File: NAS

Interdepartmental letterhead

Mail Station L

Ext:

December 18, 1984

MEMORANDUM

TO: Nuclear Winter or Global Effects Distribution

FROM: J. B. Knox J.B. Knox

SUBJECT: The Prepared Release Statement from the NAS Study -- "The Effects on the Atmosphere of a Major Nuclear Exchange."

— This is opening chapter of report.

During my visit to Washington (the week of December 11), one of our sponsors had acquired the prepared release that was given to each person attending the NAS briefing regarding their new report. I am circulating the release to you on this date in that it may be useful to you while you await the full report. Mike MacCracken assures me that there are several copies on order, so that we will all have a chance to read it. From my comments in the margin, one can gather that it is my belief the report could have been better. However, I am relieved that the NAS report is as good as it is. I believe that the uncertainties regarding the emissions from forest and urban fires were deemphasized a bit; the fact that these uncertainties may be larger than those from early microphysics, coagulation, and scavenging did not come out.

JBK:clm

Global Effects Distribution:
L. R. Anspaugh, L-453
G. F. Bing, L-19
L. C. Haselman, L-35
S-W. Kang, L-390
J. B. Knox
C. E. Leith, L-13
F. M. Luther, L-262
M. C. MacCracken, L-262
M. M. May, L-19
C. R. Molenkamp, L-262
J. H. Nuckolls, L-295
J. E. Penner, L-71
R. F. Perret, L-81
W. M. Porch, L-262
J. H. Shinn, L-524
C. B. Tarter, L-295
E. Teller, L-4

University of California
Lawrence Livermore National Laboratory

The Effects on the Atmosphere of a Major Nuclear Exchange

Committee on the Atmospheric Effects of Nuclear Explosions

Commission on Physical Sciences, Mathematics, and Resources

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1985

NATIONAL RESEARCH COUNCIL

2101 CONSTITUTION AVENUE WASHINGTON, D. C. 20418

OFFICE OF THE CHAIRMAN

In early 1983, the Department of Defense asked us to assess information on the possible atmospheric effects of nuclear war. We formed a committee of specialists from relevant fields to conduct the assessment. This is the committee's final report.

Nuclear war would have catastrophic effects beyond those that might degrade the earth's atmosphere; thus our committee examined only one part of a large and complex issue. And even within this part the committee was asked to focus only on effects on the atmosphere and not to carry the analysis to the next logical step: the consequences of changes in the atmosphere for life on earth. This is an issue that should and will be addressed.

The committee has admirably performed a task that proved even more difficult than we had anticipated. We had appreciated the difficulty of examining the scientific aspects of a subject that--for understandable reasons--provokes strong emotional reactions. An equally formidable task, however, was that of coping with profound gaps in existing knowledge. The unfortunate but unavoidable fact is that, even though we are 40 years into the nuclear age, much of the basic information needed to assess the likelihood and extent of global atmospheric consequences of a nuclear exchange simply does not exist. As a result, the committee has been unable to provide the simple, unqualified finding that we all might wish to have in order to assure that any nation's decisions about nuclear forces are not made in ignorance of their true consequences.

Under these conditions the committee determined it could best serve by summarizing existing knowledge, by drawing the partial conclusions (with necessary qualifications) that are supported by data, by clearly describing the nature and extent of uncertainties, and by indicating where those uncertainties might be reduced through further research.

Because additional knowledge might well alter our current understanding, the report can only be viewed as an interim statement. Nevertheless, we believe it can help the scientific community and the world's governments advance the time when we can adequately answer a question of surpassing international importance.

