Worldwide Effects of Nuclear War − − − Some Perspectives

U.S. Arms Control and Disarmament Agency

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FOREWORD

Much research has been devoted to the effects of nuclear weapons. But studies have been concerned for the most part with those immediate consequences which would be suffered by a country that was the direct target of nuclear attack. Relatively few studies have examined the worldwide, long term effects.

Realistic and responsible arms control policy calls for our knowing more about these wider effects and for making this knowledge available to the public. To learn more about them, the Arms Control and Disarmament Agency (ACDA) has initiated a number of projects, including a National Academy of Sciences study, requested in April 1974. The Academy's study, Long−Term Worldwide Effects of Multiple Nuclear Weapons Detonations, a highly technical document of more than 200 pages, is now available. The present brief publication seeks to include its essential findings, along with the results of related studies of this Agency, and to provide as well the basic background facts necessary for informed perspectives on the issue.

New discoveries have been made, yet much uncertainty inevitably persists. Our knowledge of nuclear warfare rests largely on theory and hypothesis, fortunately untested by the usual processes of trial and error; the paramount goal of statesmanship is that we should never learn from the experience of nuclear war.

The uncertainties that remain are of such magnitude that of themselves they must serve as a further deterrent to the use of nuclear weapons. At the same time, knowledge, even fragmentary knowledge, of the broader effects of nuclear weapons underlines the extreme difficulty that strategic planners of any nation would face in attempting to predict the results of a nuclear war. Uncertainty is one of the major conclusions in our studies, as the haphazard and unpredicted derivation of many of our discoveries emphasizes. Moreover, it now appears that a massive attack with many large−scale nuclear detonations could cause such widespread and long−lasting environmental damage that the aggressor country might suffer serious physiological, economic, and environmental effects even without a nuclear response by the country attacked.

An effort has been made to present this paper in language that does not require a scientific background on the part of the reader. Nevertheless it must deal in schematized processes, abstractions, and statistical generalizations. Hence one supremely important perspective must be largely supplied by the reader: the human perspective−−the meaning of these physical effects for individual human beings and for the fabric of civilized life.

Fred C. Ikle Director U.S. Arms Control and Disarmament Agency

INTRODUCTION

It has now been two decades since the introduction of thermonuclear fusion weapons into the military inventories of the great powers, and more than a decade since the United States, Great Britain, and the Soviet Union ceased to test nuclear weapons in the atmosphere. Today our understanding of the technology of thermonuclear weapons seems highly advanced, but our knowledge of the physical and biological consequences of nuclear war is continuously evolving.

Only recently, new light was shed on the subject in a study which the Arms Control and Disarmament Agency had asked the National Academy of Sciences to undertake. Previous studies had tended to focus very largely on radioactive fallout from a nuclear war; an important aspect of this new study was its inquiry into all possible consequences, including the effects of large−scale nuclear detonations on the ozone layer which helps protect life on earth from the sun's ultraviolet radiations. Assuming a total detonation of 10,000 megatons−−a large−scale but less than total nuclear "exchange," as one would say in the dehumanizing jargon of the strategists−−it was concluded that as much as 30−70 percent of the ozone might be eliminated from the northern hemisphere (where a nuclear war would presumably take place) and as much as 20−40 percent from the southern hemisphere. Recovery would probably take about 3−10 years, but the Academy's study notes that long term global changes cannot be completely ruled out.

The reduced ozone concentrations would have a number of consequences outside the areas in which the detonations occurred. The Academy study notes, for example, that the resultant increase in ultraviolet would cause "prompt incapacitating cases of sunburn in the temperate zones and snow blindness in northern countries . . "

Strange though it might seem, the increased ultraviolet radiation could also be accompanied by a drop in the average temperature. The size of the change is open to question, but the largest changes would probably occur at the higher latitudes, where crop production and ecological balances are sensitively dependent on the number of frost−free days and other factors related to average temperature. The Academy's study concluded that ozone changes due to nuclear war might decrease global surface temperatures by only negligible amounts or by as much as a few degrees. To calibrate the significance of this, the study mentioned that a cooling of even 1 degree centigrade would eliminate commercial wheat growing in Canada.

Thus, the possibility of a serious increase in ultraviolet radiation has been added to widespread radioactive fallout as a fearsome consequence of the large−scale use of nuclear weapons. And it is likely that we must reckon with still other complex and subtle processes, global in scope, which could seriously threaten the health of distant populations in the event of an all−out nuclear war.

