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INTERNAL REPORT

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LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California

LLNL STUDY OF THE GLOBAL-SCALE PHYSICAL EFFECTS OF A NUCLEAR EXCHANGE: PRELIMINARY FINDINGS

August 15, 1983

Project Leaders:

Bruce Tarter, Michael MacCracken, Joseph Knox,
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OVERVIEW

The potential global-scale physical effects of a strategic nuclear exchange of approximately 5300 Mt have been analyzed. Such an exchange leads to an average Northern Hemisphere radionuclide dose of 20 rem, and predicts a reduction in stratospheric ozone that could increase the ultraviolet flux at the earth's surface by a factor of 5. A principal new result is the potential impact of smoke and gases produced by fires initiated by the exchange. This injected material can reduce the visible light reaching the surface in the Northern Hemisphere by 90% or more, and can lead to a cooling of continental land areas by up to 30°C. It can also suppress atmospheric scavenging mechanisms, such as rain, so that the recovery to a normal atmosphere may take a number of months. The overall qualitative results of our study are similar to those found in ongoing work by other groups.

EXECUTIVE SUMMARY

- Scenarios

A global nuclear exchange of about 5300 Mt composed of land-based, submarine, and aircraft-delivered nuclear weapons of the U.S. and U.S.S.R. targeted on military installations, industrial centers and critical urban centers in the combatant countries is assumed as a reference case.

- Radionuclides

Global-scale deposition of fission products would lead to an average, whole body integrated dose in the 30°N-70°N latitude band of about 20 rem. Large-scale hotspots of ten times this average, local fallout and smaller-scale hotspots, destruction of nuclear power plants, and the relative locations of population centers and deposition peaks could make the dose to a particular unsheltered individual much higher (hundreds of rem). The details are highly dependent on the exchange scenario, specific meteorological conditions, and the timing of the interaction of the debris clouds with weather systems.

- Stratospheric Chemistry and Ultraviolet Radiation

Nitrogen oxides injected into the stratospheric ozone layer by the weapons of the reference scenario will lead to a peak reduction in the hemispheric-average, vertically-integrated ozone by about 35% approximately four months after the exchange, with recovery to near normal levels taking several years. The 35% decrease in ozone would lead to an increase in ultraviolet flux by a factor of 5 at .30 μm. However, this estimate neglects possible interactions with dust, smoke, and hydrocarbon-induced production of tropospheric ozone, each of which could contribute appreciably to ultraviolet absorption.

- Radiative Effects of Dust and Nitrogen Dioxide

Particulate matter (lofted dust and condensation of vaporized material) and nitrogen dioxide injected into the stratosphere will reduce the total solar radiation transmitted at 0.55 μm by 15% after a few weeks and 2% after 1 year, based on a Northern Hemisphere average and continued scavenging at current rates. A maximum surface cooling of roughly 5°C might be expected over mid-continental regions, but such cooling would be lessened substantially in coastal areas.

- Fires and Smoke

Extensive burning of cities, industrial complexes, and surrounding wooded areas can inject a few hundred teragrams (10^{12} g = 1 Tg) of smoke (including soot and other particulate matter) and large amounts of gaseous pollutants into the lower atmosphere. Within about 20 days, thick smoke clouds with horizontal scales of a few thousand kilometers will circle the Northern Hemisphere mid-latitudes, gradually dispersing and being scavenged at quite uncertain rates. This material will lead to significant reduction in the light (including ultraviolet radiation) reaching the Earth's surface (e.g., about 80% reduction in total solar radiation reaching the surface in mid-latitudes of the Northern Hemisphere after one month, assuming continued scavenging at present rates, or 95% reduction assuming reduced scavenging).

- Tropospheric Chemistry

Emissions of carbon monoxide, hydrocarbons, and nitrogen oxides from fires may lead to increased tropospheric ozone and peroxyacetyl-nitrate, although the reduction in sunlight caused by the smoke will delay and moderate this effect. Surface ozone concentrations may be increased in some areas, but smoke will inhibit this increase as the smoke becomes mixed throughout the troposphere.