Frank Press

Frank Press
Chairman

Committee on the Atmospheric Effects of Nuclear Explosions

GEORGE F. CARRIER, Division of Applied Sciences, Harvard University, Cambridge, [illegible]achusetts; Chairman
[illegible]AM J. MORAN, Vice Admiral USN (Ret.), Los Altos, California; Vice Chairman
[illegible] W. BIRKS, Department of Chemistry, University of Colorado, Boulder, Colorado
ROBERT W. DECKER, U.S. Geological Survey, Menlo Park, California
DOUGLAS M. EARDLEY, Institute for Theoretical Physics, University of California, Santa Barbara, California
JAMES P. FRIEND, Department of Chemistry, Drexel University, Philadelphia, Pennsylvania
ERIC M. JONES, Los Alamos National Laboratory, Los Alamos, New Mexico
JONATHAN I. KATZ, Department of Physics, Washington University, St. Louis, Missouri
SPURGEON M. KEENY, JR., National Academy of Sciences, Washington, D.C.
CONWAY B. LEOVY, Department of Atmospheric Sciences and Graduate Program in Geophysics, University of Washington, Seattle, Washington
CONRAD L. LONGMIRE, Mission Research Corporation, Santa Barbara, Califor[illegible]
MICHAEL B. McELROY, Harvard Center for Earth and Planetary Physics, Harvard University, Cambridge, Massachusetts
WILLIAM PRESS, Department of Astronomy, Harvard College Observatory, Cambridge, Massachusetts
[illegible]CK P. RUINA, Department of Electrical Engineering, Massachusetts Institute of Technology, [illegible]bridge, Massachusetts
[illegible]NE M. SHOEMAKER, U.S. Geological Survey, Flagstaff, Arizona
[illegible]ERING SMITH, Vice Admiral USN (Ret.), San Diego, California
O. BRIAN TOON, Ames Research Center, NASA, Moffett Field, California
RICHARD P. TURCO, R&D Associates, Marina del Rey, California

Staff

LAWRENCE E. McCRAY
PEGGY POWERS

Contents

1
Summary and Conclusions

The Committee on the Atmospheric Effects of Nuclear Explosions addressed the following charge: (1) determine the manner in which the atmosphere of the earth would be modified by a major exchange of nuclear weapons and, insofar as the current state of knowledge and understanding permits, give a quantitative description of the more important of the changes, and (2) recommend research and exploratory work appropriate to a better understanding of the question.

The committee was not asked to (and did not) address the related but distinct questions of the extent of radioactive fallout or the biological or social implications of postwar atmospheric modification.

Recent calculations by different investigators suggest that the climatic effects from a major nuclear exchange could be large in scale. Although there are enormous uncertainties involved in the calculations, the committee believes that long-term climatic effects with severe implications for the biosphere could occur, and these effects should be included in any analysis of the consequences of nuclear war. However, the committee cannot subscribe with confidence to any specific quantitative conclusions drawn from calculations based on current scientific knowledge. The estimates are necessarily rough and can only be used as a general indication of the seriousness of what might occur.

Despite the early state of understanding of these matters, the possibility of severe degradation of the atmosphere after a major nuclear exchange is of sufficient national and international concern that a major effort to narrow the scientific uncertainties should be given a high priority.

BACKGROUND

It is widely understood that any major nuclear exchange would be accompanied by an enormous number of immediate fatalities; nevertheless, a much larger fraction of the human population would survive the immediate effects of a nuclear exchange. This study addresses current knowledge about the nature of the physical environment the survivors would have to face.

The realization that a nuclear exchange would be accompanied by the deposition into the atmosphere of large amounts of particulate matter is not new. However, the suggestion that the associated attenuation of sunlight might be so extensive as to cause severe drops in surface air temperatures and other major climatic effects in areas that are far removed from target zones is of rather recent origin. That perception has grown out of a number of recent investigations. Crutzen and Birks (1982) recognized that the amount of smoke from the fires ignited by nuclear blasts could be of crucial importance, and Alvarez et al. (1980) hypothesized that the massive species extinctions of 65 million years ago were part of the aftermath of the lofting of massive quantities of particulates resulting from the collision of a large meteor with the earth. Others have recognized the similarity between the Alvarez dust hypothesis and the effects of nuclear war (see Appendix).

The consequences of any such changes in atmospheric state would have to be added to the already sobering list of relatively well-understood consequences of nuclear war, including prompt radiation, blast, and thermal effects, short-term regional radioactive fallout, inadequate medical attention for surviving [illegible], and the long-term biological effects of global fa[illegible]spheric consequences imply additional problems that [illegible] mitigated by prior preparedness and that are not in harmony with any notion of rapid postwar restoration of social structure. They also create an entirely new threat to populations far removed from target areas, and suggest the possibility of additional major risks for any nation that itself initiates use of nuclear weapons, even if nuclear retaliation should somehow be limited.

