Chapter 6
The Physical Consequences of Nuclear Weapons Use

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The considerable body of knowledge on the consequences of nuclear weapons use—accumulated through an extensive, sustained, and costly national investment in both testing and analysis over two-thirds of a century—underlies all operational and policy decisions related to US nuclear planning. We find that even when consideration is restricted to the physical consequences of nuclear weapons use, where our knowledge base on effects of primary importance to military planners is substantial, there remain very large uncertainties. These uncertainties exist in no small part because many facets of the issue, such as the effects on the infrastructures that sustain society, have not been adequately investigated. Other significant uncertainties in physical consequences remain because important phenomena were uncovered late in the nuclear test program, have been inadequately studied, are inherently difficult to model, or are the result of new weapon developments. Nonphysical consequences, such as social, psychological, political, and full economic effects, are even more difficult to quantify and have never been on any funding agency's radar screen. As a result, the physical consequences of a nuclear conflict tend to have been underestimated, and a full-spectrum all-effects assessment is not within anyone's grasp now or in the foreseeable future. The continuing brain drain of nuclear scientists and the general failure to recognize the post–Cold War importance of accurate and comprehensive nuclear consequence assessments, especially for scenarios of increasing concern at the lower end of the scale of catastrophe, do not bode well for improving this situation. This paper outlines the current state of our knowledge base and presents recommendations for strengthening it.

So long as the United States anticipates the potential for nuclear weapons use, by either its own actions or hostile actions against US interests, a more

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complete understanding of the full range of consequences is vital. This knowledge will support critical operational planning and inform policy choices, including the following:

- **Developing and evaluating war plans.** To employ weapons efficiently and to accurately predict whether they will achieve damage goals, we must be able to estimate the damage weapons will inflict on the variety of targets in a war plan. Similarly, to minimize casualties or collateral damage, as is often the mandate in the post–Cold War world, we must be able to accurately predict the effects of using nuclear weapons.
- **Managing consequences.** To develop consequence management plans, we must understand nuclear weapons effects sufficiently to answer questions such as the following: Under what circumstances should people shelter in place or evacuate? Which evacuation routes are more likely to be free of fallout? How long can first responders operate while exposed to radiation at various levels? How many deaths and injuries of various types can we expect? How far apart should we locate critical government and commercial backup systems? Are electromagnetic pulse (EMP) hardening measures adequate?
- **Determining arsenal size.** The mantra of nuclear deterrence is that threatening "unacceptable" retaliatory damage will prevent war. Clearly, whatever the criteria for unacceptable damage, one must assess whether it is achievable with a specific arsenal. Thus, determining how many nuclear weapons are enough depends critically on the ability to assess the consequences of their use. However, traditional military assessments omit many significant damage mechanisms (e.g., fire, atmospheric contamination); thus, more comprehensive consequence assessments might support lower arsenal levels.
- **Contributing to forensics.** With more and more states and potentially non-state actors acquiring nuclear weapons and delivery means that cannot be traced back to the country of origin, it may not be clear which actor is responsible for a nuclear detonation. Analysts can estimate the yield of the weapon and other information about its design by studying the effects of the

detonation. Such analysis contributes to forensics, the science of analyzing the physical evidence from a nuclear detonation, which provides a basis for attribution.

- **Avoiding unintended and unwanted effects.** Finally, nuclear weapons have geographically extended effects that are generally undesirable and possibly catastrophic for belligerent and nonbelligerent alike. In addition to assessing the intended effects of nuclear weapons use, those making policies and decisions on the use of nuclear weapons must also evaluate these unintended effects.

Clearly, the utility of a consequence assessment of nuclear weapons use and the level of uncertainty that we can tolerate depend on the decisions the assessment is intended to support. This chapter summarizes the state of knowledge and the corresponding state of uncertainty presently available to support such operational and policy choices.

Overview

Nuclear weapons were first developed in the 1940s. We have since amassed a considerable body of knowledge on the consequences of their use by studying the two instances of actual use and also through an extensive, sustained, and costly national investment in both testing and analysis. The question we address in this chapter is whether the existing body of accumulated knowledge is sufficient to support a nuclear weapons use consequence assessment, either as an integral component of a nuclear deterrence failure risk assessment or a stand-alone analysis informing specific decisions.

We posit that the answer to this question is a resounding *sometimes*. We review why, despite the Department of Defense's enormous investment of resources to understand the effects of nuclear weapons, we do not have sufficient understanding to assess the consequences of nuclear weapons use in many significant scenarios. We then ask how well we must understand the consequences to enable a useful assessment. The answer will be seen to depend on the overall magnitude of the consequences as well as the nature of the decision the assessment is intended to inform.

We begin with an overview of our experience with the effects of nuclear weapons, first discussing the Trinity explosion and the nuclear attacks on Japan and then discussing the Cold War nuclear weapons test and analysis program. We emphasize major surprises uncovered during testing, by analyses of non-Department of Defense scientists, and by observations of analogous natural phenomena. We then summarize, effect by effect, what we have learned from this experience, as well as the steady accumulation and refinement of knowledge through the weapons effects research program, and what important uncertainties remain. We pose several potential scenarios of nuclear weapons use to provide a more holistic perspective on the totality of nuclear effects. Looking beyond the current knowledge base, we identify trends relevant to our future ability to support a consequence assessment. We conclude by evaluating whether and under what circumstances the current knowledge base can support a useful assessment. And, finally, in light of current trends, we provide several recommendations for the Department of Defense to strengthen our knowledge base.

Before proceeding, we must emphasize an important caveat. Our discussion focuses on the physical consequences of nuclear weapons use. Only tangentially considered are social and psychological effects and other such intangibles. Although lack of such consideration reflects a serious gap in our knowledge and methodological tools, physical consequences by themselves represent an important component of a more complete assessment and provide the essential foundation for understanding nonphysical effects. Restricting attention to physical consequences thus provides a lower bound and a first step to any determination of the consequences of nuclear weapons use.

Historical Context

The world's first nuclear test, with the code name Trinity, took place on July 16, 1945, near Socorro, New Mexico, at a location that is now part of the White Sands Missile Range. Pretest yield predictions[1] varied widely—from a zero-yield fizzle to forty-five kilotons[2]—and it took a number of years to converge to a best estimate of twenty-one kilotons.[3] The yield of Little Boy, detonated over Hiroshima in history's second nuclear explosion, remains a matter of contention to the present day. Estimated yields range from six to twenty-three kilotons, converging to the current best estimate of fifteen kilotons.[4] In many ways, our uncertainty in the yield of these first nuclear events is paradigmatic of the large uncertainties that still attend nuclear phenomenology and challenge our ability to perform a meaningful consequence assessment today.

The United States' use of nuclear weapons against Japan at the end of World War II was also accompanied by a number of surprises and uncertainties. Although military planners anticipated that the blast damage would result in massive destruction, no one had predicted the ensuing catastrophic firestorms or the black rain containing radioactive soot and dust that contaminated areas far from ground zero.[5] Postwar investigations attribute the majority of the estimated two hundred thousand casualties to inflicted burns rather than to the nuclear shock wave as originally thought.[6] Additionally, there are large uncertainties in casualty estimates because hospitals and local government population records were destroyed and some of the health effects resulting from radiological exposure were slow to manifest.

Figure 6.1. Trinity Fireball. As the culmination of the Manhattan Project, the Trinity atomic test was conducted in New Mexico on July 16, 1945. This photograph shows the shape of the fireball, which had a radius of approximately four hundred feet at sixteen milliseconds after detonation. Note the dust skirt traversing the terrain ahead of the main blast wave.[7] (Image courtesy of the Department of Defense.)

Since World War II, the United States has undertaken an extensive nuclear test and analysis program, with the last atmospheric test conducted in 1962 and the last underground test in 1992. During that period, the United States conducted more than one thousand nuclear tests for purposes of warhead design and development, stockpile assurance and safety, and weapon effects, with the last category constituting approximately 10 percent of the total.[8] Although it is difficult to assign a definitive figure, the most authoritative estimate based on publicly available information suggests a lower bound of about eight trillion dollars (adjusted to 2012 dollars) for development, deployment, and maintenance of the US nuclear arsenal from the Manhattan Project through 1996.[9]

Most of this cost is attributed to building and maintaining the variety of delivery platforms and the nuclear command and control system. As extensive as nuclear weapons effects research has been, it accounts for less than 0.5 percent of the total cost of the nuclear weapons enterprise.[10]

Our national investment in research on the effects of nuclear weapons developed out of Cold War exigencies, with a focus on the damage expectancy projected for each weapon–target combination. This information provided the basis for developing the Single Integrated Operational Plan and the hypothetical Red Integrated Strategic Offensive Plan, which together envisioned a strategic nuclear exchange between the United States and the Soviet Union involving up to thousands of nuclear weapons targeted at nuclear forces, leadership, conventional military, and war-supporting industry.[11] Other military applications produced manuals for ground combatants, which established doctrine for tactical operations on a nuclear battlefield and for protecting the force from the effects of nuclear weapon detonations.

Left out of such developments were single low-yield (less than twenty kiloton) weapons that might be part of a modern terrorist or rogue state threat today; the effects of weapons with sophisticated designs that might be achieved by a technologically advanced adversary; and some known weapon effects, such as fire damage and EMP effects, to which less attention was paid because they are difficult to quantify and hence were never included in the damage expectancy calculus. Blast and shock effects, in contrast, were understood to be the primary damage mechanisms and also considered more tractable, requiring less detailed information regarding the physical features and operational state of the target. Accordingly, these effects enjoyed focused attention and healthy funding and they are thus relatively well understood.

Surprises

Another persistent theme throughout the history of nuclear effects knowledge acquisition is the element of surprise. Many surprises pertain to how military systems responded when exposed to actual and simulated nuclear test environments; open discussion of these instances is constrained by security and classification restrictions. However, some of the greatest surprises are completely unclassified. Among these are effects that simply had not previously occurred to Department of Defense scientists, including some that first became evident through observations of naturally occurring phenomena.