Up to now, many of the important discoveries about nuclear weapon effects have been made not through deliberate scientific inquiry but by accident. And as the following historical examples show, there has been a series of surprises.

"Castle/Bravo" was the largest nuclear weapon ever detonated by the United States. Before it was set off at Bikini on February 28, 1954, it was expected to explode with an energy equivalent of about 8 million tons of TNT. Actually, it produced almost twice that explosive power−−equivalent to 15 million tons of TNT.

If the power of the bomb was unexpected, so were the after−effects. About 6 hours after the explosion, a fine, sandy ash began to sprinkle the Japanese fishing vessel Lucky Dragon, some 90 miles downwind of the burst point, and Rongelap Atoll, 100 miles downwind. Though 40 to 50 miles away from the proscribed test area, the vessel's crew and the islanders received heavy doses of radiation from the weapon's "fallout"−−the coral rock, soil, and other debris sucked up in the fireball and made intensively radioactive by the nuclear reaction. One radioactive isotope in the fallout, iodine−131, rapidly built up to serious concentration in the thyroid glands of the victims, particularly young Rongelapese children.

More than any other event in the decade of testing large nuclear weapons in the atmosphere, Castle/Bravo's unexpected contamination of 7,000 square miles of the Pacific Ocean dramatically illustrated how large−scale nuclear war could produce casualties on a colossal scale, far beyond the local effects of blast and fire alone.

A number of other surprises were encountered during 30 years of nuclear weapons development. For example, what was probably man's most extensive modification of the global environment to date occurred in September 1962, when a nuclear device was detonated 250 miles above Johnson Island. The 1.4−megaton burst produced an artificial belt of charged particles trapped in the earth's magnetic field. Though 98 percent of these particles were removed by natural processes after the first year, traces could be detected 6 or 7 years later. A number of satellites in low earth orbit at the time of the burst suffered severe electronic damage resulting in malfunctions and early failure. It became obvious that man now had the power to make long term changes in his near−space environment.

Another unexpected effect of high−altitude bursts was the blackout of high−frequency radio communications. Disruption of the ionosphere (which reflects radio signals back to the earth) by nuclear bursts over the Pacific has wiped out long−distance radio communications for hours at distances of up to 600 miles from the burst point.

Yet another surprise was the discovery that electromagnetic pulses can play havoc with electrical equipment itself, including some in command systems that control the nuclear arms themselves.

Much of our knowledge was thus gained by chance−−a fact which should imbue us with humility as we contemplate the remaining uncertainties (as well as the certainties) about nuclear warfare. What we have learned enables us, nonetheless, to see more clearly. We know, for instance, that some of the earlier speculations about the after−effects of a global nuclear war were as far−fetched as they were horrifying−−such as the idea that the worldwide accumulation of radioactive fallout would eliminate all life on the planet, or that it might produce a train of monstrous genetic mutations in all living things, making future life unrecognizable. And this accumulation of knowledge which enables us to rule out the more fanciful possibilities also allows us to reexamine, with some scientific rigor, other phenomena which could seriously affect the global environment and the populations of participant and nonparticipant countries alike.

This paper is an attempt to set in perspective some of the longer term effects of nuclear war on the global environment, with emphasis on areas and peoples distant from the actual targets of the weapons.

THE MECHANICS OF NUCLEAR EXPLOSIONS

In nuclear explosions, about 90 percent of the energy is released in less than one millionth of a second. Most of this is in the form of the heat and shock waves which produce the damage. It is this immediate and direct explosive power which could devastate the urban centers in a major nuclear war.

Compared with the immediate colossal destruction suffered in target areas, the more subtle, longer term effects of the remaining 10 percent of the energy released by nuclear weapons might seem a matter of secondary concern. But the dimensions of the initial catastrophe should not overshadow the after−effects of a nuclear war. They would be global, affecting nations remote from the fighting for many years after the holocaust, because of the way nuclear explosions behave in the atmosphere and the radioactive products released by nuclear bursts.

When a weapon is detonated at the surface of the earth or at low altitudes, the heat pulse vaporizes the bomb material, target, nearby structures, and underlying soil and rock, all of which become entrained in an expanding, fast−rising fireball. As the fireball rises, it expands and cools, producing the distinctive mushroom cloud, signature of nuclear explosions.