THE COMMITTEE'S BASELINE CASE

To provide a framework for its study, the committee first constructed a baseline war scenario, made up of assumptions concerning the nature of the weapon exchange. The baseline scenario (see Chapter 3 for greater detail) was selected so as to be representative of a general nuclear war: one-half—about 6500 megatons (Mt)—of the estimated total world arsenal would be detonated. Of this, 1500 Mt would be detonated at ground level. Of the other 5000 Mt that would be detonated at altitudes chosen so as to maximize blast damage to structures, 1500 Mt would be directed at military, economic, and political targets that coincidentally lie in or near about 1000 of the largest urban areas. All explosions would occur between 30°N and 70°N latitude.

The committee also chose, on the basis of a review of the scientific literature, a set of baseline physical parameters to use in calculating the effects of the baseline weapon exchange. Each baseline parameter was chosen to lie well within the spectrum of scientifically plausible values, values in the middle ranges of plausibility being preferred.

There are three immediate consequences of a major nuclear exchange that could have a significant impact on the subsequent state of the atmosphere. Large amounts of dust could be lofted high into the atmosphere; large fires could be initiated; and large amounts of undesirable chemical species could be released. Some of the key parameters assumed for the baseline case follow. specifity?

The amount of dust (Chapter 4) that would be deposited in the stratosphere is related to total megatonnage. The committee assumes that the total amount lofted is 0.3 teragrams (1 Tg = 10^{12} g = 10^{6} metric tons) per megaton detonated. Eight percent of the mass of dust would be of submicron size, which remains aloft for long periods. The 1500 Mt in ground bursts would raise about 15 Tg of submicron dust into the stratosphere, where it could reside for more than a year. During that time, the solar radiation through that dust, and into the lower atmosphere, would be reduced. Compare to Rausen—

The analysis of fires and smoke is complex (Chapter 5). The 5000 Mt of air bursts would initiate vigorous fires in cities and forests over areas where the thermal radiation incident on combustible material was 20 calories per square centimeter (cal/cm^{2}) or greater, a number well in excess of that known to be adequate to ignite the fuels at hand. In the city-scale urban conflagrations that would ensue, the baseline assumption is that three-quarters of the combustible material in affected areas would be consumed. 75% burned! (Nearly complete consump[illegible] of [illegible]tible materials is typical of large city-wide fires for which [illegible]e available.) Although many of the urban fires would probably sp[illegible] beyond the 20 cal/cm^{2} ignition zone, no additional fuel burden from that spreading is assumed in the baseline case. Of the material that burned in cities, the baseline case assumes that some 4 percent (limited data suggest values lying between 1 percent and 6 percent) — laboratory data, what energy flux would be converted to smoke particles in a range of submicron sizes that would absorb and scatter sunlight very effectively.

Certain processes may, however, diminish the optical effects of the smoke at this stage. During the burning of the urban and/or forest fires, the very fine smoke particles would undergo some coagulation in the rising plume. Over regions where the ambient ground-level humidity was high, the condensation of moisture entrained in the plume could incorporate some of the smoke. There is little empirical evidence to suggest extensive scavenging of the smoke by these processes, but in the baseline case, 50 percent of the smoke is assumed to be removed from the plumes of urban fires in this manner. SIRO (50%)

On the basis of available information on plume dynamics, it is assumed that, shortly after deposition the smoke from the ensemble of fires would be uniformly distributed vertically (mass per unit height) between 0 and 9 km over the entire affected area; the local vertical distribution would be nonuniform, however, because the altitudes of the smoke plumes would vary from one fire to another and would also vary with the time-dependent intensity of the fire. Although under special meteorological circumstances some of the smoke might be deposited at altitudes significantly higher than 9 km, this effect is ignored in the baseline case. Initially, and for some weeks, the smoke would have a very nonuniform horizontal distribution, but would be distributed throughout the troposphere of the northern temperate zone.

The injection of nitrogen oxides from the nuclear clouds into the upper atmosphere would lead to a depletion of the ozone column, which would be restored in about 2 years (Chapter 6).

The atmospheric implications of the baseline case (and of the results of other groups' analyses) are presented in Chapter 7. The committee expects that solar radiation passing through the stratospheric layer of nuclear dust would be absorbed in the upper regions of the smoke layer. The smoke layer would heat up, and since little solar radiation would reach lower levels, the air over land surfaces would cool.

Although a few types of natural events can provide marginally relevant information on aspects of the problem (see also Chapter 8), much of our understanding of the atmospheric response to large amounts of airborne particulates will come from model simulations. These models are validated within relatively small natural variations, so their predictive capability is limited for these large perturbations. Only preliminary estimates can be made of the rate of spreading of particulates over initially clear latitudes and of the rate of removal of particulates.

