On minimizing the consequences of nuclear war

from Carl Sagan

The likely long-term global consequences of nuclear war remain catastrophic, despite attempts to minimize the dangers.

A FULL-SCALE nuclear war would be an unprecedented human catastrophe. But because we have no direct experience of such a war, the consequences and the policy implications must to some extent be uncertain. After an initial indication that soot from nuclear fires might provide significant atmospheric opacity[1], recent calculations (refs 2, 3 and subsequent investigations) have shown that the soot and dust attendant on nuclear war could, under many contingencies, cool and darken the Earth, with devastating global biological consequences[4]. This climatic catastrophe is called nuclear winter.

We believe our calculations[2,3] to be a valid first-order assessment, although further research is needed to reduce uncertainties. We know of no factors that significantly and reliably reduce the possibility of grave worldwide climatic effects after a large-scale nuclear war. A survey by the US National Academy of Sciences[5] concludes that there is a "clear possibility" both of "severe" consequences and of effects "that would be greater than, and would last longer than, that estimated in the baseline case". It is also possible that uncertainties might ameliorate the baseline climatic catastrophe. A study, by a committee appointed by the Royal Society of Canada[46], concludes "we believe nuclear winter to be a formidable threat" and its analyses "tend to confirm that a drastic cooling will occur in the wake of a major nuclear war". An extensive analysis by a committee of the International Council of Scientific Unions[49] concludes "There is a considerable probability a major nuclear war could gravely disrupt the global environment and world society."

Because these results and their implications for policy and doctrine[6] are at considerable variance with the prevailing wisdom, it is natural and healthy that competent criticism be aired. However, in parallel with an inclination in the popular literature to exaggerate the consequences of nuclear war, there has also been a tendency in many professional pronouncements to down-play the consequences, a tendency which has been noted (and not only with respect to nuclear war) in the risk-assessment literature[45].

In a recent *Nature* article[7]; in *The Reader's Digest*[8] and in testimony before the Committee on Science and Technology of the US House of Representatives[9], Edward Teller has demonstrated a dangerous propensity to minimize or ignore the consequences of nuclear war. He concludes that radioactive fallout, depletion of the protective ozone layer, and nuclear winter following a major nuclear war have all been "exaggerated". He artificially divides the total problem into small pieces[4], and then pronounces each piece "manageable".

Fallout

Teller concludes that fallout is "far less important than originally feared". Unaccountably he does not deal with the prompt fallout that would contaminate large areas of the target zones and adjacent territory in a nuclear war, eventually causing at least tens of millions of civilian fatalities[10]. In a major nuclear war, 30 per cent of Northern mid-latitude land areas, where the majority of people live, could receive fallout burdens approaching or exceeding the acute mean lethal dose for unprotected populations[2,3]. By any standard, such effects would seem worthy of note.

On an intermediate timescale, still more widespread radioactive fallout would, over the years, cause further millions of cases of cancer and birth defects among the survivors of a nuclear war[11] and would produce serious effects synergistic with other consequences of nuclear war[4]. Teller says that the "best current calculations" from the Livermore weapons laboratory[12] indicate average long-term mid-latitude doses of about 20 rem, provided nuclear reactors, fuel reprocessing plants and spent fuel storage facilities are not targeted. But these calculations (still unpublished in a refereed journal) are based on relatively simple empirical scaling from nuclear test explosions, few of which were of a yield, or in a location, corresponding to a realistic war situation.

We independently[2,3] used a microphysical model to predict likely radiation doses two to three times larger than did the Livermore study, with the same exclusion of nuclear power facilities. Neither model is entirely suited to this problem, but we must at least consider that the plausible range of such average long-term doses is 20 to 50 rem, at least an order of magnitude greater than the conventional wisdom, from which Teller did not, until recently, dissent. Both calculations also assume a fission yield fraction of 0.5, when smaller modern warheads may have fission yield fractions closer to 1.0.

Considering the other multiplicative factors quoted by Teller and by us[2,3] (for 'hotspots' and concurrent internal doses), plus the computational factors mentioned, which increase the dose range by factors of 2.5 to 5, it seems clear that long-term radiation exposure could be much more serious than Teller assumes. The radiation dose would be still larger if more than 5,000 MT were detonated (more than twice this yield exists in the current strategic arsenals) or if nuclear fuel processing and storage sites were attacked, which is not unlikely in a major nuclear war.