Radiation Belt Pumping and High-Altitude EMP

Perhaps the most glaring surprises came during the 1962 high-altitude test series nicknamed Operation Fishbowl. In particular, the July 1962 exoatmospheric detonation of Starfish Prime, a 1.4-megaton nuclear test explosion at a height of burst of four hundred kilometers over the Pacific Ocean, produced two significant and unwelcome surprises. One surprise dawned only after a number of months when Telstar 1, an AT&T telecommunications satellite that first demonstrated the feasibility of transmitting television signals by space relay, died prematurely after only a few months of successful operation.[12] The same fate befell other satellites,[13] and within a short span of time, all publicly acknowledged space assets were disabled. Thus was discovered the phenomenon of "pumping the belts," wherein bomb-generated electrons enhanced natural radiation belts encircling Earth, creating an unanticipated hazard for satellites orbiting through the newly hostile environment. This observation, along with known prompt radiation effects, helped motivate the Department of Defense to invest significantly over the following thirty years in underground nuclear testing, aboveground radiation simulators, and computational approaches. With this investment, the Department of Defense hoped to better understand the effects of the full complement of ionizing radiation on electronic systems and to develop appropriate hardening measures.

The other major surprise from Starfish Prime was the discovery of a high-altitude EMP as some street lights in Honolulu, eight hundred nautical miles from the detonation, went dark at the time of the explosion and other instances of electronic interference manifested.[14] Within a few years of the test, a satisfactory physics model that explained the large EMP footprint had been developed.[15] However, the United States' adherence to the terms of the Atmospheric Test Ban Treaty—signed by President Kennedy in 1962 and ratified by the Senate in 1963—precluded empirical validation of the theoretical model.

Over the next two decades, a robust research and development effort executed by the Defense Nuclear Agency greatly expanded understanding of this phenomenon as the military scrambled to identify vulnerabilities and develop hardening methodologies to protect critical strategic military assets from the threat of EMP exposure. Researchers used pulse power sources coupled to suitable antennae to expose many key assets to simulated environments, and they quantified the electronic systems' thresholds for damage caused by exposure to EMP levels. No comparable effort was ever expended to explore the vulnerabilities of the nation's civil infrastructures to the potential perils of an EMP attack.

In the 1990s, after the dissolution of the former Soviet Union, the Department of Defense investment in expanded understanding of all matters nuclear, including EMP, declined precipitously as nuclear effects programs fell prey to the quest for the "peace dividend." Meanwhile, as electronic technology evolved toward new generations of low-power integrated circuits with ever smaller feature sizes—increasing their inherent susceptibility to EMP-induced damage—our ability to predict survivability to EMP environments grew increasingly uncertain. At the same time, our military forces became increasingly reliant on potentially vulnerable electronic warfare systems. The late 1990s also coincided with a push, still ongoing, to increase reliance on commercial off-the-shelf acquisition to complement the standard Military Specification (MILSPEC) approach. While a MILSPEC-focused acquisition system delivered us the twenty-six-page MILSPEC for the chocolate brownie[16] and the fabled seven-thousand-dollar coffee pot,[17] it also ensured that standards were defined based on military requirements, whereas an emphasis on commercial off-the-shelf skewed requirements in the direction of what was commercially available.

As a result of these developments, by the late 1990s, investment in EMP-related matters had declined and uncertainties had grown to such a degree that concerns initially confined to a relatively ineffectual internal Department of Defense advocacy had attracted the attention of Congress. In 2001, Congress stood up the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack (hereinafter referred to as the EMP Commission) and charged it with developing recommendations that addressed both military and hitherto neglected civilian infrastructures.[18] The EMP Commission's final report, delivered in January 2009, highlights the potential for catastrophic, multiyear EMP effects that might cause irreparable harm to the installed electrical infrastructure and ultimately lead to a large number of deaths due to the inability of critical infrastructures to sustain the population.[19] To date, there is scant evidence that the report's recommendations to protect these infrastructures have resulted in concrete actions by the Department of Homeland Security.

Figure 6.2. The Starfish Prime High-Altitude Test. This 1.4-megaton detonation at an altitude of four hundred kilometers on July 9, 1962, created copious electrons from the beta decay of fission products. These electrons became trapped in the Van Allen radiation belts, creating a spectacular auroral display and a hazardous environment that led to the demise of satellites orbiting near this altitude. Eight hundred nautical miles away, an EMP from the blast turned off some street lights in downtown Honolulu. The United States conducted only five high-altitude tests, limiting our understanding of EMP and other high-altitude nuclear effects. (Image courtesy of Los Alamos National Laboratory.)

The EMP Commission report also contains recommendations to address classified deficiencies of both knowledge and practice related to the vulnerabilities and hardening of military systems. In its response, the Department of Defense concurred with all the substantive recommendations. The secretary of defense promulgated a classified action plan, and out-year funding was budgeted to address shortcomings. Subsequently, the Department of Defense reinstituted EMP testing on major systems; stood up a permanent Defense Science Board committee to follow EMP matters; established a special EMP action officer in the Office of the Assistant Secretary of Defense for Nuclear, Chemical, and Biological Matters; and incorporated EMP survivability in a policy instruction.[20] In addition, the US Strategic Command reinvigorated an EMP hardness certification program.

The decline in funding has been reversed, and EMP is once again an important consideration in system survivability. Notwithstanding these developments, there is no guarantee that EMP will continue to receive the high-level interest needed to maintain these developments indefinitely. Experience shows that without the sustained interest of the highest levels of Department of Defense leadership, EMP research and hardness surveillance and maintenance programs will be at risk.

Ozone Depletion

In the 1970s, during the prolonged political-economic-scientific debate over the fate of the proposed US Supersonic Transport, a powerful argument contributing to its demise was the notion that nitrogen oxides produced in its exhaust would chemically combine to reduce the atmospheric layer of ozone protecting human life from the harmful effects of solar ultraviolet radiation.[21] Subsequently, similar concerns that had not been previously considered by Department of Defense scientists were raised against the prospect of renewed nuclear testing when models indicated nitrogen oxides might be produced by the atmospheric chemistry catalyzed by the thermal environment of a rising nuclear fireball.[22]

In 1982, in an emotive and persuasive presentation, Jonathan Schell painted the case against nuclear war—as if it were not already bad enough—as an apocalyptic scenario in which all human life on Earth might be extinguished as a result of nuclear weapon-induced ozone depletion. In Schell's hauntingly elegiac description, nuclear war perpetrates a "second death"—not merely the extinction of all that exists but, with the death of future generations of the unborn, the extinction of all that might ever have been—leaving behind only an "empire of insects and grass."[23]

However, a funny thing happened on the way to ozone Armageddon. With the confluence of both changed external circumstances and the eventual acceptance of prior contradictory scientific observations, both officialdom and the public stopped worrying about it. The changed external circumstances were by far the most noticeable and dramatic. Arms control treaties and agreements resulted in significant reductions in the numbers of weapons in the nuclear arsenals of the United States and the Soviet Union. At the same time, accuracy improvements in the missile-delivered warheads meant that very large yields were no longer required to achieve high damage expectancy. As a result of these changes, the total yield calculated in a worst-case strategic arsenal exchange between warring states decreased significantly from the 10,000-megaton exchange, which underlies Schell's lament. By 2007, the total number of deployed warheads was less than a quarter of that available in 1982,[24] while the total yield of the US operational arsenal was estimated at no more than 1,430 megatons.[25] With the probability of a full arsenal exchange receding even further after the collapse of the Soviet Union, and the continued reduction of numbers of warheads, earlier calculations predicting planetary-scale impact seemed increasingly irrelevant.

Scientific work based on real data, rather than models, also cast additional doubt on the basic premise. Interestingly, publication of several contradictory papers describing experimental observations actually predated Schell's work. In 1973, nine years before publication of *The Fate of the Earth*, a published report failed to find any ozone depletion during the peak period of atmospheric nuclear testing.[26] In another work, published in 1976, attempts to measure the actual ozone depletion associated with Russian megaton-class detonations and Chinese nuclear tests were also unable to detect any significant effect.[27] At present, with the reduced arsenals and a perceived low likelihood of a large-scale exchange on the scale of Cold War planning scenarios, official concern over nuclear ozone depletion has essentially fallen off the table. Yet continuing scientific studies by a small dedicated community of researchers suggest the potential for dire consequences, even for relatively small regional nuclear wars involving Hiroshima-size bombs.[28]

Nuclear Winter

The possibility of catastrophic climate changes came as yet another surprise to Department of Defense scientists. In 1982, Crutzen and Birks highlighted the potential effects of high-altitude smoke on climate,[29] and in 1983, a research team consisting of Turco, Toon, Ackerman, Pollack, and Sagan (referred to as TTAPS) suggested that a five-thousand-megaton strategic exchange of weapons between the United States and the Soviet Union could effectively spell national suicide for both belligerents.[30] They argued that a massive nuclear exchange between the United States and the Soviet Union would inject copious amounts of soot, generated by massive firestorms such as those witnessed in Hiroshima, into the stratosphere where it might reside indefinitely. Additionally, the soot would be accompanied by dust swept up in the rising thermal column of the nuclear fireball. The combination of dust and soot could scatter and absorb sunlight to such an extent that much of Earth would be engulfed in darkness sufficient to cease photosynthesis. Unable to sustain agriculture for an extended period of time, much of the planet's population would be doomed to perish, and—in its most extreme rendition—humanity would follow the dinosaurs into extinction and by much the same mechanism.[31] Subsequent refinements by the TTAPS authors, such as an extension of computational efforts to three-dimensional models, continued to produce qualitatively similar results.

The TTAPS results were severely criticized, and a lively debate ensued between passionate critics of and defenders of the analysis. Some of the technical objections critics raised included the TTAPS team's neglect of the potentially significant role of clouds;[32] lack of an accurate model of coagulation and rainout;[33] inaccurate capture of feedback mechanisms;[34] "fudge factor" fits of micrometer-scale physical processes assumed to hold constant for changed atmospheric chemistry conditions and uniformly averaged on a grid scale of hundreds of kilometers;[35] the dynamics of firestorm formation, rise, and smoke injection;[36] and estimates of the optical properties and total amount of fuel available to generate the assumed smoke loading. In particular, more careful analysis of the range of uncertainties associated with the widely varying published estimates of fuel quantities and properties suggested a possible range of outcomes encompassing much milder impacts than anything predicted by TTAPS.[37]

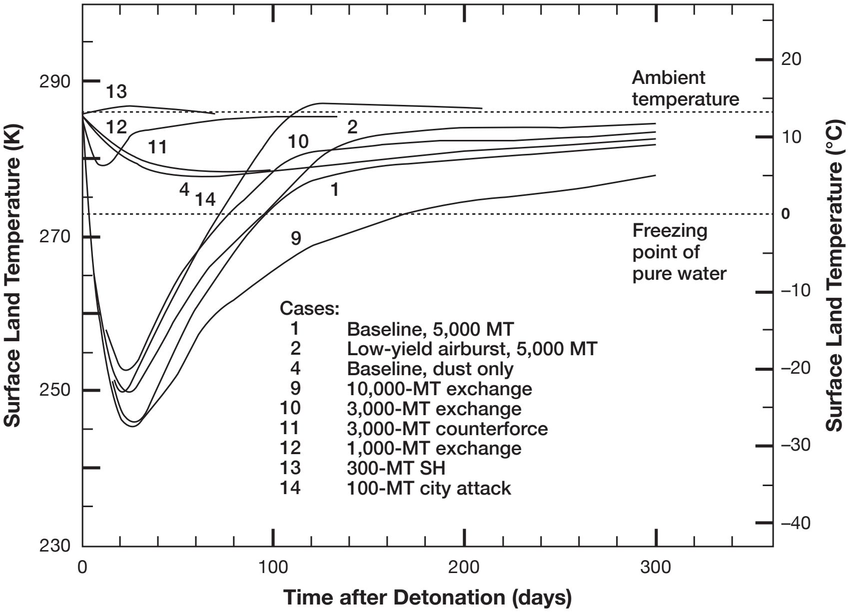

Figure 6.3. TTAPS Nuclear Winter Predictions. These calculations show the drop in surface land temperature levels over time for various nuclear exchange scenarios. Note the prediction of temperature drops for most of the exchange scenarios considered below the freezing point of water for months. The scientific controversy over these results remains unresolved. (Reprinted with permission from AAAS: Richard P. Turco, Owen B. Toon, Thomas P. Ackerman, James B. Pollack, and Carl Sagan, "Nulcear Winter: Global Consequences of Multiple Nuclear Explosions," *Science* 222, no. 4630 [1983]: 1283–1292.)