The duration and magnitude of atmospheric effects would depend on how long the absorbing particulates remained aloft. There is especially large uncertainty associated with long-term removal processes for smoke that survives the early scavenging. Low-altitude precipitation processes might remove the low-altitude smoke, that below 4 km (the normal range for smoke), rather efficiently. But at high altitudes, the increased air temperature and the low humidity could lead to a removal rate in the 4- to 9-km range that would be slower than the removal rate in today's troposphere. The baseline assumes that removal rates would be at least [illegible] removal rates in the lower atmosphere (below 5 km), but would [illegible] slower than normal in the upper troposphere (5 to 10 km), with about one-half of the initial particulates removed from the lower atmosphere in 3 days, and from the upper atmosphere in 30 days.* It is unlikely that the average residence times for postwar smoke would be much less than these values, and quite possible that the mean residence time in the upper troposphere would be longer.

It is hoped that the committee's baseline case will provide a useful point of departure for those who wish to identify and assess the environment that would prevail following a major nuclear exchange.

---

*If the smoke particles acquired electrical charges, the coagulation and smoke removal times could be affected. However, there is no evidence from large historical fires that electrical activity intense enough to be observed was operative. Furthermore, there is no evidence that the sometimes large and visible electrical effects in intense natural events (e.g., tornadoes and volcanoes) influence the dynamics of the storm. Thus, having no reliable basis on which to do otherwise, the committee has disregarded potential electrical effects.

NOTES ON THE NATURE AND SIGNIFICANCE OF UNCERTAINTY

As may be clear from this brief description of the baseline case, there are many points in the analysis at which there is a wide range of parameter values that are consistent with the best current scientific knowledge. Any estimate of the overall atmospheric response will involve a compounding of the effects of these uncertainties. Obviously, calculations made under these conditions cannot be read as a scientific prediction of the effects of a nuclear exchange; rather, they represent an interim estimate from which the reader can infer something of the potential seriousness of the atmospheric degradation that might occur.

Some reviewers of earlier drafts of this report cautioned that even the most qualified numerical results produced under these conditions could be misinterpreted, and some suggested that at present the only scientifically valid conclusion would be that it is not at this time possible to calculate the atmospheric effects of nuclear war. The committee believes, however, that an appropriately qualified, preliminary quantitative treatment of the problem is warranted on two grounds. First, given the enormous human stakes that may be involved, it may not be advisable to wait until a strong scientific case has been assembled before presenting tentative results; there is a danger that a report that reached no conclusions at all would be misconstrued to be a refutation of the scientific basis for the suggestion that severe atmospheric effects are possible. Second, a quantitative approach to the problem is the best way to ensure that all important factors are systematically considered, and quantification helps distinguish the important factors from the less important ones in the overall analysis. Such results are necessary to the orderly allocation of resources to the most pertinent research questions.

The findings of this report depend in rather large measure on a still limited body of scientific inquiry, some of which is not yet fully documented. Attention to the subject is so recent, in fact, that some of the underlying analysis has not yet undergone the peer review process that precedes publication in most scientific journals.

The reader should appreciate the possibility that further research will invalidate some of the estimates discussed in this report. As recently as 1975, when the National Research Council report <u>Long-Term Worldwide Effects of Multiple Nuclear Weapons Detonations</u> appeared, plausible weapon use scenarios differed significantly from those envisaged today, and the crucial importance of fires and smoke had not then been recognized. It follows that the findings presented in this report differ from those of the 1975 report. Furthermore, the pervasive uncertainties in the data and the limited validity of the atmospheric models used to date imply that some future study, conducted at a time when the data and models have been improved, could produce quite different analyses and conclusions. It is possible that improved understanding of some mechanisms (e.g., early scavenging) could so affect the results that the atmospheric degradation would be shown to be weaker than that estimated in the baseline case, but the same uncertainty also makes it a clear possibility that the exchange could produce a degradation that would be greater than, and would last longer than, that estimated in the baseline case.

In short: the committee's findings are clearly and emphatically of an interim character.

well said; — but media did not listen to this.

A vigorous research effort is now needed. Nevertheless, one cannot expect that long-term nuclear effects will be characterized with great precision or confidence in the next few years. Many uncertainties cannot be narrowed because they depend on human decisions that can be made, or changed, long after any particular prediction has been issued. These include, for example, the total yield of the exchange, individual warhead yields, the mix of targets, the mix of altitudes at which the bursts would occur, and the season of the year in which the exchange would occur. In addition, there are obvious limits to the use of large-scale experiments in this field, and the evolution of atmospheric models will require some time.