- Global Climate

Tropospheric injection of soot, and to a lesser extent stratospheric injections of dust and nitrogen dioxide, will significantly alter the global radiation balance, obscuring the sun, and cooling large mid-latitude land surfaces by 5-30°C, depending on their proximity to the moderating effects of ocean temperatures. There will be a warming of the upper troposphere of the Northern Hemisphere by 30-50°C, thereby sharply reducing cloud cover and the precipitation that would normally scavenge the absorbing particles on time scales of a few weeks.

- Coupling of Effects

Because the individual impacts on the atmosphere are occurring simultaneously, the synergistic interactions that occur are an important, but seriously underanalyzed, aspect of estimating global effects. For example, if the smoke reduces the rate of scavenging by precipitation, radioactive particles will remain aloft for longer periods, thereby reducing the estimated dose rates. The initial injection and spreading of the smoke and gases and their effects on the dynamics of the atmosphere (including scavenging and recovery rates) are critical areas deserving further attention.

- Other Work

The present study represents a major advance over the 1975 National Academy Study in which radionuclide deposition was greatly underestimated, and atmospheric effects from fires were ignored. The results given here are broader in scope, but in qualitative accord with those of a group from RDA/NASA-Ames (referred to as Turco et al. 1983), and with those anticipated from an ongoing National Academy study to be published this winter.

I. GLOBAL EFFECTS SCENARIO

Summary: Our reference global nuclear exchange is composed of landbased, submarine, and aircraft-delivered nuclear weapons of the US and USSR targeted on military installations, industrial centers, and critical urban centers in combatant countries. The reference strategic scenario involves a total yield of about 5300 Mt (about one third US and twothirds USSR) spread among about 6300 warheads and bombs (about equally divided between US and USSR). About 2500 Mt are surface burst (about 85% by USSR).

- Although some previous scenarios (e.g., NAS, 1975) suggested a total yield of 10000 Mt or more, consideration of potential targets, the number of submarines on station, and the readiness and composition of forces makes such large exchanges implausible, although not impossible. Our reference scenario is similar to those being used in other current studies of global effects.

- A second scenario involving an additional significant European theater component has also been considered. This scenario has a total yield of roughly 6500 Mt spread among about 10,000 warheads. Most of the additional warheads are employed in a tactical air burst mode.

- The mix of weapons yields available in systems (at least in the US) has changed in the last ten years, with larger numbers of sub-megaton and low megaton devices replacing multi-megaton devices. The trend toward lower yields is expected to continue.

Key assumption: Although the reference scenario is considered plausible in terms of total exchange, variations by factors of at least two in total yield are also possible depending on several assumptions, such as survivability of systems and conduct of the war.

<u>Status of effort</u>: Plausible exchanges have been developed by D-Division. Refinement of scenarios (e.g., readiness of forces, deployment options, stockpile uncertainties, etc.) continues at a low level of effort.

<u>Further work needed</u>: Assessment of the effects of weapons technology trends should be carried out, including both planned stockpile changes and the possible introduction of defensive systems.

II. RADIONUCLIDES

Summary: The reference strategic nuclear exchange of about 5300 Mt would lead to an average whole body, total integrated dose from gross fission products (assuming no reduction by sheltering or weathering) over the Northern Hemisphere of 20 rem. Hot spots of up to 200 rem additional potential dose are possible in large regions (e.g., eastern Europe, southeastern United States, etc.) where fresh tropospheric debris clouds enter regions with frequent or persistent precipitation. Of course, as has been known for many years, within a few hundred km of detonations, a fallout plume may contribute lethal radiation doses to unsheltered populations, depending on the height and yield of the burst and the local weather and topographic conditions.

- Previous estimates (e.g., NAS, 1975) that the average Northern Hemisphere dose would be only a few rem are about a factor of five to ten too low because the estimates were based on a scaling from the 1960's nuclear test series, a process that would be valid only if the mix of weapons yields and locations of detonation of nuclear tests had been similar to the hypothetical nuclear exchange. Neither assumption is valid given current weapons inventories and reasonable assumptions concerning targets.

- Potential dose on the hemispheric scale is strongly scenario dependent. It is reduced as the fraction of surface bursts is increased (there is, then, more local fallout and less global deposition) and it is also reduced as the same total yield is concentrated in fewer, higher-yield detonations (since the cloud rises higher and more decay can occur before deposition).