Aside from the technical issues critics raised, the five-thousand-megaton baseline exchange scenario TTAPS envisioned was rendered obsolete when the major powers decreased both their nuclear arsenals and the average yield of the remaining weapons. With the demise of the Soviet Union, the nuclear winter issue essentially fell off the radar screen for Department of Defense scientists, which is not to say that it completely disappeared from the scientific literature. In the last few years, a number of analysts, including some of the original TTAPS authors, suggested that even a "modest" regional exchange of nuclear weapons—one hundred explosions of fifteen-kiloton devices in an Indian–Pakistani exchange scenario—might yet produce significant worldwide climate effects, if not the full-blown "winter."[38] However, such concerns have failed to gain much traction in Department of Defense circles.

Impact of Dust and Debris on Aircraft

Some natural phenomena emulate certain effects of nuclear explosions and are comparable in terms of total energy release. They too have yielded surprising results. One such event was the 1982 volcanic eruption of Mount Galunggung in Indonesia. This event lofted many millions of tons of volcanic ash high into the atmosphere—an amount that would roughly correspond to that created by a nuclear surface burst of several tens of megatons. A British Airways 747 accidentally traversed the ash cloud during a night flight en route from Kuala Lumpur to Perth. It promptly lost all four engines and descended without power for sixteen minutes from 38,000 to 25,000 feet, after which the crew was able to restart three of the four engines. During a landing diverted to Jakarta, the crew reported that the cockpit windscreens were completely opaque, a result of sandblasting by the highly erosive volcanic ash. By the same mechanism, the glass lenses on the landing lights had been so scoured that the light was barely visible. Subsequent inspection of the engines showed severe erosion of the compressor rotor blades and glass-like deposits of fused volcanic ash on the high-pressure nozzle guide vanes and the turbine blades.[39]

Recognizing that a nuclear surface burst is similar to a volcanic event in terms of its dust-lofting potential, the Defense Nuclear Agency alerted the Strategic Air Command (now US Strategic Command) of the imminent hazard facing strategic bombers entering airspace where missile strikes had already created dust and debris clouds. This was the start of a multiyear program to investigate how strategic aircraft engines respond to dust ingestion, leading to the development of both technical and operational mitigation measures.

Enduring Uncertainties, Waning Resources

It is important not to conflate surprises with uncertainties. Surprises are unanticipated phenomena uncovered through testing or late-breaking insight. Once a surprise has been realized and the new phenomenology understood, large residual uncertainties may still exist because the unanticipated phenomena were uncovered late in the test program, were inadequately studied, or are inherently difficult to model. Moreover, our historical experience with research on the effects of nuclear weapons imparts a nagging feeling that some surprises yet to come will be revealed only through the actual use of nuclear weapons.

Figure 6.4. Mount Galunggung Volcanic Eruption. Atmospheric particulates from this volcano, which erupted August 16, 1982, and is shown here towering over Tasikmalaya, Indonesia, damaged commercial aircraft traversing the plume and alerted scientists to the possibility of analogous effects produced by geological particulates scoured by a nuclear blast and lofted to altitude in the iconic nuclear mushroom cloud. (Image courtesy of the United States Geological Survey.)

Although surprises helped to shape investment in studying nuclear weapons effects over the years, not everything was learned as a result of surprises. Indeed, the Defense Nuclear Agency spent tens of millions of dollars each year until the mid-1990s to maintain a robust research program in nuclear weapons effects, spanning computer modeling, simulator design, fabrication and operation, and large-scale field testing (including underground nuclear tests until 1992). Such a sustained program was key to amassing the wealth of knowledge available to the community today.

However, current efforts to maintain and extend the existing knowledge base on nuclear weapons effects produce decidedly mixed results.

The United States, in voluntary compliance with the still unratified Comprehensive Nuclear-Test-Ban Treaty, has not carried out a nuclear test since 1992, nor is there any realistic prospect that such testing will be resumed in the foreseeable future. To compensate for the lack of testing, the Department of Energy adopted a program known as Science-Based Stockpile Stewardship,[40] which advocates the use of high-performance computing to better understand nuclear weapons physics along with heavy reliance on highly specialized experimental facilities, such as the National Ignition Facility, to validate key modeling features. The national laboratories have made impressive strides in simulating the end-to-end performance of nuclear warheads and the associated effects. However, critics argue that the vagaries of aging warheads and the complexity of the governing physics will always befuddle the conclusions drawn from such simulations.

With the intense competition for resources in the Department of Defense, the prospects for establishing an analogous nuclear weapons effects stewardship program remain dim. After the Defense Nuclear Agency[41] transitioned to the Defense Threat Reduction Agency in 1988 and considerably expanded its mission portfolio, research on nuclear weapons effects has taken a backseat in both the experimental and computational domains. No replacement for the loss of underground nuclear testing has been adequately developed or funded. The Defense Threat Reduction Agency no longer conducts large-scale aboveground blast and shock simulations, and radiation simulators have been reduced to bare essentials. Despite several feeble attempts, there has been no meaningful revitalization of scientific computing to help compensate for the lack of testing capabilities.

A common affliction at both the Department of Energy and Department of Defense is the continuing brain drain of national nuclear expertise as nuclear experts retire. It has also become more difficult to recruit younger scientists, who are less likely to be attracted to a field where they can no longer aspire to test their creations and where overall government funding has declined precipitously since the end of the Cold War. These factors do not inspire much confidence that persisting uncertainties in understanding nuclear effects are likely to be reduced any time soon.

Figure 6.5. DECADE X-Ray Simulator Module. This photograph shows the first of four pulsed power modules planned for the DECADE simulator. The simulator was never completed, a victim of post–Cold War apathy and budgetary declines visited on all matters nuclear. A similar fate eventually befell many other nuclear effects simulators. (Image courtesy of the Department of Defense.)

The ongoing diminution of American nuclear expertise is occurring against a backdrop of growing nuclear expertise in other countries. The spread of sophisticated weapon designs from scientifically advanced countries to less advanced nuclear aspirants is no longer a threat but a fait accompli. Although these designs may not yet include the most sophisticated yield-to-mass ratio or specially tailored output designs, there is little doubt that capabilities are spreading and, without an effective treaty regime, will continue to do so. Much nuclear weapon information has diffused even into the public sphere, from the classic *Los Alamos Primer*[42] and the Smyth report[43] to the Department of Defense's *Effects of Nuclear Weapons*.[44] In addition, many nongovernmental resources are available on websites such as *Wikipedia* and those of organizations such as the Federation of American Scientists, the Union of Concerned Scientists, the Natural Resources Defense Council, and the Nuclear Weapon Archive, which maintains "Nuclear Weapons Frequently Asked Questions."[45]

Recently, increased attention and resources have been devoted to answering new questions and reducing older uncertainties in the nuclear effects knowledge base. After experiencing funding cuts in the 1990s following the collapse of the Soviet Union and a deeper decline in the first decade of the new century, military funding agencies are showing modestly revived interest in nuclear effects because of the reality of continuing nuclear proliferation to rogue regimes and rising concern over nuclear terrorism. Congress is also increasingly interested in the vulnerability of our civilian infrastructures to both nuclear and nuclear-like events, such as very large geomagnetic solar storms; this interest has also contributed to increased attention—although so far almost no funding—on the part of civilian funding agencies. However, the current status of nuclear effects research remains dismal. Most notably, the newer questions that focus on more general societal consequences and directly affect our ability to perform a credible consequence assessment have not been aggressively pursued.

Physical Effects: What We Know, What Is Uncertain, and Tools of the Trade

Although we have not likely exhausted potential occasions for surprise, and uncertainties persist, after nearly seven decades of intensive investigation, we actually know quite a bit. In this section, we first summarize the state of our knowledge across a range of physical nuclear effects and qualitatively characterize the attendant uncertainties associated with each. These summaries are followed by a description of currently used tools for consequence prediction and other sources of knowledge influential in shaping public perceptions.

Nuclear Weapons Effects Phenomena

In each of the following summaries, we briefly describe the phenomenon and the nature of its effects. We then characterize our level of knowledge as well as lingering uncertainties that may stem from an inaccurate prediction of the nuclear environment, errors in characterization of system response, or both. We tried to limit the technical complexity of the descriptions without sacrificing accuracy.

Prompt Radiation

A detonating weapon emits ionizing radiation in the form of high-energy particles (alpha, beta, and neutron) and electromagnetic energy (gamma rays, x-rays, and ultraviolet rays). Because of radioactive decay, the fission fragments continue to release alpha, beta, and gamma radiation. The prompt radiation environment is traditionally defined as the combination of radiation from the fission event and the radioactive decay of the fission fragments up to one minute after detonation.

Ionizing radiation is highly injurious to personnel and, at high dosage levels, can lead to rapid incapacitation and death. Lower levels of exposure can increase a person's probability of contracting various cancers.

Gamma rays and neutrons can also penetrate deeply into electronic components and may damage the materials and electronic devices that compose integrated circuits. Gamma rays induce stray currents that produce strong local electromagnetic fields; neutrons interact directly with semiconductor materials and change their electrical properties. X-rays and gamma rays may also darken optical fibers and damage optical elements. Additionally, energetic neutrons in near-surface bursts activate various elements in air, soil, structures, and other man-made infrastructural components. Activated elements subsequently undergo radioactive decay, releasing potentially harmful ionizing radiation.

