total U.S. and Soviet arsenals (essentially the world arsenals) climbing upward since about 1970 with a very steep slope, the slope steepening still more if the projection is valid. Such exponential or near-exponential runaways are expected in arms races where each side's rate of growth is proportional to its perception of the adversary's weapons inventory; but it is likewise clear that such rapid growth cannot

[28] The total warheads calculated in Figure 2 include strategic and theater weapons, but not tactical weapons. Not all published sources are in perfect agreement on these numbers. The principal sources used here are the *Report of the Secretary of Defense [Harold Brown] to the Congress on the FY 1982 Budget, FY 1983 Authorization Request* and *FY 1986 Defense Programs*, Washington: Department of Defense, 1981; and *National Defense Budget Estimates, FY 1983*, Office of the Assistant Secretary of Defense, Comptroller, March 1982.

Beyond 1983, projected increases in arsenals are shown for U.S. and Soviet arsenals as nearly vertical dashed lines, with the sum of these arsenals as the line at the top of the Figure terminating in an arrowhead. The data are from Frank Barnaby in the special issue of *Ambio* cited in footnote 5, pp. 76–83. See also *Counterforce Issues for the U.S. Strategic Nuclear Forces*, Congressional Budget Office, January 1978.

Figure 2 shows three regions: an upper region in which the nuclear winter could almost certainly be triggered; a lower region at which it could not be triggered; and a transition zone, shown shaded. The boundaries of this transition zone are more uncertain than shown, and depend among other things on targeting strategy. But the threshold probably lies between several hundred and a few thousand contempory strategic weapons.

FIGURE 2
PAST AND FUTURE NUCLEAR STOCKPILES



continue indefinitely. In all natural and human systems, such steep growth rates are eventually stopped, often catastrophically.

It is widely agreed—although different people have different justifications for this conclusion—that world arsenals must be reduced significantly. There is also general agreement, with a few demurrers, that at least the early and middle stages of a significant decline can be verified by national technical means and other procedures. The first stage of major arms reduction will have to overcome a new source of reluctance, when almost all silos could be reliably destroyed in a sub-threshold first strike. To overcome this reluctance, both sides will have prudently maintained an invulnerable retaliatory force, which itself would later move to sub-threshold levels. (It would even be advantageous to each nation to provide certain assistance in the development of such a force by the other.)

As arsenals are reduced still further, the fine tuning of the continuing decline may have to be worked out very carefully and with additional safeguards to guarantee continuing rough strategic parity. As threshold inventories are approached, some verifiable upper limits on yields as well as numbers would have to be worked out, to minimize the burning of cities if a nuclear conflict erupted. On the other hand, the deceleration of the arms race would have an inertia of its own, as the acceleration does; and successful first steps would create a climate conducive to subsequent steps.

There are three proposals now prominently discussed in the United States: Nuclear Freeze, Build-Down, and Deep Cuts. Their possible effects are diagrammed in Figure 2. They are by no means mutually exclusive, nor do they exhaust the possible approaches. A negotiated Freeze would at least prevent the continuing upward escalation in stockpiles, would forestall the deployment of more destabilizing systems, and would probably be accompanied by agreement on immediate annual phased reductions (the curved lines in the middle to late 1980s in Figure 2). To reduce the perceived temptation for a first strike, de-MIRVing of missiles during arms reduction may be essential.

The most commonly cited method of following the Freeze with reductions is incorporated in the Kennedy-Hatfield Freeze Resolution: percentage reductions. Under this approach, the two sides would agree on a percentage—often quoted as being between five percent and ten percent—and would agree to decrease deployed warheads by that percentage annually. The percentage reduction method was proposed to the Soviet Union by the United States at the Vienna Summit in June 1979 and was to be applied to the limits and sub-limits of the SALT II accords until these reached a reduction of 50 percent.

The Build-Down proposal is one in which modernization is permitted, but each side must pay a price in additional reductions of warheads for each warhead mounted on a modernized missile. In many current versions of the proposal, it would also require both sides to decrease their total warhead inventories by about five percent a year (again, the percentage annual reduction approach), to ensure that at least some reductions would take place even if modernization did not. The rate of decline for Build-Down illustrated in Figure 2 is essentially that of Representative Albert Gore (D.-Tenn.), in which rough parity at 8,500 warheads each is adopted as a goal for 1991–92, and the levels are reduced to 6,500 warheads each by 1997.[29]

There is concern that the "modernization" of strategic systems that Build-Down encourages might open the door to still more destabilizing weapons. It is also by no means clear that all proponents of Build-Down envision further reductions below the interim goal of about 5,000 warheads each for the United States and Soviet Union. If this rate of Build-Down continued indefinitely, the two nations would not cross back below threshold until about the year 2020. As dramatic a change from the present circumstances as this represents, in light of the present global crisis, it is, I think, too leisurely a pace.