- A European theater-only nuclear exchange would involve lower-yield explosions than a strategic exchange, leading to lower stabilization heights of debris clouds and more rapid deposition of radionuclides. The potential average mid-latitude doses from the European theater component of our strategic plus tactical exchange are about a factor of five less than for a strategic exchange because of the lower total yield. There is a greater tendency, however, for deposition to be concentrated in hot spots (with doses as large as 200 rem) because of the enhanced probability of early interaction with precipitation systems.

- If nuclear power and fuel cycle installations became priority targets, release of the inventory of longer-lived radionuclides would pose serious long-term problems for survivors of an exchange. The global dose contribution from such a focused attack would be 70-80 rem from U.S. installations and reach 200-300 rem if the nuclear power facilities of Western Europe and the USSR were also attacked.

Key assumption: The global burden of radionuclides is highly dependent on the particular nuclear exchange scenario.

Key uncertainty: The deposition at early time (and therefore production of hotspots) is highly dependent on the specific meteorological conditions and weather systems that the debris clouds encounter.

Status of effort: Model development and improvement for this study have substantially upgraded our capabilities. Scenarios, assumptions, and estimates are being refined.

Further work needed: Given the increasing importance of radionuclide deposition as device yield is reduced and warhead number increased, further model development work is needed so that critical assumptions (e.g., very approximate representations of tropospheric scavenging mechanisms) can be improved. Additional calculations are needed to establish typical distributions of dose, probable locations of hot spots, smaller scale variations, etc.

III. STRATOSPHERIC CHEMISTRY AND ULTRAVIOLET RADIATION

Summary: Injection into the stratosphere of 8.3 Tg (1 Tg = 1 Mt) of odd nitrogen (injected as nitrogen oxides) created by the 4700 Mt of 0.5 megaton or larger explosions in our reference scenario would lead to a Northern Hemisphere average reduction in stratospheric ozone of 30-35% after four months with recovery to within 10% of normal after 3 to 4 years. The ultraviolet radiation at the earth's surface would be increased by about a factor of 5 at 300 nm in the absence of smoke and dust.

- Previous estimates (e.g., NAS, 1975) that NO_x injection from a 10000 Mt nuclear exchange would lead to hemispheric ozone reductions on the order of 50% after six months and 20% after three years are consistent with our calculations.

- The percentage increase in ultraviolet radiation received at the Earth's surface is several times the percentage decrease in total ozone. An ozone decrease of 30% causes an increase of a factor of 5 in biologically active ultraviolet radiation at 300 nm at the surface. For a 70% decrease of ozone, which might occur regionally, the ultraviolet radiation would be increased severalfold more (depending on latitude and season).

- Much of the NO_x will be injected into the stratosphere over relatively small areas (e.g., $\sim$ 75% over the U.S., most above ICBM fields). Such localization can lead to large radius (several hundred to several thousand km) "ozone holes" in which vertically integrated ozone is reduced by much larger than average amounts (e.g., 50-70%), depending on the yields (and hence stabilization heights) of the explosions. Such holes will grow to several million km^2 in area and persist from a few days to a few weeks (based on ambient dynamics) until the NO_x is diluted to the point where chemical recovery begins. Potential enhancement of the ultraviolet flux by factors of ten or more under the "holes" could be substantially reduced by the co-located injected dust if the weapons are surface burst. Once the holes are broken up and the nitrogen oxides spread through the hemisphere, the ultraviolet flux at the surface, assuming no smoke or dust and about 30% ozone reduction, will be increased by about 5 times ambient at 300 nm.

Key assumption: Calculations assume that the effect of NO_x on stratospheric ozone can be evaluted independent of climatic effects that might lead to changes in atmospheric transport.

Key uncertainty: Assessments to date have not treated the interaction of the large change in stratospheric ozone on stratospheric dynamics, which may influence dispersal and recovery times.

Status of effort: Stratospheric injections from our base case have been developed and hemispheric average perturbations have been estimated. The effects of localized NO_x injection (thereby creating ozone holes) and the latitudinal spread of the emissions after injection have been analyzed.

Further work needed: Calculations with "real" two dimensional codes should be done to check the accuracy of our estimates derived from a sequence of one-dimensional models. The effect of NO_x heating on stratospheric dynamics and spreading rates should be evaluated.