When delivered acute whole-body doses exceed about 100 rem, the human immune system begins to be compromised; when coupled with other assaults on people and their environment occasioned by nuclear warfare, such doses can have extremely serious implications[4]. Nevertheless, prompt radioactive fallout, in almost every case, presents the more serious threat to mid-latitude populations. But fallout on an intermediate timescale could produce serious, unpredictable and continuing morbidity worldwide and for generations to come.

It is thus simply untrue that fallout is "far less important than originally feared". Fallout, not taken properly into account when nuclear weapons were first designed, began to be studied seriously only after the Bravo test of the Castle series at Bikini on 1 March 1954, which accidentally contaminated (with doses in excess of 100 rem) the atoll of Rongelap in the Marshall Islands, and the Japanese fishing vessel *The Lucky Dragon*. Although some work on fallout was done as early as the Trinity Test in 1945[14], not until Castle Bravo was there extensive public discussion of the issue, eventually contributing to the 1963 Limited Test Ban Treaty.

Ozonosphere depletion

On the effects of nuclear explosions on the ozone layer, it is misleading merely to compare the widespread systematic decreases in ozone caused by massive NO_x injections in a nuclear war with the natural fluctuations and latitudinal variations observed in the ambient ozone layer. Such fluctuations would be superimposed on a decrease by several tens of per cent caused by a large nuclear war.[3] Here, as in other long-term consequences of nuclear war, it is important to distinguish between mean values and maximum excursions, both in time and in space. After a major nuclear war, average ultraviolet-B intensity would be increased above background by several factors for years, almost everywhere[2,3]. Ecosystems are generally adapted to local ultraviolet fluxes, and serious damage can result from a sudden increase in exposure on this scale[15].

Teller states that there are comparatively few nuclear weapons of yield sufficient to lift NO_x high enough to cause ozone depletion. At mid-latitudes, the fireball from a 100 KT explosion will just penetrate the lower stratosphere. Most strategic warheads deployed and planned by both nuclear alliances have warheads exceeding 100 KT and, especially when gravity bombs are included, span the rough yield range from 100 KT to 1 MT (with some older weapons ranging an order of magnitude higher and some submarine-launched ballistic missile warheads a factor $\simeq 2$ lower)[16,17]. Teller overlooks the reinforcing effects of multiple nuclear explosions (such as from two or three bursts in rapid succession over one missile silo, with perhaps 100–200 MT detonated over a silo complex) in propelling nuclear debris to high altitudes, and the possibility of large-scale firestorm injection into the stratosphere. For these reasons, the present and future potential for ozonosphere depletion must continue to be monitored as an important secondary effect of nuclear weapons. It is noteworthy that the threat to the ozonosphere from nuclear weapons was first publicly identified not by those working on the development of nuclear weapons but by those studying an apparently unrelated problem, the effluents from proposed supersonic transport aircraft[18].

Dust

Teller invokes a still classified Livermore report, with no designation number, on the climatic effects of dust. Perhaps the report alluded to is an early analysis of the dust mass in nuclear clouds from test explosions, recently released by the cited authors as an informal and unclassified Livermore publication[19] (and which does not mention climatic effects at all).

Teller told the US House of Representatives committee[9] that, after assuming the directorship of the Lawrence Livermore National Laboratory in 1958, and after having been "troubled" by the possible climatic effects of dust "for decades before the publication of the ... report" (ref. 3), he initiated an early computer study: "Without that, ... all this discussion could not have taken place." In fact, none of the recent studies, and certainly none of our results, arise from these investigations, once again unpublished in refereed scientific journals. That during this period the US government was ignorant of the climatic consequences of nuclear war is made clear by the manner in which this topic is overlooked in the official study "*An assessment of frequently neglected effects of nuclear attacks*" prepared in 1978 and recently declassified[20]. Moreover, there is no record of Teller having spoken publicly about such climatic effects before 1982.

Teller's assertions that "dust raised by a large-scale war is comparable with that produced in the largest volcanic eruptions" and that the "most probable conclusion is that the ... effects of dust would be noticeable but by no means severe on a hemispheric scale" have no quantitative foundation, and fly in the face of contrary evidence. Again, Teller divorces dust effects from all other simultaneous effects. Even isolated volcanic eruptions have been associated with striking weather anomalies, crop failures and significant human suffering. Through changes in the planetary albedo and general circulation, dust can have major climatic consequences[2,3].