At low altitudes, the atmosphere absorbs all x-rays within a few meters, creating a hot fireball that subsequently drives a strong air blast. In space, x-rays travel unimpeded and imperil satellites to great distances, damaging optics and distorting critical-tolerance structural components.

The physics of prompt ionizing radiation is well understood, and uncertainties likely would not preclude a consequence assessment. However, greater emphasis needs to be placed on three-dimensional calculations to better understand how shadowing mitigates effects of detonations in urban landscapes. Such effects could significantly alter prompt radiation casualty counts.

Electromagnetic Pulse

A high-altitude (more than forty kilometers) nuclear burst, through a photon-scattering process known as the Compton effect, produces copious quantities of electrons whose interaction with Earth's natural magnetic field generates a massive electromagnetic field with a terrestrial footprint extending over thousands of square miles. For example, the EMP footprint of a detonation at an altitude above approximately five hundred kilometers over Omaha, Nebraska, would encompass the entire contiguous forty-eight states. However, because the intensity of the electrical disturbance weakens as the distance from the detonation point increases, an EMP attack may more likely be targeted at lower altitudes and closer to areas of the country with higher population densities (i.e., above either the East or West Coasts or above both).

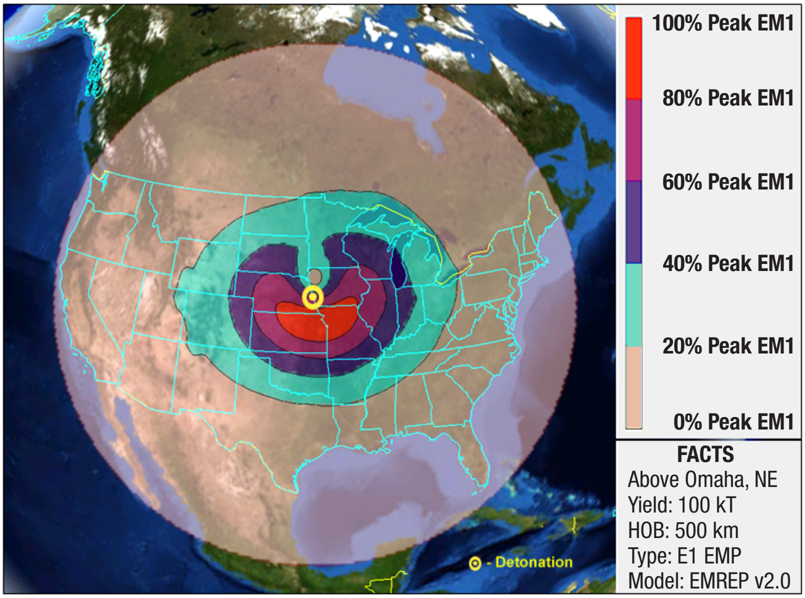

Figure 6.6. EMP Coverage Contours. EMP coverage area on the ground increases as the height of the burst increases. A nuclear detonation at an altitude of five hundred kilometers over Omaha, Nebraska, will generate an EMP that covers the contiguous land mass of the United States. The electric field strength diminishes with increased distance from ground zero directly under the burst. The asymmetry in contours is a result of the orientation of Earth's magnetic field with respect to the detonation point. (Image courtesy of the Department of Defense.)

The electromagnetic impulse itself includes a "fast" shock component (termed E1)[46] whose duration may last only billionths of a second but may couple damaging energies into electronic components such as computers, switches, and short runs of electrical wires. For weapons with large energy yields, the impulse also includes a "slow" shock component (termed E3),[47] which may last milliseconds to seconds and impress damaging impulses on long runs of conducting wires such as the transmission lines that tie the power grid together.[48]

Detonations near ground level generate an additional EMP by a different physical mechanism.[49] This phenomenon, termed source region EMP (SREMP), may severely damage electronic components that fall within its footprint. However, its effects tend to be localized, generally within the blast-damaged region already affected by the immediate destructive effects of the bomb. Nevertheless, in some scenarios, the damaging electric currents may convey on long runs of conductors to regions beyond those immediately proximate to the burst location, contributing additional electronic damage beyond the blast zone.

The Department of Defense sponsored a number of attempts to achieve a robust predictive capability for EMP-induced damage against specific targets but, in the final analysis, relegated EMP damage to a "bonus effect." Nonetheless, our critical military systems have generally been hardened against the sort of electronic damage that an adversary's weapon might inflict.

However, only very recently has attention been paid to assessing the broader societal and infrastructural issues associated with EMP. Specifically, the EMP Commission has focused on damage that might result from the vulnerability of critical digital control systems and other electronic systems that pervade and sustain modern technological societies. Although progress has been made, there remain wide uncertainty bands.

Air Blast

A nuclear blast wave emerges from the fireball as a spherical shock front characterized by a sharp increase in static overpressure (above ambient pressure). Behind the shock front, the overpressure decays sharply and actually reaches negative values (below ambient pressure) in the tail of the blast wave. The blast wave also produces strong winds (dynamic pressure) as the air is displaced radially outward and subsequently inward during the negative phase. Overpressure can crush or weaken a structure; dynamic pressure can displace or tear a structure apart through drag forces. The range from ground zero to a specific level of overpressure increases with the height of the detonation to an optimal height of burst and then decreases sharply for greater heights.[50] The dynamic pressure follows similar trends.

Air blast is perhaps the most studied and best understood of all the nuclear weapon effects because the propagation medium (air) is well characterized and similitude considerations allow scaling of air blast from small-scale conventional explosions to large-yield nuclear explosions. However, real-world environments can introduce significant perturbations in so-called idealized air blast approximations. Terrain, whether natural or man-made, can significantly modify the local blast environment. Also, past nuclear tests show that fireball heating of certain surfaces can produce a blow-off of hot particulates, which in turn heat a layer of air adjacent to the surface. The higher sound speed in this heated layer causes the portion of the shock wave traveling within it to speed up, creating a precursor wave that propagates ahead of the main shock. The resulting near-surface, dust-laden flow field is highly turbulent and is characterized by significantly enhanced dynamic pressure. Finally, atmospheric conditions such as temperature inversions can significantly affect the range for low overpressure effects, including damage to unhardened structures and window breakage. These nonideal blast perturbations depend on the vagaries of the local environment and are largely ignored in present-day predictive tools.

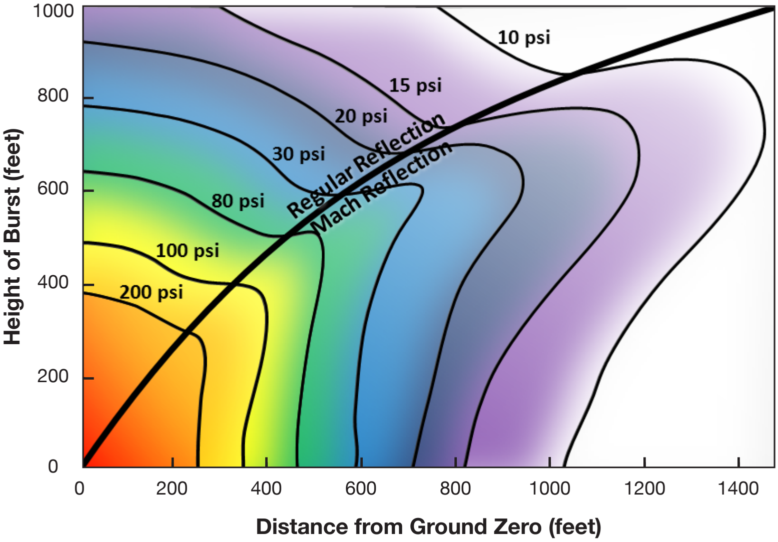

Figure 6.7. One Kiloton Iso-Pressure Contours. In the Mach reflection region, the incident and reflected shock waves have merged to form a single shock front called the Mach stem. Extended knees in the Mach reflection region, more prominent at overpressure levels below one hundred pounds per square inch, make air bursts more effective for maximum overpressure damage to structures and other ground targets.[51] (Adapted from the Department of Defense.)

Most of our predictive air blast algorithms assume the air–ground interface is a flat and perfectly smooth surface. For nuclear weapons detonated within or above a city, such an assumption is not valid. However, with modern computational techniques, it is possible to create a computational grid for an entire city and calculate the shock waves as they reverberate and diffract in and around buildings. Although such calculations may be computationally intensive, current knowledge supports an assessment of air blast effects at painstaking levels of detail and fidelity.

Ground Shock

Ground shock is created by the direct coupling of energy to the ground in the vicinity of the crater, assuming a ground burst, and by the air blast-induced motions at the air–ground interface for both ground and air bursts. The subsequent propagation of the stress wave in the ground is governed by the geologic stratification and the material properties of the various strata, which are rarely known to fidelity sufficient to allow confident prediction of stress, acceleration, velocity, and displacement at depth. Most ground shock predictive codes assume continuum behavior of geologic material, when in fact many geologic materials, such as jointed rock, behave in a much more discretized manner.

Ground shock effects on structures are closely related to effects of an earthquake, although they are considerably lower in displacement and duration. For a surface burst, the ground shock domain of plastic deformation extends out to about two to three crater radii. Within this region, the combined direct and air blast-induced ground shock can significantly damage unhardened infrastructure components such as utility pipes and subway tunnels. Beyond the plastic region, air blast effects will dominate any ground shock effects with respect to structural damage.

For underground explosions, as in the case of a terrorist device detonated on the lower levels of an underground parking garage, ground shock will be the dominant damage mechanism for the surrounding buildings. Assuming a rudimentary understanding of the local geology and constitutive properties, extant predictive tools are sufficient to support order-of-magnitude assessments of the effects of ground shock. For surface or aboveground detonations, air blast will dominate and ground shock will not be a significant contributing factor.

Cratering

Most of the nuclear cratering data come from the large-yield (megaton) testing program conducted on various islands of Enewetak Atoll, also known as the Pacific Proving Grounds. A small number of low-yield (kiloton) tests were conducted at the Nevada Test Site. The morphology of the craters from the Nevada Test Site tests, with their characteristic bowl shape, was significantly different from the pancake-shaped craters observed during the EMP events—an anomaly that was not resolved until the 1980s when it was ultimately attributed to the gradual slumping of the weaker crater walls in the coral geology of the EMP. A considerable number of subsurface cratering bursts were also conducted at the Nevada Test Site to evaluate the excavation potential of nuclear weapons for peaceful purposes, under the Plowshare Program.