IV. RADIATIVE EFFECTS OF DUST AND NITROGEN OXIDES

Summary: Injection of material into the stratosphere will have significant direct effects on radiative fluxes, as well as indirectly through stratospheric chemical changes. About 50 to 75 Tg of particles with radius less than 1 μm (including dust lofted by the nuclear explosions and particles formed by condensation of material vaporized at the surface) will be injected into the stratosphere by megaton range explosions, leading to significant scattering of solar radiation. Larger particles lofted by surface bursts will also affect radiative transport, but for relatively short times since they are removed quite rapidly.

- Stratospheric dust reduces the solar radiation transmitted through the stratosphere to the troposphere. A few weeks after injection, the injected dust would reduce the direct solar flux to the troposphere by about 60%. Because the dust primarily scatters solar radiation, much of the deficit in the direct flux is made up by an increase in the diffuse (scattered) solar flux. The total net flux transmitted through the stratosphere would be reduced about 15% after a few weeks, about 9% after 4 months and about 2% after a year.

- The effect of the dust on the transmission of ultraviolet radiation varies greatly with wavelength and solar zenith angle. For small solar zenith angles (near overhead sun), dust decreases the ultraviolet flux transmitted through the stratosphere. However, for large solar zenith angles (greater than about 60°), the dust can, at wavelengths where absorption by ozone is very strong, lead to an increase in transmission by scattering some of the direct flux in a more vertical direction so that there is less attenuation by ozone.

- In regions around missile fields, the stratospheric dust would initially be much greater than the hemispheric average loading. For example, stratospheric dust would have an optical depth of greater than 10 over an area of a few million km^2 up to 2-3 days after injection, thus effectively eliminating solar transmission into the troposphere, resulting in rapid cooling of the air below the cloud.

This colder, denser air would tend to mix the stratospheric layers into the troposphere, perhaps reducing the stratospheric residence time of injected radionuclides, chemical species, and the dust itself.

- In the natural atmosphere, NO_2 absorbs much less than 1% of the incoming solar radiation. With the stratospheric injection of NO_x from nuclear explosions, the total column of NO_2 is increased several orders of magnitude, which reduces the transmission of visible radiation through the stratosphere by about 2% after a few weeks. Increased solar absorption by NO_2 warms the stratosphere significantly, which leads to a change in its temperature structure, and contributes to cooling of the troposphere.

Key assumption: The amount of stratospheric dust is directly proportional to the total yield of megaton range warheads that are used in a surface burst mode.

Key uncertainty: There is only fragmentary data on the amount and size distribution of dust particles produced in a surface burst of given yield.

Status of effort: Initial radiative calculations have been completed, but additional analysis of different assumptions concerning dust distribution and opacity is continuing.

Further work needed: The influence of stratospheric changes on the troposphere and the subsequent feedback on the stratosphere could alter the static results described here; dynamical estimates are needed. Infrared effects of the dust must be investigated.

V. FIRE AND SMOKE

Summary: A major strategic nuclear exchange involving more than 6000 warheads is likely to start fires in many urban and developed areas and perhaps in some forest areas. The potential mass of particulate and gaseous emissions from these fires is large compared to present atmospheric burdens and, because of the radiative and chemical characteristics of these materials, the impacts are likely to be significant.

- Previous studies (e.g., NAS, 1975) neglected any non-local effects from fires. Crutzen and Birks (1982) were the first to recognize that smoke, hydrocarbons, CO, and NO_x emissions from fires might play a key role in altering the atmosphere after a nuclear war. Turco et al. (1983) have carried out detailed parametric studies of the kinds of material injected, and the possible implications for radiative transfer and energy balance in the atmosphere.

- Urban fires are expected to be intense, burning most combustible material during the first two or three days after an exchange and injecting smoke up to several km altitude. Turco et al. estimate that urban fires will inject about 350 Tg of highly absorbing sooty material (30% elemental carbon surrounded by 70% condensed hydrocarbons together having a density of 2 g/cm^2). This result is based on a 10,000 Mt exchange, half landing on urban areas, and assumes that fires occur in half the urban areas bombed, cover 6.8 x 10^5 km^2 (twice the area exposed to 10 cal/cm^2 pulse radiation, because of spreading), burn half the available urban fuel loading of 3 g/cm^2, and loft 5% of the material burned (with 25% scavenged close in). Assuming most injection occurs at 1-8 km altitude and rapid hemispheric spreading with scavenging at current rates (i.e., 10-20 day particle lifetimes), the smoke-induced opacity would be equivalent to a hemispheric average optical depth at one week of about 3.5. Because spreading is not actually this rapid, Northern Hemisphere mid-latitudes would generally experience greater optical depths, with patches of much cleaner air in lower latitudes.