Tests with chemical explosives are not a reliable basis for nuclear dust calculations. Unlike their chemical counterparts, nuclear explosions attain such great temperatures and pressures that vaporized and melted surface material contributes in a major way to the generation of fine dust particles (smaller than several micrometres in radius), and the steep thermal gradients can produce effects (such as 'popcorning') essentially unknown in chemical explosions. Tests of high explosives may, however, tell us something about the ejecta and sweep-up components of dust clouds, and place lower limits on these components in nuclear explosions. Multi-burst phenomena are also likely to augment dust production and injection heights over those expected from individual non-interacting explosions.

Smoke

Descriptions of severe climatic effects caused by smoke and dust in a nuclear war are based on detailed energy-balance calculations, including a parametric treatment of important three-dimensional processes. In our calculations, we did not 'assume' large smoke emissions, but calculated them using data from the fire and civil defence literature. We selected the most probable values of key input parameters and considered likely variations of each parameter from that choice. Generally speaking, our climatic results, for almost fifty different cases, fall within a broad range of plausible outcomes that vary from significant to grave. The results remain within this range as key physical parameters describing dust and smoke production and their properties are varied over their intervals of uncertainty. In this sense, the results can be described as 'robust' (we do not insist on the term), although not 'conclusive' or 'proved'. Compared with our predictions, including our allowances for the thermal inertia of the oceans, the actual after-effects of a full-scale nuclear war are as likely to be more as less severe. Moreover, even small-scale nuclear wars may produce major climatic effects, on at least hemispheric scales, provided cities are targeted[2,3]. Wind transport of dense smoke patches and streamers can produce "quick freezes" in distant localities very soon after the explosions[21].

To mitigate nuclear winter, Teller seems to be invoking a meteorological miracle, involving various speculative 'abnormal mechanisms'. He mentions the importance of the water vapour budget of the atmosphere. But we explicitly accounted for water cycling and scavenging by precipitation in our calculations of smoke lifetime, employing the conservative assumption that smoke is efficiently scavenged, which may not be true. Up to 50 per cent of all smoke was taken to be removed in immediate black rain. There is therefore no evidence that the water issue raised by Teller is more important than already allowed for in our calculations.

Capping clouds. One of Teller's arguments is that capping clouds will form above large fires, accelerating smoke removal. But such clouds do not occur over all fires; their occurrence depends on the local meteorology. It is not even clear that smoke particles contained in a capping cloud are removed from the atmosphere; micrometre-sized cloud particles are different from millimetre-sized precipitation particles. L. Radke observed a capping cloud over a prescribed forest burn in 1978[5], and by good chance measured the smoke properties in two dissimilar air parcels within the plume: one parcel had passed through the capping cloud, the other had not. In the cloud-processed smoke, the concentration of the smallest particles, ≤ 0.05 μm radius, was less by a factor of about 10 than in the free-drifting smoke, but the total smoke mass was comparable in both parcels. The larger particles were similar in number, and the measured optical scattering coefficients were essentially indistinguishable. In other words the processed and unprocessed smokes would have nearly equal climatic impact. (The Stokes-Cunningham fall velocities of these smoke particles are entirely negligible.) Downwind of wild-fires, the submicrometre smoke particle size distributions are usually very similar[22,23], which further suggests that cloud processing is not significant in the average case.

Washout in storms. We made separate climate calculations for ocean and land environments, using knowledge of ocean/continent wind patterns and the normal climate to estimate the ameliorating effects of the oceans on land temperatures[2,3]. Thus, while we did not perform a three-dimensional calculation, the mean effects of oceans were approximately included "in a quantitative manner". Our estimates were later supported by Livermore[24], NCAR[21,26,47], Los Alamos[48] and Soviet[25,26] two- and three-dimensional calculations for similar conditions. (The important Livermore calculations unfortunately remain unpublished in refereed journals.) The ameliorating effect of oceanic temperature must, of course, be limited; otherwise natural winters would not occur every year. While storms at ocean/continent margins would remove some of the lower-level smoke, they would also carry some to higher altitudes. Further work is needed on initial and subsequent removal rates and on the height of the stabilized smoke cloud.