The altitude reached by the cloud depends on the force of the explosion. When yields are in the low−kiloton range, the cloud will remain in the lower atmosphere and its effects will be entirely local. But as yields exceed 30 kilotons, part of the cloud will punch into the stratosphere, which begins about 7 miles up. With yields of 2−5 megatons or more, virtually all of the cloud of radioactive debris and fine dust will climb into the stratosphere. The heavier materials reaching the lower edge of the stratosphere will soon settle out, as did the Castle/Bravo fallout at Rongelap. But the lighter particles will penetrate high into the stratosphere, to altitudes of 12 miles and more, and remain there for months and even years. Stratospheric circulation and diffusion will spread this material around the world.

RADIOACTIVE FALLOUT

Both the local and worldwide fallout hazards of nuclear explosions depend on a variety of interacting factors: weapon design, explosive force, altitude and latitude of detonation, time of year, and local weather conditions.

All present nuclear weapon designs require the splitting of heavy elements like uranium and plutonium. The energy released in this fission process is many millions of times greater, pound for pound, than the most energetic chemical reactions. The smaller nuclear weapon, in the low−kiloton range, may rely solely on the energy released by the fission process, as did the first bombs which devastated Hiroshima and Nagasaki in 1945. The larger yield nuclear weapons derive a substantial part of their explosive force from the fusion of heavy forms of hydrogen−−deuterium and tritium. Since there is virtually no limitation on the volume of fusion materials in a weapon, and the materials are less costly than fissionable materials, the fusion, "thermonuclear," or "hydrogen" bomb brought a radical increase in the explosive power of weapons. However, the fission process is still necessary to achieve the high temperatures and pressures needed to trigger the hydrogen fusion reactions. Thus, all nuclear detonations produce radioactive fragments of heavy elements fission, with the larger bursts producing an additional radiation component from the fusion process.

The nuclear fragments of heavy−element fission which are of greatest concern are those radioactive atoms (also called radionuclides) which decay by emitting energetic electrons or gamma particles. (See "Radioactivity" note.) An important characteristic here is the rate of decay. This is measured in terms of "half−life"−−the time required for one−half of the original substance to decay−−which ranges from days to thousands of years for the bomb−produced radionuclides of principal interest. (See "Nuclear Half−Life" note.) Another factor which is critical in determining the hazard of radionuclides is the chemistry of the atoms. This determines whether they will be taken up by the body through respiration or the food cycle and incorporated into tissue. If this occurs, the risk of biological damage from the destructive ionizing radiation (see "Radioactivity" note) is multiplied.

Probably the most serious threat is cesium−137, a gamma emitter with a half−life of 30 years. It is a major source of radiation in nuclear fallout, and since it parallels potassium chemistry, it is readily taken into the blood of animals and men and may be incorporated into tissue.

Other hazards are strontium−90, an electron emitter with a half−life of 28 years, and iodine−131 with a half−life of only 8 days. Strontium−90 follows calcium chemistry, so that it is readily incorporated into the bones and teeth, particularly of young children who have received milk from cows consuming contaminated forage. Iodine−131 is a similar threat to infants and children because of its concentration in the thyroid gland. In addition, there is plutonium−239, frequently used in nuclear explosives. A bone−seeker like strontium−90, it may also become lodged in the lungs, where its intense local radiation can cause cancer or other damage. Plutonium−239 decays through emission of an alpha particle (helium nucleus) and has a half−life of 24,000 years.

To the extent that hydrogen fusion contributes to the explosive force of a weapon, two other radionuclides will be released: tritium (hydrogen−3), an electron emitter with a half−life of 12 years, and carbon−14, an electron emitter with a half−life of 5,730 years. Both are taken up through the food cycle and readily incorporated in organic matter.

Three types of radiation damage may occur: bodily damage (mainly leukemia and cancers of the thyroid, lung, breast, bone, and gastrointestinal tract); genetic damage (birth defects and constitutional and degenerative diseases due to gonodal damage suffered by parents); and development and growth damage (primarily growth and mental retardation of unborn infants and young children). Since heavy radiation doses of about 20 roentgen or more (see "Radioactivity" note) are necessary to produce developmental defects, these effects would probably be confined to areas of heavy local fallout in the nuclear combatant nations and would not become a global problem.