- Our review of the Turco et al. analysis indicates that the injected amount and resulting radiative effects could be somewhat smaller, but this depends on a number of important uncertainties (e.g., the net emission may be lower because the ignition energy fluence may be closer to 15 cal/cm^2, fuel loading may be only 1.5 g/cm^2 and the emission factor may be as much as a factor of 10 less than 5%, but the net effects may be larger because more of the fuel load may be burned, particle number will be higher since the density is only 1 g/cm^3, and scavenging rates may be reduced). The size distributions and radiative properties of smoke from city fires are not well known, but the total mass may be large enough to have a significant atmospheric impact despite these uncertainties. For purposes of comparison of climatic effects, our reference smoke scenario for urban fires assumes 150 Tg, which may be uncertain by a factor of at least 5 or more. Turco et al. also include 40 Tg from urban firestorms that inject material into the upper troposphere and lower stratosphere, an event we consider unlikely.

- The areal extent of major forest fires appears to be highly dependent on the local conditions at the time of the exchange. According to expert foresters, sustained fires (i.e., lasting days to weeks) require specific conditions (e.g. low humidity, favorable winds, etc.) that are of relatively low frequency ($\sim$ 10%) in most locations. Under conditions conducive to forest fire spread, Turco et al. estimated that as much as 175 Tg of soot would be released into the lower troposphere from fires covering up to 10^6 km^2, which is 55 times the area burned by U.S. forest fires per year at present rates. Reducing the emission by a factor of about 2 based on our review of experimental burn results, and accounting for particle density differences, our reference case for comparison of climatic effects assumes about 58 Tg are injected. Because forests are not direct targets, but are assumed to be ignited because they surround cities or other targets, this estimate may be higher than would result from analysis of a very specific scenario. Optical properties and size distributions for forest fire smoke have been estimated based on observations of natural burns. Our results indicate this material may not be as highly absorbing as assumed in the Turco et al. study.

- Our reference scenario for comparison of climatic effects thus includes 150 Tg from urban fires and 58 Tg from forest fires, whereas Turco et al. estimated 390 Tg from urban fires, 175 Tg from forest fires, and 17 Tg from long term fires (oil and gas fields, coal seams, dry peat). We did not include this last source, believing such long term fires unlikely unless a special, focused attack is made on susceptible targets.

- Our reference scenario also produces emissions of 60 Tg C as CH_4, 640 Tg C as CO, 80 Tg C as NMHC and 26 Tg N as nitrogen oxides in addition to the 208 Tg smoke. Our scenario assumes that urban fuel produces the same emission rates as forest fire fuel on a per-gram fuel basis. Information on emission rates from urban fires is based on fragmentary laboratory data and on emission rates from forest fires is scanty. In our scenario, the amount of NO_x released, in particular, was estimated from laboratory tests of forest fuels and amounts to about 20% of the nitrogen contained in the fuel itself. A very hot fire might produce more NO_x via thermal processes, but this has not been considered.

Key assumption: Many assumptions determine the emissions that we are considering including fraction of material burned, completeness of burn, fraction of material lofted, etc.

Key uncertainties: The fraction of combusted material lofted as small particles from urban fires depends strongly upon the kind of fuel, the amount of oxygen available, and the rate of burn. These conditions can vary so that the fraction lofted can range from about .002 to .05, or possibly higher. The threshold ignition of material by the thermal radiation is believed to require 10 to 20 cal/cm^2, depending on weapon yield, thereby introducing uncertainty into the area of the fires initially ignited and the fuel loading that is available to burn. Extent of spreading of urban and rural fires is poorly known, as is the likelihood of forest fires and long term fires (e.g., oil wells, coal seams, dry peat). Thus the total injected smoke burden may be uncertain by more than a factor of 10.

<u>Status of effort</u>: The assumptions made in available scenarios have been evaluated. Our estimates are in general agreement with other recent assessments: specifically, large amounts of particles can be injected, although we believe the size and radiative properties of the soot are not well known. Our estimates of gaseous emission rates are lower than recent projections, but since previous studies did not include such emissions from urban fires, our total emission burden is similar.