Figure 6.8. The Sedan Crater. A physical relic of the days when the United States and the Soviet Union explored the peaceful uses of nuclear weapons, the Sedan Crater still looms large today at the Nevada National Security Site. Created by a specially designed high-fusion output device with a yield of 104 kilotons detonated at the optimum depth of burst, it is one of the largest such excavations on Earth and served as a training venue for Apollo astronauts. (Image courtesy of the Department of Energy National Nuclear Security Administration/Nevada Field Office.)

In general, the size and shape of the crater strongly depend on the burst height (or depth), the yield, and the geology. Assuming a weapon with a fixed yield, as the burst height is lowered, the first crater to manifest is a compression crater created by the reflection of the shock wave from the air–ground interface. As the burst height approaches the surface, an excavation crater begins to form. The crater volume increases substantially for detonations below the surface and reaches a maximum at the optimal depth of burst.[52] Below this depth, the crater size and volume decrease, largely because of fallback and ultimately because the downward force of the geologic overburden approaches the upward force produced by the explosion. At that point, there may still be a surface vestige of the explosion, manifested in some geologies as a bulking or uplift near ground zero. This is sometimes referred to as a "retarc" (crater spelled backward). At still deeper depths, where the overburden is sufficient to fully contain the energy release, the underground cavity created by the explosion will eventually collapse, causing the column of soil above it to slump and form a subsidence crater at the surface.

Although the cratering phenomenon is reasonably well understood, the variation in the geology and uncertainties in geophysical properties make it difficult to confidently predict crater size for an arbitrary location and burst geometry. However, the combined weapon effects environment in the vicinity of the crater virtually ensures total destruction. Accordingly, the inherent uncertainties in the cratering phenomenon are important primarily as a source function for lofted radioactive particulates and their subsequent fallout.

Underwater Explosions

One of the first nuclear tests after the Trinity event was a twenty-one-kiloton underwater explosion, detonated ninety feet below the surface (halfway to the ocean bottom) near the island of Bikini. Dubbed Operation Crossroads, Event Baker, the explosion created a bubble that vented and formed a tall column of water, collapsing under its own weight seconds later. This in turn created a nine-hundred-foot tall "base surge," not unlike the mist created by a waterfall. Unfortunately, the mist was highly radioactive and it coated virtually every ship involved in the test. Because this was totally unexpected, no provisions for decontamination were made.

While we understand the physics of underwater shock formation and associated damage to ships, the base surge effect is still poorly understood. The detonation of even a relatively low-yield nuclear explosion in the harbor of a large coastal city could result in massive contamination of high-population centers. The additional damage that any associated water waves might create is also poorly understood, and tool sets for measuring such damage are lacking.

Figure 6.9. Operation Crossroads, Event Baker. The Baker atomic test was conducted at Bikini Atoll on July 25, 1946, using a Fat Man device. It was the second test conducted after the Hiroshima and Nagasaki bombings in 1945 and the first underwater test. Eight of 57 Navy test ships were unintentionally sunk; all ships within one thousand yards of the detonation sustained serious structural damage, and all vessels were heavily contaminated by unexpected base surge from the collapsing water-laden cloud stem. (Image courtesy of the Department of Defense.)

Fires

The initiation of fires by nuclear explosion is a multifaceted and temporally staged phenomenon. The thermal pulse emanating from the fireball and heated air surrounding it will initially ignite many of the exposed flammable surfaces within its line of sight, out to some distance where the intensity of the radiated pulse has weakened sufficiently. There follows a complex interaction with the trailing nuclear blast wave, which may snuff out many of the initial ignitions. Subsequently, secondary ignitions will contribute to fire growth following blast damage to gas lines, stoves, and similar fire sources. These fires may continue to grow and spread damage beyond the initial blast damage zone.

In the two instances of nuclear weapons use during World War II, the large number of simultaneous ignitions produced firestorms—extraordinarily intense, large-area mass fires, with most of the encompassed fuel burning all at once and radially inward directed hurricane-scale winds feeding fresh oxygen to the inferno—that made it almost impossible for survivors from the blast-affected areas in Hiroshima and Nagasaki to escape.[53] Modern urban centers with concrete and steel construction instead of wood may prove more resistant to such firestorm formation, but many cities in the developing world remain susceptible to the outbreak of such a conflagration.

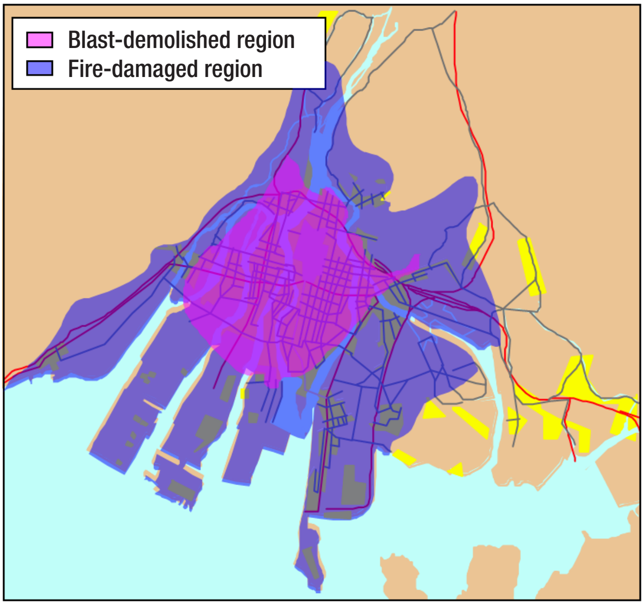

Figure 6.10. Hiroshima Fire Damage. The fire damage region from the Hiroshima bombing extended well beyond the region of damaging blast. A firestorm raged for several hours, destroying 4.5 square miles of the city and two-thirds of its buildings, adding considerably to the total casualty reckoning. The great majority of deaths at Hiroshima and Nagasaki were due to burns, although the relative contributions of prompt radiation and subsequent fires remain unknown. (Image courtesy of the Department of Defense.)

While the incidence of nuclear-weapon-ignited fires is inevitable, predicting the scale of such events has proven difficult. The nuclear weapons community has incentive to account for such fires because incorporating these effects in targeting plans means each weapon can be counted as more effective. The community is also motivated by a desire to avoid unwanted collateral effects. These goals spawned multiyear efforts to develop a robust tool to predict fire effects in support of military planning. These efforts were all judged failures and, in a military context, could not be relied on when estimating target effects. However, the inability to predict precise target effects does not mean that the knowledge base precludes a statistically meaningful estimation of the contribution of fire damage to the net destruction in a broad assessment of nuclear consequences.

Lofting of Dust and Soot

Nuclear explosions detonated at the surface or at heights low enough to produce strong ground-level blast waves entrain large amounts of particulate matter, which then commingles with the highly radioactive detonation products in the rising thermal column of the nuclear fireball. The amount entrained and the level of activation depends on variables such as the explosive yield and the height of burst, the nature of the ground cover, and many other complex factors relating to such matters as vaporization and condensation and particulate clumping. The buoyant dust cloud cools as it rises and stabilizes at a height where its temperature equilibrates with the ambient temperature. Maximum cloud height is strongly influenced by such environmental factors as atmospheric stability, humidity, winds, and seasonal variations in the height of the tropopause. The subsequent transport and dispersion of the lofted dust is governed by the local wind field, which can vary greatly both spatially and temporally. The eventual fallout of the radioactive particulates can create a significant downwind radiation hazard to unsheltered personnel.

Fires started by the explosion produce soot particles, which may also be lofted to altitude. As discussed previously, lofted soot in particular became an issue with the new nuclear winter scenario modeling, which first came to the Department of Defense's attention in the 1980s. However, traditional Department of Defense concern over the atmospheric residence of such nuclear-generated particulate clouds has focused on such issues as reentry vehicle fratricide, fallout, and aircraft engine ingestion hazard zones. Less seems to be known about dust production from heavily urbanized centers, so we must assign large uncertainty bands to our current understanding of urban dust phenomenology.

To calibrate hydrocode models of the particle production and transport processes, many measurements of dust production have been taken in both conventional and nuclear explosions, and there seems to be reasonable confidence that the phenomenon is sufficiently well understood to support a consequence assessment for fallout and engine ingestion phenomenology. The reentry vehicle fratricide issue is well understood and, in any event, was primarily a Cold War concern related to specific nuclear attack scenarios.

Department of Defense concern over an extreme nuclear winter scenario, which anticipated a major nuclear exchange that would darken the atmosphere and lower global temperatures sufficiently to end agriculture and destroy a significant fraction of human life, at least in the Northern Hemisphere, has receded considerably in the face of both scientific challenge and the continuing reductions in nuclear weapons arsenals. However, a number of scientists, some of whom continue to investigate the ozone depletion issue, still argue for its importance.

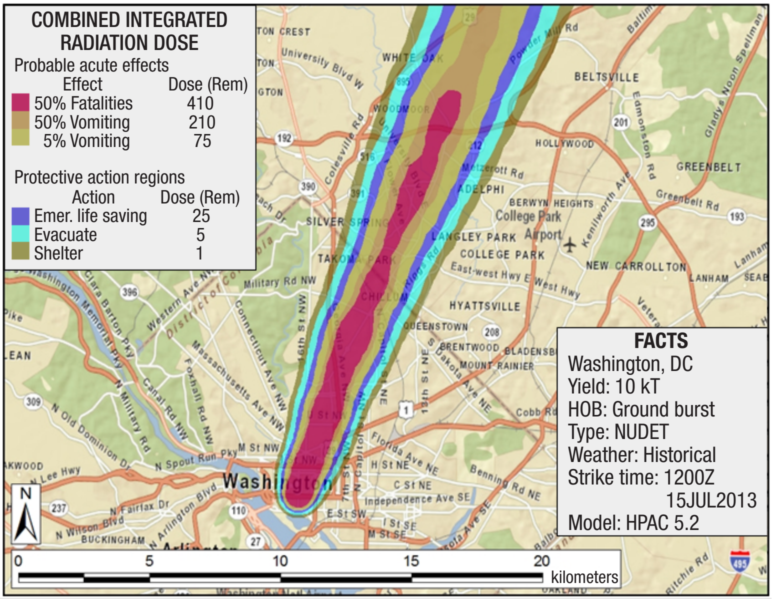

Figure 6.11. Hazard Prediction Assessment Code Fallout Prediction. Depicted are the bands of varying fallout contamination as predicted by the Hazard Prediction Assessment Code (HPAC). Each color contour represents the cumulative dose that would be seen by a sensor situated at that location from the time of detonation. Because many fission products decay rapidly, a sensor introduced at later times would accumulate a significantly lower total dose. (Image courtesy of the Department of Defense.)