Deep Cuts, originally advocated by George Kennan and Noel Gayler[30] as an initial halving of the global arsenals in some relatively short period of time, proposes the turning in of the fission triggers of thermonuclear weapons, deployed or undeployed, to a binational or multinational authority, with the triggers subsequently gainfully consumed in nuclear power plants (the ultimate in beating swords into plowshares). A highly schematic curve for something like Deep Cuts is also shown in Figure 2, starting from Gore's assumption of parity by 1991–92. Halving of the present global arsenals would then occur around 1995, and the global arsenals would return to below the Doomsday Threshold by the year 2000.

The actual shape of these declining curves would very likely have kinks and wiggles in them to accommodate the details of a bilaterally—and eventually multilaterally—agreed-upon plan to reduce the arsenals without compromising the security of any of the nuclear powers. The Deep Cuts curve shown has a rate of decline only

[29] *Congressional Record*, August 4, 1983, Vol. 129, No. 114.

[30] George F. Kennan, *loc. cit.* footnote 24; Noel Gayler, "How to Break the Momentum of the Nuclear Arms Race," *The New York Times Magazine*, April 25, 1982.

about as steep as the rate of rise beginning in 1970. Much steeper declines may be feasible and should be considered.

No one contends it will be easy to reverse the nuclear arms race. It is required at least for the same reasons that were used to justify the arms race in the first place—the national security of the United States and the Soviet Union. It is necessarily an enterprise of great magnitude. John Stuart Mill said: "Against a great evil, a small remedy does not produce a small result. It produces no result at all." But if the same technical ingenuity, dedication and resources were devoted to the downward slopes in Figure 2 as to the upward slopes, there is no reason to doubt that it could be negotiated safely.

In the deployment of more stabilizing weapons systems, in the possible development—especially in later stages of arms reductions—of novel means of treaty verification, and (perhaps) in the augmentation of conventional armaments, it will, of course, be expensive.

But, given the stakes, a prudent nuclear power should be willing to spend more every year to defuse the arms race and prevent nuclear war than it does on all military preparedness. For comparison, in the United States the annual budget of the Department of Defense is about 10,000 times that of the Arms Control and Disarmament Agency, quite apart from any questions about the dedication and effectiveness of the ACDA. The equivalent disparity is even greater in many other nations. I believe that the technical side of guaranteeing a major multilateral and strategically secure global arms reduction can be devised and deployed for considerably less—perhaps even a factor of 100 less—than the planet's direct military expenditures of $540 billion per year.[31]

Such figures give some feeling for the chasm that separates a prudent policy in face of our present knowledge of nuclear war from the actual present policies of the nuclear powers. Likewise, nations far removed from the conflict, even nations with little or no investment in the quarrels among the nuclear powers, stand to be destroyed in a nuclear war, rather than benefiting from the mutual annihilation of the superpowers.. They too, one might think, would be wise to devote considerable resources to help ensure that nuclear war does not break out.

VII

In summary, cold, dark, radioactivity, pyrotoxins and ultraviolet light following a nuclear war—including some scenarios involving

[31] Ruth Leger Sivard, *World Military and Social Expenditures*, Leesburg (Va.): World Priorities, 1983.

only a small fraction of the world strategic arsenals—would imperil every survivor on the planet. There is a real danger of the extinction of humanity. A threshold exists at which the climatic catastrophe could be triggered, very roughly around 500–2,000 strategic warheads. A major first strike may be an act of national suicide, even if no retaliation occurs. Given the magnitude of the potential loss, no policy declarations and no mechanical safeguards can adequately guarantee the safety of the human species. No national rivalry or ideological confrontation justifies putting the species at risk. Accordingly, there is a critical need for safe and verifiable reductions of the world strategic inventories to below threshold. At such levels, still adequate for deterrence, at least the worst could not happen should a nuclear war break out.

National security policies that seem prudent or even successful during a term of office or a tour of duty may work to endanger national—and global—security over longer periods of time. In many respects it is just such short-term thinking that is responsible for the present world crisis. The looming prospect of the climatic catastrophe makes short-term thinking even more dangerous. The past has been the enemy of the present, and the present the enemy of the future.

The problem cries out for an ecumenical perspective that rises above cant, doctrine and mutual recrimination, however apparently justified, and that at least partly transcends parochial fealties in time and space. What is urgently required is a coherent, mutually agreed upon, long-term policy for dramatic reductions in nuclear armaments, and a deep commitment, embracing decades, to carry it out.

Our talent, while imperfect, to foresee the future consequences of our present actions and to change our course appropriately is a hallmark of the human species, and one of the chief reasons for our success over the past million years. Our future depends entirely on how quickly and how broadly we can refine this talent. We should plan for and cherish our fragile world as we do our children and our grandchildren: there will be no other place for them to live. It is nowhere ordained that we must remain in bondage to nuclear weapons.