<u>Further work needed</u>: Many of the uncertainties identified in our evaluation (particularly those concerning particle size distribution, fire ignition and propagation in cities, height of injection, and gaseous emissions) may have important influences on the estimation of impacts and deserve further study.

VI. TROPOSPHERIC CHEMISTRY AND SCAVENGING

Summary: Estimated soot emissions into the troposphere from our reference nuclear exchange are about 100 times larger than the present atmospheric burden of carbonaceous aerosol. Such an injection would dramatically affect the troposphere, altering its temperature structure so as to mix the smoke vertically upward from the lower troposphere while reducing the convective instability and precipitation that normally lead to scavenging of tropospheric pollutants.

- A new global tracer transport model (GRANTOUR) that is driven by representations of present atmospheric transport indicates that soot and gas plumes will spread from the combatant countries and be mixed by atmospheric motions, leading to relatively high concentrations throughout the middle latitudes within a few weeks to a month, assuming that normal scavenging mechanisms are inhibited (see below). Polar regions will fill with the smoke and gases shortly thereafter. Because injections do not occur in low latitudes (e.g., south of 30° N), spread of smoke toward the equator will be on a time scale of a few months with spread to the Southern Hemisphere much slower unless transport mechanisms are significantly altered (which appears possible).

- Radiative calculations that include the soot indicate that the flux of visible light to the surface may be reduced by more than 90% in passage through vertical aerosol burdens of about 0.5 g/m^2 (which is projected to be a hemispheric average value) , depending on the amount and radiative characteristics of the soot. The solar radiation absorbed by the smoke aerosol leads to tropospheric heating rates that rapidly tend to warm the middle and upper troposphere, thereby in effect, lowering the troposphere-stratosphere boundary.

- Radiative stabilization of the middle and upper troposphere will suppress convective precipitation, thereby making "tropospheric" lifetimes of small soot particles comparable to present stratospheric lifetimes (i.e., months to years). Because the areal distribution of the soot will be non-uniform, horizontal temperature gradients may augment scavenging rates, particularly where land-sea temperature contrasts develop.

- Recent estimates (Crutzen and Birks, 1982) that gaseous emissions of hydrocarbons, nitrogen oxides and carbon monoxide would increase surface and tropospheric O_3 concentration severalfold are based on estimates that neglect smoke and assume that many sub-megaton devices will inject substantial amounts of NO_x into the troposphere. Our 1-D model results, which include a more thorough treatment of the important non-methane hydrocarbon chemistry as well as dust and smoke effects, indicate that the reduced photolysis rates for NO_2 substantially reduce the ozone forming potential of the global tropospheric "smog" chemistry, but that an ozone increase will occur in the upper troposphere. The Northern Hemispheric average tropospheric total column of ozone is somewhat increased (25%) over the current ambient value for several months although surface ozone may be decreased below the current ambient concentration. Our model results depend, however, on the assumption of normal scavenging rates for NO_x in the perturbed atmosphere, and this and other factors leads to an overall uncertainty ranging from no increase in surface ozone to Crutzen's suggestion of perhaps a 4 fold increase in local areas. Similarly, although the tropospheric column content of peroxyacetyl nitrate (PAN) is increased by $\sim$ 4 fold after a few months, surface values remain low. (PAN is a principal eye irritant in urban photochemical smog, and is a strong oxidant with the potential for deleterious plant and animal health effects at sufficiently high levels.)

Key assumption: Calculations to date assume either rapid dispersal of the soot without significant scavenging, or that soot lifetimes will be unaltered. High ozone (smog) concentrations could occur, however, in patchy areas where enough light is present to drive the photochemistry.

Key uncertainty: The scavenging rates of the soot are very poorly known, although preliminary indications are that the lifetime of soot will be extended because of increased atmospheric stability and delay in the oxidation of the soot (thereby leaving it in a low solubility form).

Status of effort: A new global tracer model including transport and precipitation scavenging has been developed and our 1-D radiation-chemical kinetics model has been modified to include relevant tropospheric chemistry. We are just beginning to apply these models to the issues raised by a nuclear exchange.