A. Local Fallout

Most of the radiation hazard from nuclear bursts comes from short−lived radionuclides external to the body; these are generally confined to the locality downwind of the weapon burst point. This radiation hazard comes from radioactive fission fragments with half−lives of seconds to a few months, and from soil and other materials in the vicinity of the burst made radioactive by the intense neutron flux of the fission and fusion reactions.

It has been estimated that a weapon with a fission yield of 1 million tons TNT equivalent power (1 megaton) exploded at ground level in a 15 miles−per−hour wind would produce fallout in an ellipse extending hundreds of miles downwind from the burst point. At a distance of 20−25 miles downwind, a lethal radiation dose (600 rads) would be accumulated by a person who did not find shelter within 25 minutes after the time the fallout began. At a distance of 40−45 miles, a person would have at most 3 hours after the fallout began to find shelter. Considerably smaller radiation doses will make people seriously ill. Thus, the survival prospects of persons immediately downwind of the burst point would be slim unless they could be sheltered or evacuated.

It has been estimated that an attack on U.S. population centers by 100 weapons of one−megaton fission yield would kill up to 20 percent of the population immediately through blast, heat, ground shock and instant radiation effects (neutrons and gamma rays); an attack with 1,000 such weapons would destroy immediately almost half the U.S. population. These figures do not include additional deaths from fires, lack of medical attention, starvation, or the lethal fallout showering to the ground downwind of the burst points of the weapons.

Most of the bomb−produced radionuclides decay rapidly. Even so, beyond the blast radius of the exploding weapons there would be areas ("hot spots") the survivors could not enter because of radioactive contamination from long−lived radioactive isotopes like strontium−90 or cesium−137, which can be concentrated through the food chain and incorporated into the body. The damage caused would be internal, with the injurious effects appearing over many years. For the survivors of a nuclear war, this lingering radiation hazard could represent a grave threat for as long as 1 to 5 years after the attack.

B. Worldwide Effects of Fallout

Much of our knowledge of the production and distribution of radionuclides has been derived from the period of intensive nuclear testing in the atmosphere during the 1950's and early 1960's. It is estimated that more than 500 megatons of nuclear yield were detonated in the atmosphere between 1945 and 1971, about half of this yield being produced by a fission reaction. The peak occurred in 1961−62, when a total of 340 megatons were detonated in the atmosphere by the United States and Soviet Union. The limited nuclear test ban treaty of 1963 ended atmospheric testing for the United States, Britain, and the Soviet Union, but two major non−signatories, France and China, continued nuclear testing at the rate of about 5 megatons annually. (France now conducts its nuclear tests underground.)

A U.N. scientific committee has estimated that the cumulative per capita dose to the world's population up to the year 2000 as a result of atmospheric testing through 1970 (cutoff date of the study) will be the equivalent of 2 years' exposure to natural background radiation on the earth's surface. For the bulk of the world's population, internal and external radiation doses of natural origin amount to less than one−tenth rad annually. Thus nuclear testing to date does not appear to pose a severe radiation threat in global terms. But a nuclear war releasing 10 or 100 times the total yield of all previous weapons tests could pose a far greater worldwide threat.

The biological effects of all forms of ionizing radiation have been calculated within broad ranges by the National Academy of Sciences. Based on these calculations, fallout from the 500−plus megatons of nuclear testing through 1970 will produce between 2 and 25 cases of genetic disease per million live births in the next generation. This means that between 3 and 50 persons per billion births in the post−testing generation will have genetic damage for each megaton of nuclear yield exploded. With similar uncertainty, it is possible to estimate that the induction of cancers would range from 75 to 300 cases per megaton for each billion people in the post−test generation.

If we apply these very rough yardsticks to a large−scale nuclear war in which 10,000 megatons of nuclear force are detonated, the effects on a world population of 5 billion appear enormous. Allowing for uncertainties about the dynamics of a possible nuclear war, radiation−induced cancers and genetic damage together over 30 years are estimated to range from 1.5 to 30 million for the world population as a whole. This would mean one additional case for every 100 to 3,000 people or about 1/2 percent to 15 percent of the estimated peacetime cancer death rate in developed countries. As will be seen, moreover, there could be other, less well understood effects which would drastically increase suffering and death.