Fallout

After a nuclear blast in the atmosphere, radioactivity from fission products and neutron-activated particulates contaminate the atmosphere when they fall back to Earth over the course of hours to days, exposing the population to the direct harmful effects of radiation and contaminating the environment for extended periods. Exposure to intense levels of radiation is lethal within a relatively short period, hours to perhaps days. Exposure that is not immediately lethal may eventually cause cancers and other life-shortening illnesses.

The morbidity and mortality curves for radiation exposure are well understood, as is the initial amount of radioactive material generated by the nuclear burst. Although excellent transport models now exist, less predictable are the subsequent physical dispersion and scavenging processes in the atmosphere and the longer-term infiltration of the agricultural cycle. Without heroic cleanup endeavors, multiyear contamination of the environment may render regions effectively uninhabitable. The Japanese fallout/rainout experience has been intensely investigated, along with US atmospheric test experience, and much progress has been made modeling the process to include such atmospheric effects as scavenging and rainout. Available statistical tools provide reasonable estimates of population exposure.

Human Response

Humans are susceptible to virtually all nuclear weapons effects except EMP, save for those who depend on electrical devices for their viability. Prompt ionizing radiation causes cellular damage; the thermal pulse causes flash blindness and burns; the shock wave can induce blunt-force trauma, eardrum rupture, contusions, and bone fractures; and fallout creates a radiation hazard that, depending on dose, can result in responses ranging from prompt death to late-stage cancers.

The experiences at Hiroshima and Nagasaki remain, thankfully, the only direct source of information about the human response to the thermal pulse of a nuclear weapon and have been analyzed extensively. Decades of research including extensive animal studies, wartime use, and inadvertent human exposures in military, medical, and the civilian power industries provide a firm basis for understanding and predicting the human response to different levels of radiation exposure. The response of unprotected human bodies to the impulsive force of a nuclear air blast is also very well understood from extensive past explosive effects testing and insights gained from wartime experience.

High-Altitude Nuclear Effects (Other Than EMP)

High-altitude nuclear explosions create significant regions of ionization above ambient conditions, caused by direct interaction of bomb gamma rays, neutrons, and x-rays with air molecules, beta decay of bomb fission products, and positive ions in the weapon debris. These regions can interfere with radio frequency (radar and radio) propagation by causing refraction and scattering, phase errors, and multipath interference. Critical satellite communications can be disrupted, including GPS outages. Fortunately, most of these effects are relatively short-lived, lasting from minutes to no more than hours.

There is one notable exception: bomb-generated electrons trapped in the Van Allen belts. Low-Earth-orbiting satellites traversing these belts will demise over a period of days to months as they accumulate lethal doses of radiation. The 1.4-megaton Starfish Prime high-altitude burst, detonated over Johnston Island in the Pacific in 1962, resulted in the demise of all publicly acknowledged satellites, and the pumped belts lasted into the early 1970s. Today, with the vast proliferation of space-based assets, the ensuing disruption would be far more serious. Computational tools can assess the radiation dose that accumulates on orbiting space assets as a result of the trapped electron phenomenon, but there is significant uncertainty in predicting space environments produced by modern weapon designs that were never tested before the end of the atmospheric test program in 1962.

Weapon Design Considerations

We note that weapon design can potentially influence the weapons effects discussed previously, and in some cases the influence is significant. However, to a first-order approximation, the nuclear analog of Saint-Venant's principle[54] holds—the difference between the effects of different weapon designs that produce the same total energy yield is vanishingly small at sufficiently large ranges from ground zero, regardless of the initial energy partitioning among x-rays, gamma rays, neutrons, and bomb debris. This is not so for close-in effects, for which the details of the output energy spectrum are more important. For example, highly energetic (hot) x-rays will couple more deeply into geologic media, resulting in enhanced ground shock. High-energy x-ray deposition near ground zero can also result in a dense, dusty blow-off layer, which can retard the shock wave traveling within it, leading to increased overpressure when compared to calculations that ignore such surface interactions. The magnitude of the EMP environment resulting from a high-altitude burst may also vary depending on the device design.

Public revelations[55] by senior Russian officials over the past fifteen years suggest plans to field a new class of tactical, low-yield weapons whose dominant energy output is from fusion reactions. Others[56] have suggested that it may be possible to fabricate pure fusion weapons by using various alternatives to the classic fission trigger. If such a weapon could be fabricated, it would be inherently more usable because it would produce no fallout, greatly reduce the radioactive contamination of the environment, and minimize blast damage while delivering an enhanced lethal radiation footprint. Effects of such weapons cannot be presumed to be the same as those predicted by current handbooks and computational algorithms, but the effects are nonetheless calculable within reasonable accuracies despite limited experimental data.

Predictive Tools

In addition to acquiring this substantial body of knowledge, over the years the Department of Defense has developed a large suite of handbooks and predictive tools to assess the consequences of the military application of nuclear weapons. A host of official handbooks provide nuclear effects assessments and operational guidance. The most authoritative of this genre is the venerable, and classified, official “bible” of nuclear weapons effects, *Capabilities of Nuclear Weapons*. Widely referred to by its original document designation, Effects Manual-1, or EM-1,[57] this manual originated in the former Defense Nuclear Agency and is presently maintained and periodically updated by its successor organization, the Defense Threat Reduction Agency. In the unclassified domain are *Mathematical Background and Programming Aids for the Physical Vulnerability System for Nuclear Weapons*,[58] which describes the mathematics of selected portions of the *Physical Vulnerability Handbook—Nuclear Weapons*, and the classic and oft-quoted *Effects of Nuclear Weapons,*[59] which was jointly published by the Departments of Defense and Energy and offers an authoritative primer on a wide range of nuclear weapons effects.

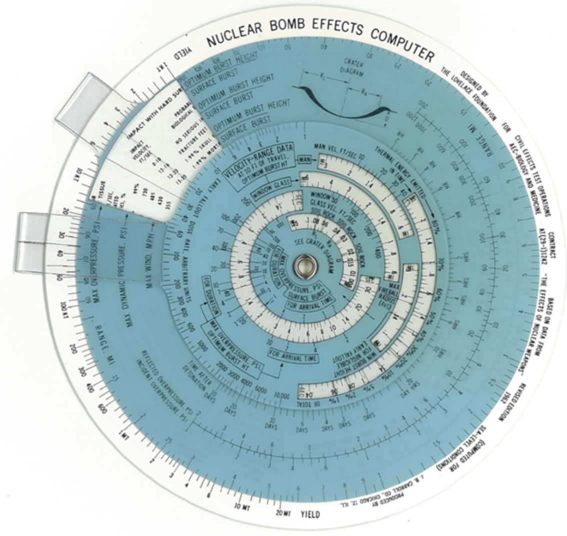

Figure 6.12. Nuclear Bomb Effects Computer. Previously provided as a supplement to Glasstone and Dolan's classic *Effects of Nuclear Weapons*, this shirt pocket slide rule calculator was widely used in the 1950s–1970s but has now been replaced by digital computational resources that use fast-running predictive codes and algorithms. (Image courtesy of Oak Ridge Associated Universities.)

Available as well is a large library of modeling and simulation tools accessible through the Defense Threat Reduction Agency's Integrated Weapons of Mass Destruction Toolset enterprise services. These computational tools range from simple predictive algorithms to first-principles, finite-difference, and finite-element models and cut across the full spectrum of conventional, nuclear, radiological, biological, and chemical weapon effects.

While some tools carry more uncertainties than others—in particular, the high-altitude codes suffer from a lack of opportunity for validation—they all seem adequate to provide input to a general consequence assessment, but that is also their main limitation. Because these tools were developed by the Department of Defense to speak to issues focused on specific defense applications, they were never asked to assess the impact of all these effects on the broader society. How will the various weapon effects enumerated herein affect our ability to generate electric power to sustain a technologically advanced society, to maintain a robust telecommunications network that enables every financial transaction involving a bank or the stock exchanges, or to protect the food chain that feeds a population? These questions have never been asked of our tools, and while they have much to contribute in response, there remains much work to be done.

Other Sources of Knowledge

Often overlooked perspectives on the consequences of nuclear weapons use are those of the general public and the political leadership of the country. For these groups, technical descriptions of nuclear weapons effects are largely irrelevant. Their views of consequences are shaped instead by their exposure to the history of Hiroshima and Nagasaki, as well as by representations of nuclear war and its aftermath in popular media such as movies, television, photographs, drawings, books, and museum exhibits.

These media sources are far too vast to survey in this chapter. Instead, we merely describe a small sample to convey a sense of the emotional power of this material as a whole. Much of it falls into three broad categories: (1) fictional depictions of nuclear war in books and movies; (2) victims' autobiographical accounts, personal reflections, and drawings; and (3) artifacts and photographs of the physical destruction and human casualties in Hiroshima and Nagasaki. Our selection is heavily influenced by the sources' popularity and, by implication, their influence on the public.

- ***On the Beach***[60] describes the aftermath of a nuclear war in which all that remains of humanity is a small group in Australia facing certain death as lethal radioactive fallout approaches. This book, later released as a movie, was enormously influential in shaping public perceptions about nuclear war, even though its central premise that human extinction would be the inevitable outcome was and remains vanishingly improbable.
- ***Hadashi no Gen***[61] (*Barefoot Gen*) is the semiautobiographical story of a six-year-old boy, Gen, and his family, starting shortly before the atomic bombing of Hiroshima. It began as a form of manga serialized in the Japanese weekly comic *Shukan Shonen Jampu* and was later made into several film versions, a television drama series, and ten books, which follow Gen's experiences through 1953. The central themes of heartbreak, loss, despair, and anger are tempered by subthemes of courage and endurance.