Teller's speculation that smoke removal might be self-accelerating is unsound. Satellite photographs of fire plumes[27] typically show smooth and rapid dispersion over many hundreds of kilometres, with no indication of induced turbulence and washout. Furthermore, enhanced spreading and stabilization of dark oil fire plumes have been observed[28].

Smoke nucleation. The nucleating ability of smoke particles depends on their origin. In forest fires, where induced winds are expected to lift quantities of ash, char and soil debris, a substantial fraction of the particles (around 10 per cent) may act as water condensation nuclei[29]. However, in an oil fire plume without extraneous contaminating particle sources, there appears to be no significant increase of nuclei concentration over background[30]. There is also substantial observational evidence that fire plumes do not enhance, and may indeed suppress, rain formation in cane field fires[31], forest fires[29] and oil fires[30].

The origins of the black rains at Hiroshima and Nagasaki have not been unambiguously determined, although the phenomenon is clearly related to the large fires. Recent fire plume simulations based on detailed cloud physics models[32] suggest that smoke rainout may not be as frequent or as efficient as has been inferred from the anecdotal accounts at Hiroshima, or as was assumed in our calculations. A range of recent studies, presented at a Defense Nuclear Agency Conference on Large-Scale Fire Phenomenology (National Bureau of Standards, 10–13 September 1984), suggests that intense urban firestorms can propel tens of per cent of fine soot particles to high altitudes. (See also ref. 32.) Solar radiative heating of low-altitude soot can also propel it to even higher altitudes, where the residence time is approximately one year, and the coverage can rapidly become global.[3,48] These are additional respects in which the calculations in ref. 3 may be conservative.

Teller's mechanism for smoke removal depends on at least two unsupported contentions:

(1) that turbulent coastal weather can wash out a significant fraction of nuclear smoke before it can be widely dispersed; and

(2) that smoke clouds tend to become more patchy, not less, as they disperse through the atmosphere, which is contradicted by direct observations of pollutant tracers.

Urban smoke estimates. Broyles[33], the Livermore consultant whose estimates of urban smoke emission are cited by Teller, relies heavily on forest fire data, and does not review the urban fire literature or discuss smoke emissions characteristic of urban materials and conflagrations. Thus "proper modifications" for the urban case have not all been made. For example, Broyles, in his analysis, adopts smoke emission factors ranging from 0.1 per cent to 6.3 per cent, but the lower value is clearly inapplicable to cities, with their fossil fuel stocks and plastics. Accordingly, it is likely that Broyles' lower limit to smoke emission of 15 Tg (incidentally, not a strict limit) greatly understates the problem. However, even 10 Tg of sooty smoke, uniformly distributed, could decrease the average amount of sunlight reaching the Earth by one-third. Moreover, because of the necessarily uneven burning and restricted ventilation of large fires, more smoke than expected may be produced; experimental data show that restricted air flow greatly increases smoke generation[34].

Assessments of the quantities of "fuels" available in urban areas have been made by several groups[3,35,36]. These assessments are all in general agreement, although more detailed information is clearly needed. Teller notes that 150 Tg of "fuel" is available at US oil refineries[37]. However—including refineries throughout North America, the Soviet Union, Europe and the Middle East, as well as fuels in storage at transit nodes in urban areas, processed flammables in tankage, warehouses and transport, and such end products in use as roofing, paving and plastics—the actual figure for available fossil fuels and products seems to be ten times Teller's figure, or some 1,500 Tg (refs 5, 36). US strategic oil reserves in underground salt domes amount to about 80 Tg (the reserves are currently about one-half full). In some cases, the oil is close enough to the surface to pool and burn within a weapons-generated crater[38].

While Teller agrees that 10 per cent of the fossil fuel compounds would be converted to smoke when burned, some 60 per cent or more of the smoke would consist of soot with large absorption coefficients in the visible, not the 10 per cent he assumes[39,40]. Hence, Teller's estimate of potential soot emission from fossil-based fuels alone is low by a factor of some $10 \times 6 = 60$. A total petroleum-derived soot emission of 90 Tg is possible if major urban/industrial areas are attacked—sufficient to reduce average direct global sunlight intensities to 4% of ambient.