ALTERATIONS OF THE GLOBAL ENVIRONMENT

A nuclear war would involve such prodigious and concentrated short term release of high temperature energy that it is necessary to consider a variety of potential environmental effects.

It is true that the energy of nuclear weapons is dwarfed by many natural phenomena. A large hurricane may have the power of a million hydrogen bombs. But the energy release of even the most severe weather is diffuse; it occurs over wide areas, and the difference in temperature between the storm system and the surrounding atmosphere is relatively small. Nuclear detonations are just the opposite−−highly concentrated with reaction temperatures up to tens of millions of degrees Fahrenheit. Because they are so different from natural processes, it is necessary to examine their potential for altering the environment in several contexts.

A. High Altitude Dust

It has been estimated that a 10,000−megaton war with half the weapons exploding at ground level would tear up some 25 billion cubic meters of rock and soil, injecting a substantial amount of fine dust and particles into the stratosphere. This is roughly twice the volume of material blasted loose by the Indonesian volcano, Krakatoa, whose explosion in 1883 was the most powerful terrestrial event ever recorded. Sunsets around the world were noticeably reddened for several years after the Krakatoa eruption, indicating that large amounts of volcanic dust had entered the stratosphere.

Subsequent studies of large volcanic explosions, such as Mt. Agung on Bali in 1963, have raised the possibility that large−scale injection of dust into the stratosphere would reduce sunlight intensities and temperatures at the surface, while increasing the absorption of heat in the upper atmosphere.

The resultant minor changes in temperature and sunlight could affect crop production. However, no catastrophic worldwide changes have resulted from volcanic explosions, so it is doubtful that the gross injection of particulates into the stratosphere by a 10,000−megaton conflict would, by itself, lead to major global climate changes.

B. Ozone

More worrisome is the possible effect of nuclear explosions on ozone in the stratosphere. Not until the 20th century was the unique and paradoxical role of ozone fully recognized. On the other hand, in concentrations greater than I part per million in the air we breathe, ozone is toxic; one major American city, Los Angeles, has established a procedure for ozone alerts and warnings. On the other hand, ozone is a critically important feature of the stratosphere from the standpoint of maintaining life on the earth.

The reason is that while oxygen and nitrogen in the upper reaches of the atmosphere can block out solar ultraviolet photons with wavelengths shorter than 2,420 angstroms (A), ozone is the only effective shield in the atmosphere against solar ultraviolet radiation between 2,500 and 3,000 A in wavelength. (See note 5.) Although ozone is extremely efficient at filtering out solar ultraviolet in 2,500−3,OOO A region of the spectrum, some does get through at the higher end of the spectrum. Ultraviolet rays in the range of 2,800 to 3,200 A which cause sunburn, prematurely age human skin and produce skin cancers. As early as 1840, arctic snow blindness was attributed to solar ultraviolet; and we have since found that intense ultraviolet radiation can inhibit photosynthesis in plants, stunt plant growth, damage bacteria, fungi, higher plants, insects and annuals, and produce genetic alterations.

Despite the important role ozone plays in assuring a liveable environment at the earth's surface, the total quantity of ozone in the atmosphere is quite small, only about 3 parts per million. Furthermore, ozone is not a durable or static constituent of the atmosphere. It is constantly created, destroyed, and recreated by natural processes, so that the amount of ozone present at any given time is a function of the equilibrium reached between the creative and destructive chemical reactions and the solar radiation reaching the upper stratosphere.

The mechanism for the production of ozone is the absorption by oxygen molecules (O2) of relatively short−wavelength ultraviolet light. The oxygen molecule separates into two atoms of free oxygen, which immediately unite with other oxygen molecules on the surfaces of particles in the upper atmosphere. It is this union which forms ozone, or O3. The heat released by the ozone−forming process is the reason for the curious increase with altitude of the temperature of the stratosphere (the base of which is about 36,000 feet above the earth's surface).

While the natural chemical reaction produces about 4,500 tons of ozone per second in the stratosphere, this is offset by other natural chemical reactions which break down the ozone. By far the most significant involves nitric oxide (NO) which breaks ozone (O_3) into molecules. This effect was discovered only in the last few years in studies of the environmental problems which might be encountered if large fleets of supersonic transport aircraft operate routinely in the lower stratosphere. According to a report by Dr. Harold S. Johnston, University of California at Berkeley−− prepared for the Department of Transportation's Climatic Impact Assessment Program−−it now appears that the NO reaction is normally responsible for 50 to 70 percent of the destruction of ozone.