- ***The Day After***,[62] a television movie first aired in 1983 to an audience estimated at over one hundred million, depicts the buildup and aftermath of a nuclear war, the culmination of a crisis over Berlin. In the movie, although NATO first uses nuclear weapons to stop the advance of Warsaw Pact armies into Western Europe, which side escalates to massive strikes against the other is unclear. What is clear are the devastating consequences to individuals and to society, conveyed by following the survivors in a small town in Kansas as they succumb to radiation poisoning, disease, and the collapse of civil infrastructures and norms of civilized behavior. The film, distributed internationally and shown on Soviet television, was widely discussed in the United States and both depressed President Reagan and affirmed his belief in the importance of a strong deterrent to prevent nuclear war.[63]
- ***Unforgettable Fire: Pictures Drawn by Atomic Bomb Survivors***[64] is a compelling testament to the human toll of nuclear war. The book originated with a survivor spontaneously bringing a single drawing to Japan's public broadcasting corporation. Over the next several years, thousands of other survivors contributed their own drawings and paintings of their memories. These drawings, many of which are accompanied by eloquent descriptions of the experience of the survivor, evoke deep empathy with the survivors suffering from blast, fire, radiation, and black rain. The book's message is simple: this must not happen again.
- **The Hiroshima Peace Memorial Museum**[65] is a memorial to the victims of Hiroshima, a compelling reminder of the catastrophic consequences of atomic warfare and a call for a future of peace and the abolition of nuclear weapons. Its permanent exhibits—*Damage by the Blast*, *Damage by the Heat Rays*, and *Damage by the Radiation*—convey the physical devastation and human toll of the atomic bombing of the city through photographs, displays of personal effects of the victims, and other artifacts. Other materials include eyewitness survivor testimony, films, and a library. More than one million people visit the museum every year.[66]

These public resources clearly impart impressions that are not achievable in technical manuals. Although some of this material may lack the scientific accuracy of results from nuclear effects testing and analysis, in many ways it is far more effective in conveying the human and societal horrors of nuclear war. It is the perception of these horrors, rather than the cold calculations of military planners, that may have done the most to preserve the nuclear peace throughout the Cold War.

Nonphysical Effects

As mentioned in the introductory section, we recognize that the full spectrum of consequences of nuclear weapons use exceeds, perhaps greatly, this chapter's narrow focus on the physical consequences. A full-spectrum, all-consequences assessment would thus include an assessment of economic, social, psychological, and policy impacts among other things. Such a review deserves a special study and is beyond the scope of this chapter. Below we merely point to some of the relatively few analyses that have addressed these issues.

The EMP Commission conducted a number of studies to assess the effects of an EMP attack on critical national infrastructures such as power, telecommunications, banking, agriculture, and transportation. However, these studies were quite limited and did not extend to the much larger total cost of loss of national economic activity in the absence of available power. Nor did they attempt to deal with social, psychological, or policy effects of an attack.

Another EMP Commission effort comprised two independent analyses using the same initial conditions that characterized the direct and immediate effects of an EMP attack: The University of Virginia used a Leontief input-output economic model of the US economy, and Sandia National Laboratories used the National Infrastructure Simulation and Analysis Center[67] to determine how the initial effects would reverberate throughout the economy. Interestingly, the outputs of these studies differed by an order of magnitude, and no clear explanations for the discrepancy were developed. This experience supports the judgment of the EMP Commission that "no currently available modeling and simulation tools exist that can adequately address the consequences of disruptions and failures occurring simultaneously in different critical infrastructures that are dynamically interdependent."[68]

Many infrastructure models that do exist are local to regional in scope. For example, in 2007, the Sage Policy Group authored a study of the economic impact of an EMP event on the greater Maryland region.[69] The Cato Institute authored a study that addresses economic, national security policy, and social aspects of nuclear weapons use in two different scenarios.[70] In 1958, Fred Iklé published an analysis of the social disruption following widespread destruction, using the World War II bombing experience as a paradigmatic scenario and extrapolating his analysis to the even more widespread destruction of a nuclear scenario.[71] His conclusions, which downplayed the likely impact on more rural social matrices vis-à-vis urban centers, seem dated from the perspective of today's much more interdependent populations, but there is also much valuable data and insight to be gleaned from the work. The Office of Technology Assessment's two-city study (Detroit and Leningrad) addresses the economic, social, political, and psychological aftermath of a single megaton-class explosion in each city.[72] Dresch and Baum developed a quantitative methodology using published economic data to estimate economic recovery schedules from nuclear attack scenarios as a function of different recovery investment policies.[73] In another dated work, Haaland, Chester, and Wigner address such issues as agricultural impact, social organization, food, and distribution infrastructures for a post–Cold War scenario involving a 6,559-megaton attack.[74]

When contemplating these and other efforts, the common impression is that they are sparse, narrow in scope, and lack analytic rigor. The number of studies is relatively modest, and many are case studies limited to analyzing the effects on one or two cities. Simply stated, negligibly small resources—compared to the investment in understanding the physical effects of nuclear weapons—have been devoted over the years to understanding these nonphysical consequences. Without a commitment to new investment, the situation is unlikely to improve much in the future. This is particularly regrettable because it seems that addressing this knowledge gap is both important and amenable to progress with relatively modest investments. Unlike the investments in understanding physical effects, field experiments costing millions of dollars—as were common in the pursuit of the existing nuclear weapons effects knowledge base—are not usually contemplated for such “soft science” efforts.

Scenarios

We consider a number of scenarios, ordered roughly by number of nuclear detonations and overall severity of consequences, and ask whether the knowledge and tools we have on hand are adequate to confidently assess the consequences of nuclear weapons use, and, if not, how much more information might be needed to do so.

In addition to uncertainties in nuclear weapons-created environments and how physical and biological systems respond to those environments, we now must also consider scenario uncertainties. What do we know and not know about the designs of the weapons used and how many weapons are used? What are the aim points, accuracies, reliabilities, yields, and heights of burst? What is the weather at these locations and throughout the zone in which fallout is transported and deposited? What is the status of the population in the target areas, which is dependent on the time of day, day of the week, and specific date the nuclear use occurs? Some answers to these questions are imponderable; others are likely to be better known to one side—generally the attacker—than to the other prior to nuclear weapons use. Many are evident to all after an attack has taken place.

The range of consequences associated with uncertainties in a scenario can easily overwhelm the range of consequences associated with uncertainties that result from imperfect understanding of physical effects. Therefore, the preferred analytic approach is to make informed choices for scenario parameters and conduct sensitivity analyses that address the uncertainties in these choices.

A Single Weapon Detonated in a City

The detonation of a single nuclear weapon by a terrorist organization is one of the fifteen disaster scenarios defined by the Department of Homeland Security as part of its emergency preparedness planning activities.[75] We consider here a near-ground-level explosion with yields ranging from one to ten kilotons and ask what we know, what tools are available, and whether these resources are adequate to describe the consequences of such an attack.

The first thing we note is that the immediate physical consequences would be fairly localized. Physical consequences far from the point of detonation would be limited, and at some radius measured from the blast site in kilometers at most, no appreciable prompt physical effects would likely be felt. Five pounds per square inch of overpressure is commonly accepted as the threshold for widespread destruction, including building collapse. In an unimpeded environment, a ten-kiloton surface burst may be expected to project such an environment out to about 1.5 kilometers from the detonation site, whereas a one-kiloton blast may extend such effects only to seven hundred meters or so. At one pound per square inch overpressure—an environment projected 4.7 kilometers from a ten-kiloton blast and 2.3 kilometers from a one-kiloton explosion—the nuclear blast wave may still be sufficient to break glass windows. Outside the one-pound-per-square-inch radius, there may be little noticeable physical damage, although individuals at even greater distances who stare directly at the fireball might experience instances of flash blindness.

Many of the standard tools from the nuclear consequences toolbox in development for decades may prove essentially useless for such a domestic scenario. An urbanized downtown with large buildings is not an unimpeded environment, and the reach and distribution of observed damage may be significantly different from the expected "textbook" numbers because of phenomena such as shadowing, channeling, and absorption. Fire, whose incidence is uncertain and whose World War II experience may not be representative of modern conditions, might add significantly to the total damage but is not included in any of the damage assessment tools currently available.[76] A less well-known phenomenon associated with surface bursts is SREMP. Unlike the expansive EMP effects resulting from high-altitude bursts, SREMP effects do not extend far beyond the blast radius. However, strong SREMP-induced ground currents can couple to underground conductors (cables and conduits) that can in turn damage electronic grid components to a distance at least an order of magnitude greater. The SREMP phenomenon remains poorly understood, and its effects on complex urban infrastructure continue to be a point of contention.

Perhaps the most insidious, persistent, and widespread effect created by an urban ground burst is the radioactive contamination created by the fallout of bomb fission products. The prevailing winds dictate the specific fallout pattern and associated dosage contours, but suitable predictive tools are available, assuming an accurate depiction of the wind fields. More challenging is prediction of the source function detailing the amount and nature of the entrained mass. This can vary greatly depending on the burst location. A detonation in the open on the top deck of a parking garage has a vastly different mass loading than one in the lowest level of a parking garage under a skyscraper. Indeed, the latter burst configuration could lead to an overdense cloud with insufficient buoyancy, resulting in the collapse of the stem and a subsequent base surge that channels radioactive dust along urban canyons well beyond the range predicted by current tools. Also, a detonation on the roof of a tall building could result in an enhanced air blast environment resulting from the formation of a Mach stem and a more severe thermal environment resulting from a more favorable look angle.

So, do we have sufficient information to confidently predict the physical results of a terrorist or rogue nation attack with a single weapon on a single city? With the current state of uncertainties, where the error bars in expected damage estimates are likely to be as large or perhaps much larger than the expected damage itself, the answer is no. To change this situation, we need a more finely resolved understanding, which we have the capability to obtain with a relatively modest investment in attention and resources. The large computational hydrocodes available today are capable of computing the dispersion of destructive energy through a complicated urban geometry and modeling the damage response of specific structures to arbitrary loadings. Substantial progress predicting expected fire behavior is possible through careful analysis of available fuel loadings in an urban area of interest, a survey of thermal line-of-sight propagation, and engineering models based on observation of earthquake-associated ignitions and spread.

Chinese High-Altitude EMP Attack on Naval Forces

Plausible scenarios of concern involving China include a conventional conflict in the seas of the Western Pacific abutting China that escalates to a Chinese EMP attack on a US aircraft carrier task force in the region. The purpose of the attack could be to radically alter the prospects for victory in a regional conflict over Taiwan or other Western Pacific territorial disputes, to send a warning to the United States that it is at serious risk of further nuclear escalation, or both.

A Chinese EMP attack would be a larger-scale affair, at least by the metric of nuclear yield, than the single one- to ten-kiloton scenario previously considered. In some ways, it is also a simpler scenario to consider because many of the most significant effects associated with a ground burst are absent. An EMP attack would involve at most a few detonations at high altitude, producing an electromagnetic field over a very large geographical area spanning perhaps thousands of square kilometers. Such a large area is likely to include not just naval forces but also various countries in the region, perhaps even parts of China itself. Within the broad EMP footprint, all electronic equipment would be at risk of either temporary disruption or permanent failure.