Many significant uncertainties, however, can be narrowed by further study. In particular, the heights to which smoke is deposited in city-scale fires, the early smoke removal by coagulation and condensation in the fire plume, the extent of continued buoyant rising of sun-heated opaque clouds, and the dynamical response of the atmosphere, first to patchy high-altitude solar absorption and then to the heating of more broadly distributed but still heavy smoke cover, have received only scattered and recent attention.

CONCLUSIONS

The general conclusion that the committee draws from [illegible] is the following: a major nuclear exchange would [illegible]ts of smoke, fine dust, and undesirable chemical [illegible] atmosphere. These depositions could result in dramatic perturbations of the atmosphere lasting over a period of at least a few weeks. Estimation of the amounts, the vertical distributions, and the subsequent fates of these materials involves large uncertainties. Furthermore, accurate detailed accounts of the response of the atmosphere, the redistribution and removal of the depositions, and the duration of a greatly degraded environment lie beyond the present state of knowledge.

injections!

Nevertheless, the committee finds that, unless one or more of the effects lie near the less severe end of their uncertainty ranges, or unless some mitigating effect has been overlooked, there is a clear possibility that great portions of the land areas of the northern temperate zone (and, perhaps, a larger segment of the planet) could be severely affected. Possible impacts include major temperature reductions (particularly for an exchange that occurs in the summer) lasting for weeks, with subnormal temperatures persisting for months. The impact of these temperature reductions and associated meteorological changes on the surviving population, and on the biosphere that supports the survivors, could be severe, and deserves careful independent study.

A more definitive statement can be made only when many of the uncertainties have been narrowed, when the smaller scale phenomena are better understood, and when atmospheric response models have been constructed and have acquired credibility for the parameter ranges of this phenomenology.

The committee also draws several more specific conclusions:

1. In an extensive nuclear exchange, explosions over urban areas and forests would ignite many large fires. Massive smoke emissions are an important aspect of nuclear warfare that have only recently been recognized. For the major 6500-Mt nuclear war considered here, fires could release massive amounts of smoke into the troposphere over a period of a few days. Much of the smoke might be removed by meteorological processes within several weeks, depending on feedback [illegible]ts, but significant amounts could remain for several months. [illegible] its tenure in the atmosphere, the smoke would gradually spread [illegible]ecome more uniformly distributed over much of the northern [illegible]sphere, although some patchiness would be likely to persist. Light levels could be reduced by a factor of 100 in regions that were covered with the initial hemispheric average smoke load, causing intense cooling beneath the particulate layer and unusually intense heating of the upper layer. While large uncertainties currently attend the estimates of smoke emissions, and of their optical and physical consequences, the baseline case implies severe atmospheric consequences.

2. The production of smoke from fires, and the implied effects on the atmosphere, is more directly linked to the extent of detonation over urban areas than to the aggregate yield of a nuclear exchange. The industrialized nations of the world have concentrate[illegible] [illegible] proportion of their resources and combustible fuels in the [illegible] of the central areas of their large cities. Any war scenario that subjects these city centers to nuclear attack, even one employing a very small fraction of the existing nuclear arsenal, could generate nearly as much smoke as in the 6500-Mt baseline war scenario.

3. The climatic impact of soot is very sensitive to its lifetime in the perturbed atmosphere and the uniformity of its distribution. [illegible]e lifetime of soot is highly uncertain, particularly in the upper troposphere. The perturbation itself would produce severe new effects, many of which could tend to increase the residence time of the soot. Although the lofted soot (and dust) would rapidly spread around the latitude band of injection, the distribution could be uneven for several months, with continent-size patches of lesser and greater density, particularly near the southern edge of the affected zones.

4. In the baseline nuclear war scenario, hundreds of teragrams of dust would be injected into the atmosphere from surface detonations. A significant fraction of the dust consisting of particles with radii less than one micron (1 μm) would be expected to remain aloft for months. About one-half of these submicron particles would be injected into the stratosphere and would produce some long-term reduction of sunlight at the earth's surface, even after smoke and dust at lower altitudes were removed. This stratospheric dust alone would lead to

perceptible reductions in average light intensities, and continental surface temperatures would fall measurably. In a plausible scenario that involves more ground burst attacks against very hard targets than are assumed in the baseline case, the possible dust effects are several times larger.