In the natural environment, there is a variety of means for the production of NO and its transport into the stratosphere. Soil bacteria produce nitrous oxide (N_2O) which enters the lower atmosphere and slowly diffuses into the stratosphere, where it reacts with free oxygen (O) to form two NO molecules. Another mechanism for NO production in the lower atmosphere may be lightning discharges, and while NO is quickly washed out of the lower atmosphere by rain, some of it may reach the stratosphere. Additional amounts of NO are produced directly in the stratosphere by cosmic rays from the sun and interstellar sources.

It is because of this catalytic role which nitric oxide plays in the destruction of ozone that it is important to consider the effects of high−yield nuclear explosions on the ozone layer. The nuclear fireball and the air entrained within it are subjected to great heat, followed by relatively rapid cooling. These conditions are ideal for the production of tremendous amounts of NO from the air. It has been estimated that as much as 5,000 tons of nitric oxide is produced for each megaton of nuclear explosive power.

What would be the effects of nitric oxides driven into the stratosphere by an all−out nuclear war, involving the detonation of 10,000 megatons of explosive force in the northern hemisphere? According to the recent National Academy of Sciences study, the nitric oxide produced by the weapons could reduce the ozone levels in the northern hemisphere by as much as 30 to 70 percent.

To begin with, a depleted ozone layer would reflect back to the earth's surface less heat than would normally be the case, thus causing a drop in temperature−−perhaps enough to produce serious effects on agriculture. Other changes, such as increased amounts of dust or different vegetation, might subsequently reverse this drop in temperature−−but on the other hand, it might increase it.

Probably more important, life on earth has largely evolved within the protective ozone shield and is presently adapted rather precisely to the amount of solar ultraviolet which does get through. To defend themselves against this low level of ultraviolet, evolved external shielding (feathers, fur, cuticular waxes on fruit), internal shielding (melanin pigment in human skin, flavenoids in plant tissue), avoidance strategies (plankton migration to greater depths in the daytime, shade−seeking by desert iguanas) and, in almost all organisms but placental mammals, elaborate mechanisms to repair photochemical damage.

It is possible, however, that a major increase in solar ultraviolet might overwhelm the defenses of some and perhaps many terrestrial life forms. Both direct and indirect damage would then occur among the bacteria, insects, plants, and other links in the ecosystems on which human well−being depends. This disruption, particularly if it occurred in the aftermath of a major war involving many other dislocations, could pose a serious additional threat to the recovery of postwar society. The National Academy of Sciences report concludes that in 20 years the ecological systems would have essentially recovered from the increase in ultraviolet radiation−−though not necessarily from radioactivity or other damage in areas close to the war zone. However, a delayed effect of the increase in ultraviolet radiation would be an estimated 3 to 30 percent increase in skin cancer for 40 years in the Northern Hemisphere's mid−latitudes.

SOME CONCLUSIONS

We have considered the problems of large−scale nuclear war from the standpoint of the countries not under direct attack, and the difficulties they might encounter in postwar recovery. It is true that most of the horror and tragedy of nuclear war would be visited on the populations subject to direct attack, who would doubtless have to cope with extreme and perhaps insuperable obstacles in seeking to reestablish their own societies. It is no less apparent, however, that other nations, including those remote from the combat, could suffer heavily because of damage to the global environment.

Finally, at least brief mention should be made of the global effects resulting from disruption of economic activities and communications. Since 1970, an increasing fraction of the human race has been losing the battle for self−sufficiency in food, and must rely on heavy imports. A major disruption of agriculture and transportation in the grain−exporting and manufacturing countries could thus prove disastrous to countries importing food, farm machinery, and fertilizers−−especially those which are already struggling with the threat of widespread starvation. Moreover, virtually every economic area, from food and medicines to fuel and growth engendering industries, the less−developed countries would find they could not rely on the "undamaged" remainder of the developed world for trade essentials: in the wake of a nuclear war the industrial powers directly involved would themselves have to compete for resources with those countries that today are described as "less−developed."

Similarly, the disruption of international communications−−satellites, cables, and even high frequency radio links−−could be a major obstacle to international recovery efforts.