Further work needed: Our models, while an important step beyond recent work by others, still make important assumptions that limit our ability to evaluate interactions between mechanisms. For example, a better treatment of tropospheric mixing processes is required to narrow uncertainties involving the distribution of surface emissions.

VII. GLOBAL CLIMATE

Summary: The injection of large amounts of soot, dust, and gases (e.g., NO_2) into the atmosphere from detonation of 6,000-10,000 warheads and the burning of 13000 Tg of fuel in cities, urban areas, and forests can dramatically affect the atmosphere's temperature, dynamics, precipitation, and chemistry. These perturbations in turn lead to modification of weather and climate. Our reference scenario leads to reductions in average Northern Hemisphere land temperatures of 5-10° C, and perhaps several times more over mid-continental regions. Reductions in precipitation rate of 20-30% over the cooled land regions and by 5-10% over ocean regions, where atmospheric warming has stabilized the upper troposphere, are also projected.

- Calculations made for a recent study (Turco et al., 1983) using a one-dimensional radiative-convective model indicate that the injection of soot, dust and gases will cause Northern Hemisphere average land surface (or, at least, central continental) temperatures to drop as much as 30° C in the first two months after a nuclear exchange and not return to within 5° C of normal for about a year. Temperature reductions over oceans would be much less due to the high thermal capacity and efficient heat transfer in the upper oceanic mixed layer. Horizontal temperature contrasts between the oceans and continents would likely alter circulation patterns, with poorly understood consequences. Middle and upper tropospheric temperatures would warm by up to 40°C, thereby stabilizing the troposphere and substantially reducing precipitation and scavenging of the soot and other materials.

- Our studies with a similar 1-D model indicate that the extent of cooling is dependent on the height of the smoke and the effect of cloud cover changes, both of which are highly uncertain. When smoke is near the ground, absorption of solar radiation heats the lower atmosphere and can, thereby, keep the surface relatively warm via infrared radiation from water vapor, CO_2, etc. But such absorption of solar radiation would likely induce vertical mixing of the smoke to higher altitudes. Once smoke reaches higher altitudes, the solar radiation that is absorbed can be more easily radiated to space, but cannot be easily radiated downwards, thereby allowing the lower atmosphere and surface to cool. Water vapor clouds, if present, can radiate infrared radiation downward effectively, helping to reduce cooling of the lower atmosphere/surface system; however, stabilization of the atmosphere would reduce the vertical water transport that leads to the development of clouds and the warming would tend to evaporate existing clouds, thereby allowing the surface to further cool.

- Studies with our two-dimensional climate model that approximately take into account the time-dependent latitudinal spread of the smoke indicate that Northern Hemisphere land temperatures cool rapidly after the injection of material into the troposphere, reaching maximum cooling of about 5-10° C within 10-15 days. Cooling of mid-continental regions could be substantially larger, as is the case for seasonal climate changes. Temperature reductions would probably be larger in summer than in winter, because the absolute amount of solar radiation affected would be larger. Depending on assumptions about scavenging rates of the emissions, the recovery period from the smoke-induced portion of the cooling can take from one to six months or longer. The smaller cooling induced by stratospheric dust, NO_2 and O_3 changes would persist up to a few years because of the longer lifetime of species at those high altitudes.

Key assumption: The scavenging processes, transport mechanisms, etc. that act on the injected materials are assumed to be those of an unperturbed atmosphere. This is clearly not valid, but computational tools do not yet exist (at LLNL or elsewhere) to satisfactorily overcome this assumption. The effects of changes in tropospheric concentrations of radiatively active gases have not been considered.

Key uncertainty: The scavenging rates of soot and induced changes in the circulation pattern that may further spread the soot are very uncertain.

Status of effort: Modification of models is nearly completed and test simulations are now underway. Consideration of possible variations of scenarios, iteration between different models to achieve consistency, and analysis of results remain.

<u>Further work needed</u>: Many important assumptions and effects remain to be evaluated in available models (e.g., effect of the injected materials on dispersal mechanisms, effects of stratospheric NO_2, dust injections, and O_3 changes on climate, etc.). This work would be a step beyond most recent studies. Our ultimate goal is to treat the perturbations in coupled models of higher dimensionality with better representation of important processes.

VIII. COUPLING OF EFFECTS

Summary: Because a major nuclear exchange causes injection of a variety of materials into the atmosphere, each having different effects on various time scales, the interaction between different phenomena can either amplify or diminish the effects found when impacts are examined separately.