5. It is not possible at this time to estimate the most probable average temperature changes at the surface caused by smoke and dust lofted in the baseline case; nor would such a single value, even if available, meaningfully describe the situation. In addition to the large uncertainties in many of the critical physical parameters and the inherent limitations of the models available for computer simulations, the available calculations reflect wide seasonal and geographical differences. Recent general circulation model simulations that incorporate simplifying assumptions indicate that a baseline attack during the summer might decrease mean continental temperatures in the northern temperate zone by as much as 10° to 25°C, with temperatures along the coasts of the continents decreasing by much smaller amounts. In contrast, an attack of the same size during the winter, according to these simulations, might produce little change in temperature in the northern temperate zone, although there could be a significant drop in temperatures at more southern latitudes.

6. The nitrogen oxides deposited in the stratosphere by nuclear detonations would reduce the abundance of ozone. For the 6500-Mt nuclear war, the northern hemisphere ozone reduction could become substantial several months after the war. Estimates based on current stratospheric structure suggest that the amount of ozone reduction would decrease by one-half after about 2 years. At the time of maximum ozone reduction, the biologically effect[illegible] (using the DNA action spectrum) at the grou[illegible]ly one and one-half times the normal levels. Initially, the presence of dust and smoke particles in the atmosphere would provide a measure of protection at the surface from the enhanced ultraviolet radiation. This protection would gradually diminish as the particles were removed.

7. This study has concentrated on the possible effects that a nuclear war could have on the northern hemisphere, primarily within the mid-latitude region (30°N to 70°N) where the nuclear exchange would be concentrated. It is particularly difficult to assess the potential effects of the baseline war on the atmosphere of the northern tropics and southern hemisphere. Although southern hemisphere effects would be much less extensive, significant amounts of dust and smoke could drift to and across the equator as early as a few weeks after a nuclear exchange. A large rate of transport across the equator driven by heating in the debris cloud cannot be ruled out. Indeed, such heating-enhanced cross-equatorial circulation has been found for spring and summer months in computer simulations.

8. Some prehistoric volcanic eruptions and impacts from extraterrestrial bodies have released energies corresponding to levels that would be released in a major nuclear exchange and may have lofted massive amounts of dust; however, neither type of event provides a useful direct analog to the nuclear case because neither type involved the production of highly absorbing soot particles. Furthermore, the

atmospheric consequences of prehistoric natural events of these proportions are not known, and their effects on the fossil record, if any, have not been sought in any systematic way. Accordingly, available knowledge about prehistoric volcanic and impact events provides neither support nor refutation of the committee's conclusions.

9. All calculations of the atmospheric effects of a major nuclear war require quantitative assumptions about uncertain physical parameters. In many areas, wide ranges of values are scientifically credible, and the overall results depend materially on the values chosen. Some of these uncertainties may be reduced by further empirical or theoretical research, but others will be difficult to reduce. The larger uncertainties include the following: (a) the quantity and absorption properties of the smoke produced in very large fires; (b) the initial distribution in altitude of smoke produced in large fires; (c) the mechanisms and rate of early scavenging of smoke from fire plumes, and aging of the smoke in the first few days; (d) the induced rate of vertical and horizontal transport of smoke and dust in the upper troposphere and stratosphere; (e) the resulting perturbations in atmospheric processes such as cloud formation, precipitation, storminess, and wind patterns; and (f) the adequacy of current and projected atmospheric response models to reliably predict changes that are caused by a massive, high-altitude, and irregularly distributed injection of particulate matter. The atmospheric effects of a nuclear exchange depend on all of the foregoing physical processes ((a) through (e)), and their ultimate calculation is further subject to the uncertainties inherent in (f).

yes! emissions factors may be more important than implied

REFERENCES

Alvarez, L.W., W. Alvarez, F. Asaro, and H.W. Michael (1980) Extraterrestrial cause for the Cretaceous-Tertiary extinction. Science 208:1095-1108.

Crutzen, P.J., and J.W. Birks (1982) The atmosphere after a nuclear war: Twilight at noon. Ambio 11:114-125.

National Research Council (1975) Long-Term Worldwide Effects of Multiple Nuclear Weapons Detonations. Washington, D.C.: National Academy of Sciences.