In attempting to project the after−effects of a major nuclear war, we have considered separately the various kinds of damage that could occur. It is also quite possible, however, that interactions might take place among these effects, so that one type of damage would couple with another to produce new and unexpected hazards. For example, we can assess individually the consequences of heavy worldwide radiation fallout and increased solar ultraviolet, but we do not know whether the two acting together might significantly increase human, animal, or plant susceptibility to disease. We can conclude that massive dust injection into the stratosphere, even greater in scale than Krakatoa, is unlikely by itself to produce significant climatic and environmental change, but we cannot rule out interactions with other phenomena, such as ozone depletion, which might produce utterly unexpected results.

We have come to realize that nuclear weapons can be as unpredictable as they are deadly in their effects. Despite some 30 years of development and study, there is still much that we do not know. This is particularly true when we consider the global effects of a large−scale nuclear war.

Note 1: Nuclear Weapons Yield

The most widely used standard for measuring the power of nuclear weapons is "yield," expressed as the quantity of chemical explosive (TNT) that would produce the same energy release. The first atomic weapon which leveled Hiroshima in 1945, had a yield of 13 kilotons; that is, the explosive power of 13,000 tons of TNT. (The largest conventional bomb dropped in World War II contained about 10 tons of TNT.)

Since Hiroshima, the yields or explosive power of nuclear weapons have vastly increased. The world's largest nuclear detonation, set off in 1962 by the Soviet Union, had a yield of 58 megatons−−equivalent to 58 million tons of TNT. A modern ballistic missile may carry warhead yields up to 20 or more megatons.

Even the most violent wars of recent history have been relatively limited in terms of the total destructive power of the non−nuclear weapons used. A single aircraft or ballistic missile today can carry a nuclear explosive force surpassing that of all the non−nuclear bombs used in recent wars. The number of nuclear bombs and missiles the superpowers now possess runs into the thousands.

Note 2: Nuclear Weapons Design

Nuclear weapons depend on two fundamentally different types of nuclear reactions, each of which releases energy:

Fission, which involves the splitting of heavy elements (e.g. uranium); and fusion, which involves the combining of light elements (e.g. hydrogen).

Fission requires that a minimum amount of material or "critical mass" be brought together in contact for the nuclear explosion to take place. The more efficient fission weapons tend to fall in the yield range of tens of kilotons. Higher explosive yields become increasingly complex and impractical.

Nuclear fusion permits the design of weapons of virtually limitless power. In fusion, according to nuclear theory, when the nuclei of light atoms like hydrogen are joined, the mass of the fused nucleus is lighter than the two original nuclei; the loss is expressed as energy. By the 1930's, physicists had concluded that this was the process which powered the sun and stars; but the nuclear fusion process remained only of theoretical interest until it was discovered that an atomic fission bomb might be used as a "trigger" to produce, within one− or two−millionths of a second, the intense pressure and temperature necessary to set off the fusion reaction.

Fusion permits the design of weapons of almost limitless power, using materials that are far less costly.

Note 3: Radioactivity

Most familiar natural elements like hydrogen, oxygen, gold, and lead are stable, and enduring unless acted upon by outside forces. But almost all elements can exist in unstable forms. The nuclei of these unstable "isotopes," as they are called, are "uncomfortable" with the particular mixture of nuclear particles comprising them, and they decrease this internal stress through the process of radioactive decay.

The three basic modes of radioactive decay are the emission of alpha, beta and gamma radiation:

Alpha−−Unstable nuclei frequently emit alpha particles, actually helium nuclei consisting of two protons and two neutrons. By far the most massive of the decay particles, it is also the slowest, rarely exceeding one−tenth the velocity of light. As a result, its penetrating power is weak, and it can usually be stopped by a piece of paper. But if alpha emitters like plutonium are incorporated in the body, they pose a serious cancer threat.

Beta−−Another form of radioactive decay is the emission of a beta particle, or electron. The beta particle has only about one seven−thousandth the mass of the alpha particle, but its velocity is very much greater, as much as eight−tenths the velocity of light. As a result, beta particles can penetrate far more deeply into bodily tissue and external doses of beta radiation represent a significantly greater threat than the slower, heavier alpha particles. Beta−emitting isotopes are as harmful as alpha emitters if taken up by the body.