- High-yield detonations tend to have more effect on stratospheric ozone, but produce less potential radioactive dose, than equivalent yield spread among a higher number of lower yield detonations (and conversely).

- Smoke from fires and dust lofted during explosions may substantially moderate amplification of the surface ultraviolet radiation flux arising because of reduced stratospheric ozone concentrations, at least during the first several months after the exchange (if dust and smoke are removed more rapidly than ozone recovers).

- Stabilization of the troposphere due to injected smoke will likely take too long (i.e. a few weeks) to prevent deposition and precipitation scavenging of a large fraction of radionuclides injected into the troposphere, but stabilization will likely delay and hence reduce the potential dose from stratospheric and upper tropospheric radionuclide burdens.

- Horizontal circulations induced by the temperature contrasts between the warmed air over the oceans and the cooled air over the land may induce strongly altered scavenging rates in some regions, and spread debris (including radionuclides) throughout the hemisphere more rapidly than present estimates indicate.

Key assumption: Our assessment has tended to focus on global scale effects using a rather coarse resolution (about 1000 km), whereas many processes (e.g., precipitation) have high spatial variability on scales well below our resolution that may induce local effects well above or below our estimates.

Key uncertainty: Time and resource constraints have limited this assessment to first order results with only a limited examination of non-linear effects that may actually be of great importance. Without further examination of these issues, uncertainties remain large.

Status of effort: The interactions between various effects are only beginning to be evaluated.

Further work needed: The results obtained for individual processes need to be validated with a self-consistent multi-dimensional model. In addition, more careful evaluation and investigation is needed to assure that further important effects chains (e.g. soot falling on glacial and sea ice causing melting; forests drying out and later burning due to reduction in rainfall; focused attacks on such particularly sensitive sites as toxic chemical plants, oil fields; weather-related conductivity changes caused by increased radionuclide-induced ionization of the atmosphere; etc.) are not being overlooked.

IX. OTHER WORK

Summary: The first assessment of global scale physical effects of a nuclear exchange was carried out by the National Academy of Sciences in 1975. Their analysis of radionuclide deposition was an order of magnitude too low because of poor methodology (see II), but their calculations of ozone depletion were consistent with the present work. The qualitative impact of smoke and gas emissions from fires was first suggested by Crutzen and Birks in 1982 (Ambio, 11, 114). More detailed estimates by a group at RDA/NASA-Ames (Turco, Toon, Ackerman, Pollack, and Sagan, 1983); by a current National Academy of Sciences panel; and by us are in general agreement with the result that such fires can lead to significant reductions in visible light and lowered temperatures at the earth's surface.

- Prior to 1975 nearly all studies of the effects of nuclear war were focused on the local consequences of heat, blast, and fallout from individual explosions. This perspective was summarized in a 1978 report by the Office of Technology Assessment.

- A 1975 study by the National Academy of Sciences made the first substantive analysis of global-scale physical effects. Their report emphasized stratospheric ozone depletion and its effect on ultraviolet fluxes. Radionuclide deposition was underestimated, and other global scale phenomena were not mentioned.

- The 1982 paper by Crutzen and Birks stimulated the detailed work by Turco et al., by ourselves, and by the current National Academy group whose report is expected late in 1983. In addition to analyzing the potential impact of smoke and gas emissions from fires, each group has re-examined many of the other effects and assumptions in considerable detail.

Key assumptions: Each ongoing effort is using approximately the same war scenario, which has roughly half of the total yield employed in earlier work.

<u>Key uncertainty</u>: The most important unknown parameters in the calculations are the mass loading from fires and the residence time of the particulates in the atmosphere. Each group tries to consider a range of possibilities for these quantities, but the uncertainties are quite large; in particular, the early time development and spread of debris and smoke has not been adequately studied.

<u>Status of effort</u>: Initial work by all groups is nearly completed, with final reports from each expected by the end of 1983. A session at the December meeting of the American Geophysical Union appears to be a likely forum for simultaneous presentation of the various results.

<u>Further work needed</u>: No time-dependent three-dimensional climate calculation of the post-war state has been attempted. Some effort along these lines is needed in order to assess the validity of the different individual effects predicted by the static, one-dimensional models.

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