Realistically, absorbing and scattering particles from sources other than petroleum should also be included in the calculations. Urban combustibles (for example wood, paper, cloth, paint, household chemicals, rubber and synthetic fibres) could, we calculate, release another 10 to 100 Tg of smoke. Wildfires ignited by nuclear explosions over forest and grasslands could emit anywhere from 0 to 50 Tg of smoke. Dust would also be generated by surface nuclear detonations; attacks on hard military targets might add 10 to 100 Tg of fine scattering particles to the upper atmosphere. Powerful convective winds over fires could raise urban debris (for example, masonry dust, metal smoke, fine ash) in large quantities. In summary, it does not seem difficult, in a wide range of nuclear war scenarios, to loft sufficient sooty smoke and dust to initiate major climatic effects—especially if cities are burned.

It is also worth mentioning that explosions and fires in urban/industrial areas would release, suddenly, large quantities of toxic chemicals (pyrotoxins) into the atmosphere[2,3]. This problem remains to be fully quantified, and could provide the next departure from the conventional wisdom in studies of the consequences of nuclear war.

In his Congressional testimony, Teller[9] asserted "If you reduce the smoke by a factor of two, then instead of a temperature decrease which is sizeable, you get temperature changes which are in some cases negative, in some cases positive ... The calculations so far ... seem to show that about one-half of the smoke assumed in the paper of Turco and others, about one-half the smoke is already below the threshold [for significant climatic effects]. Now if somebody is dedicated to exaggeration, we can't stop him." In fact, as long as the smoke is injected into the upper troposphere, the abundance can be one-tenth that in our baseline case[3], or around 20 Tg, and serious climatic consequences, of at least hemispheric scale, will still follow. Regional-scale effects are likely with even smaller soot loadings.

New weapons

Teller claims that, because of a trend towards more accurate lower-yield weapons, collateral damage, ozonosphere depletion, fires and nuclear winter will, in the future, be much less likely to occur; and also that ballistic missile defence would further reduce the threat of fires and smoke. But most new strategic weapons deployments in the next decade or two will apparently involve warheads in the 100 KT to 1 MT range[16,17]. A 100 KT airburst can destroy up to 50 km^2. Weapons of this yield, used against industrial areas, are the ideal incendiary devices for adjacent or co-located cities; they have a quick thermal pulse, and do not produce large areas of deep rubble. Thus, the reconfiguration of nuclear arsenals now underway may be, inadvertently, a move towards a more effective stockpile of nuclear weapons for burning cities and triggering nuclear winter—unless it is accompanied by a dramatic reduction in the strategic arsenals. In addition, the Minuteman III and SS-18 missiles, with their 300 to 600 KT warheads, are likely to be with us for some time to come.

It is extremely shortsighted to assume that defensive measures against ballistic missiles will not stimulate new offensive deployments. Effective defence systems are not technically feasible or even designed, could not be deployed for decades, and when deployed would be vulnerable to direct attack, to underflying (for example, by aircraft and cruise missiles) and to relatively simple countermeasures[41–44]. The cities—and therefore the entire Northern Hemisphere, at least—will remain in serious jeopardy for the foreseeable future. It is not apparent that the peril can be significantly reduced without a major reversal of the nuclear arms race. Other reasons that low-yield weapons and strategic defence are unlikely to resolve the issues raised by nuclear winter are discussed elsewhere[6].

Teller's conclusions

Here, while Teller reiterates some of his arguments, he concludes, nevertheless, that severe climatic perturbations *could* occur after a nuclear war, threatening world populations. The only solution that he puts forward is to store food for survivors in the United States and some other (unspecified) nations.

Teller writes, "Highly speculative theories of world-wide destruction—even the end of life on Earth—used as a call for a particular kind of political action serve neither the good reputation of science nor dispassionate political thought." But, before it was widely known that there were dangers from fallout, or from ozonosphere depletion, or from climatic effects, we were not being warned that the alleged *absence* of widespread or long-term effects was speculative, or that the consequences of nuclear war might be more severe than asserted by those responsible for national policy and many of their scientific advisers. However, when a range of scientific evidence suggests that these effects are real, with grave biological and social consequences, then Teller comes forth to minimize the possible consequences, reminding us that not all the evidence is in. This, I suggest, is a clear double standard of scientific evidence at work. Teller's attempt to minimize the widespread and long-term consequences of nuclear war has in fact made possible "a particular kind of political action"—namely, the accession of ever-increasing numbers of weapons of mass destruction, beyond any military utility, and far beyond the requirements of strategic deterrence.

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Carl Sagan is at the Laboratory for Planetary Sciences, Cornell University, Ithaca, New York 14853-0355, USA.

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