Gamma−−In some decay processes, the emission is a photon having no mass at all and traveling at the speed of light. Radio waves, visible light, radiant heat, and X−rays are all photons, differing only in the energy level each carries. The gamma ray is similar to the X−ray photon, but far more penetrating (it can traverse several inches of concrete). It is capable of doing great damage in the body.

Common to all three types of nuclear decay radiation is their ability to ionize (i.e., unbalance electrically) the neutral atoms through which they pass, that is, give them a net electrical charge. The alpha particle, carrying a positive electrical charge, pulls electrons from the atoms through which it passes, while negatively charged beta particles can push electrons out of neutral atoms. If energetic betas pass sufficiently close to atomic nuclei, they can produce X−rays which themselves can ionize additional neutral atoms. Massless but energetic gamma rays can knock electrons out of neutral atoms in the same fashion as X−rays, leaving them ionized. A single particle of radiation can ionize hundreds of neutral atoms in the tissue in multiple collisions before all its energy is absorbed. This disrupts the chemical bonds for critically important cell structures like the cytoplasm, which carries the cell's genetic blueprints, and also produces chemical constituents which can cause as much damage as the original ionizing radiation.

For convenience, a unit of radiation dose called the "rad" has been adopted. It measures the amount of ionization produced per unit volume by the particles from radioactive decay.

Note 4: Nuclear Half−Life

The concept of "half−life" is basic to an understanding of radioactive decay of unstable nuclei.

Unlike physical "systems"−−bacteria, animals, men and stars−−unstable isotopes do not individually have a predictable life span. There is no way of forecasting when a single unstable nucleus will decay.

Nevertheless, it is possible to get around the random behavior of an individual nucleus by dealing statistically with large numbers of nuclei of a particular radioactive isotope. In the case of thorium−232, for example, radioactive decay proceeds so slowly that 14 billion years must elapse before one−half of an initial quantity decayed to a more stable configuration. Thus the half−life of this isotope is 14 billion years. After the elapse of second half−life (another 14 billion years), only one−fourth of the original quantity of thorium−232 would remain, one eighth after the third half−life, and so on.

Most manmade radioactive isotopes have much shorter half−lives, ranging from seconds or days up to thousands of years. Plutonium−239 (a manmade isotope) has a half−life of 24,000 years.

For the most common uranium isotope, U−238, the half−life is 4.5 billion years, about the age of the solar system. The much scarcer, fissionable isotope of uranium, U−235, has a half−life of 700 million years, indicating that its present abundance is only about 1 percent of the amount present when the solar system was born.

Note 5: Oxygen, Ozone and Ultraviolet Radiation

Oxygen, vital to breathing creatures, constitutes about one−fifth of the earth's atmosphere. It occasionally occurs as a single atom in the atmosphere at high temperature, but it usually combines with a second oxygen atom to form molecular oxygen (O_2). The oxygen in the air we breathe consists primarily of this stable form.

Oxygen has also a third chemical form in which three oxygen atoms are bound together in a single molecule (03), called ozone. Though less stable and far more rare than O_2, and principally confined to upper levels of the stratosphere, both molecular oxygen and ozone play a vital role in shielding the earth from harmful components of solar radiation.

Most harmful radiation is in the "ultraviolet" region of the solar spectrum, invisible to the eye at short wavelengths (under 3,000 A). (An angstrom unit−−A−−is an exceedingly short unit of length−−10 billionths of a centimeter, or about 4 billionths of an inch.) Unlike X−rays, ultraviolet photons are not "hard" enough to ionize atoms, but pack enough energy to break down the chemical bonds of molecules in living cells and produce a variety of biological and genetic abnormalities, including tumors and cancers.

Fortunately, because of the earth's atmosphere, only a trace of this dangerous ultraviolet radiation actually reaches the earth. By the time sunlight reaches the top of the stratosphere, at about 30 miles altitude, almost all the radiation shorter than 1,900 A has been absorbed by molecules of nitrogen and oxygen. Within the stratosphere itself, molecular oxygen (02) absorbs the longer wavelengths of ultraviolet, up to 2,420 A; and ozone (O_3) is formed as a result of this absorption process. It is this ozone then which absorbs almost all of the remaining ultraviolet wavelengths up to about 3,000 A, so that almost all of the dangerous solar radiation is cut off before it reaches the earth's surface.