Although the targeted carrier task force would be at risk in this scenario, the armed services have long been aware of the EMP threat and have worked over the years to reduce the vulnerability of their equipment. Nevertheless, there is significant uncertainty as to the degree to which the operability of naval forces would be impaired. Since the decommissioning of the EMPRESS II test facility in 1993, there has been no way to conduct a full system test of the EMP vulnerability of a large naval warship, and survivability assessments relying on subsystem testing and computational analysis come with significant uncertainty bounds.

We are unaware of any similar preparations or even consequence analyses that have been conducted to assess the impact on civilian infrastructures of countries that might fall within the EMP footprint of a potential Chinese EMP attack. First and foremost, national electrical power grids would be at risk of extended failure lasting months or more. Protective relays, switches, and digital control systems are vulnerable. The EMP Commission has pointed to both the vulnerability and the difficulty of replacing very large, extremely high-voltage transformers (more than 765 kilovolt), which typically require one year to manufacture and deliver overseas in small quantities. The telecommunications system, which sustains banks, stock markets, and the rest of the financial system, is also vulnerable. Oil and gas pipelines might cease to operate because their control systems fail. Equipment in hospitals might be affected and emergency generators might not work or have sufficient fuel. Pumping water might become difficult, and on and on and on. Although there may be no deaths in the immediate aftermath of a burst, over time, as the ability to maintain the taken-for-granted everyday technologies that sustain society fails, many casualties would follow.

So, will such catastrophic consequences actually unfold in an EMP attack? The short answer is that we just do not know. Neither the Department of Defense nor any US government civilian agencies responsible for protecting our infrastructures have devoted much, if any, funding to narrow the uncertainties of such a scenario and its broad impact on society. Put simply, none of these questions have even been asked, and consequently assessment tools are noticeably lacking from the toolbox.

The problem is complicated because of the complexity of assessing systems' abilities to respond after damage. Unlike in the single ground burst case, we can no longer simply answer questions such as whether a particular building a certain distance from ground zero will be damaged or whether a particular neighborhood may catch fire. Instead we ask what the failure of a number of individual components may mean for the system at large and for the failure of other systems because all our different infrastructures are now mutually interdependent. Some initial investigations have been funded and have produced models such as the Critical Infrastructure Protection/Decision Support System[77] and others produced by National Infrastructure Simulation and Analysis Center, which formally account for such mutual influences, but verifying and validating these codes is extremely difficult. Absent a concerted and sustained analytic investment, we are unlikely to be in any position to assess even the immediate physical consequences of such an attack. On the other hand, it is easier to resolve the required information to enable further progress. To assess a system's response, we do not require a finely tuned understanding of the response of every individual component. It is enough to know that, statistically, some percentage of components are likely to fail, which is a much easier assessment to make. Research must then focus on the systemwide implications of such component failures.

Scenario uncertainties are also important in this scenario but differ from those in the previous case. In this scenario, the most significant uncertainties are regarding the gamma ray and x-ray output of the nuclear weapons used (which determines the strength of the EMP field), the height of burst (which determines the range of effects as well as the strength of the field at the surface of Earth), and the number and locations of weapons used. However, assigning realistic values to these variables is amenable to strategic analysis, and there are few enough variables that parametric studies can be readily conducted and sensitivities to the variables determined.

Regional Nuclear War Between India and Pakistan

We imagine a regional nuclear war between India and Pakistan would be similar in many respects to a US–Soviet nuclear exchange during the Cold War, although at a much smaller scale in terms of both geography and weapon numbers and yields. Many scenarios are possible, including preemptive counterforce attacks on nuclear forces, "demonstration" attacks, countermilitary attacks in the context of an ongoing or impending conventional war, countervalue attacks on cities and economic targets, and combinations of these.

For all these possibilities, scenario uncertainties abound. There are numerous ways a nuclear war could start and unfold, involving different numbers of weapons, targets, heights of bursts, etc. For any specific set of values for scenario variables, our current knowledge base and analytic tools could support a physical consequence assessment limited to those effects that we have focused on for our own military assessment purposes (i.e., blast and fallout). Bringing to bear additional computational capabilities, including first-principles physics codes, we might expand our understanding of additional physical consequences to encompass the destruction of buildings and other infrastructure facilities within the blast radius of each explosion. However, we cannot analyze nearly as well the consequences of those physical effects that are not part of our damage expectancy paradigm (e.g., fire and EMP), let alone the general impact on infrastructures such as the water supply or the banking system. Moreover, assessing the cascading damage to interdependent civil infrastructures and the damages that reverberate throughout society are well beyond current modeling capabilities.

Consideration of consequences should also account for the potential impact of a regional nuclear exchange on any US troops who may be stationed in theater and potentially exposed to radioactive fallout under the right wind conditions. Other countries in the region will undoubtedly have similar concerns for their populations. Modern fallout tools, which incorporate real-time weather in their assessments, seem capable of this particular task. It is also likely that the detailed nature of the consequences in a regional nuclear exchange by India and Pakistan—large countries with much of their housing reflecting developing-world infrastructure—would differ from that expected were a similar nuclear exchange to take place in a highly industrialized venue. The greater proportion of structurally flimsy wooden structures would render India and Pakistan significantly more likely to incur damage and human casualties due to fire and to loss of sheltering protection from lethal deposits of radioactive fallout. Available tools also seem adequate to support a consequence assessment in these circumstances.

Recently, a number of scientists—some of them active in the original nuclear winter debates and now also engaged in the global warming climate controversies—suggested that even a modest nuclear exchange between India and Pakistan involving one hundred explosions, each fifteen kilotons, might engender serious consequences for global agriculture.[78] Using this estimate as a starting point, less technically intensive analyses emphasize that the Indian–Pakistani scenario sketched here would produce consequences extending far beyond the immediate confines of the region. One such forecaster, an emergency room doctor described as a "US medical expert" associated with Physicians for Social Responsibility, the US affiliate of International Physicians for the Prevention of Nuclear War, produced a widely quoted report stating that the regional scenario described here would result in one billion deaths from starvation.[79] Although the Department of Defense has not yet scrutinized such analyses for technical plausibility, it seems that the available knowledge base and analytic tools would be sufficient to make an informed assessment of the likelihood of such "nuclear-winter-lite" consequences, were resources devoted to the issue.

One issue that arises when considering this scenario is that, while we are interested in understanding the United States' ability to conduct consequence assessments, the abilities of the scenario participants are of primary importance. Based on the wealth of information in the public domain and the technological sophistication of states that can develop and deploy large numbers of nuclear weapons and delivery systems, it seems reasonable to presume that both India and Pakistan have consequence assessment capabilities approaching the level of the United States' capabilities. However, this may not have been the case when these countries first developed and tested nuclear weapons, and during that period a full appreciation of the consequences of nuclear use may not have been available to infuse caution in the behaviors of these states.

US–Russian Unconstrained Nuclear War

This scenario returns us to the darkest days of the Cold War and the Single Integrated Operational Plan, when defense intellectuals of the era strategized an all-out arsenal exchange with the Soviet Union as a peer adversary. Both sides of the conflict maintained nuclear arsenals numbering many thousands of warheads that would be launched in an all-out exchange.

As discussed in the introduction to this chapter, many nuclear strategists and political leaders think the probability of nuclear war between Russia and the United States is vanishingly small. For the purposes of this discussion, we only note that although we do not lie awake at night worrying about this scenario, we also do not think it is so unlikely that it should be dismissed. One need only consider the 1995 post–Cold War incident in which, for a brief time, Russia thought it might be under attack from the United States, and President Yeltsin opened his nuclear briefcase for the first time in history (other than as part of an exercise) to realize that the improbable can indeed lead to the unthinkable.[80] In addition, the rapidity with which the threat from the former Soviet Union declined suggests that it could also increase as rapidly (with the emergence of a hostile leader, for example). Finally, there are plausible scenarios involving the further expansion of NATO that could cross Russian red lines and provoke a crisis that escalates to a nuclear confrontation.

Somewhat paradoxically, it appears that this is the scenario for which we are currently best equipped to perform a meaningful consequence assessment, with one key exception. The resolution required for such an assessment can be rather crude. There is no need to attempt a finely tuned understanding of the extent of physical damage from every single detonation in every single city of varying geography, topology, and population. It matters little to a useful consequence assessment whether damage in this or that city extended ten kilometers or fifteen or whether the precise number of casualties that might be attributed to this or that nuclear effect is determined. We can anticipate that the scale of destruction would be so great that the precise answer, in terms of immediate population casualties for example, is, within a broad numerical range, practically irrelevant.

To clarify our perspective, we try to imagine a decision-maker contemplating alternative choices. The decision-maker is told that the consequences of one course of action might incur a risk of one hundred million casualties in an all-out nuclear exchange. Do we imagine a president's decision would be any different if they were told the contemplated choice incurred a risk of two hundred million casualties? Whereas in the first scenario of a single relatively modestly sized and localized detonation, we can easily contemplate the importance of getting it right and uncertainties of 100 percent mattering a great deal, in the truly catastrophic category, it is sufficient to simply estimate the scale of the consequences correctly. Thus, a useful consequence assessment can be conducted with relatively crude resolution as long as we have confidence in the error bounds. It seems that we are closest to such a situation in this last scenario, which also may have the least relevance to the global array of forces in the twenty-first century.

Before leaving this scenario, we should also say a few additional words about nuclear winter. At one extreme, it leads us to contemplate consequences completely beyond the scale of anything else on the table—the risk of extinguishing all human life on the planet. This is not the first time effects of nuclear weapons were seriously proposed to produce a hazard to all human existence. In earlier eras, analysis by respected scientists had proposed that chemical products of nuclear detonations injected into the atmosphere might destroy the Earth's protective ozone layer, leading to humankind's extinction. The ongoing reduction in nuclear arsenals along with countervailing data acquired following the period of atmospheric testing, which produced too little of the offending chemistry at high altitude to initiate such a doomsday scenario,[81] together conspired to mitigate the urgency and lower the interest of funding organizations in further pursuit of nuclear-driven ozone depletion investigations.

It appears to us that much the same fate befell the nuclear winter scenario. For a period of a few years in the 1980s, a lively scientific debate unfolded, with skeptics detailing perceived sins of both omission and commission on the part of the global climate modelers touting the winter scenario, while the latter responded vigorously. It should be noted that the Department of Defense—in the persons of two of the coauthors of this paper (Frankel and Ullrich)—provided even-handed funding to both the skeptics and proponents of nuclear winter. Eventually, based first on further fuel inventory research sponsored by the Department of Defense and later on decreasing arsenal sizes, a consensus emerged that whatever modeling issues might remain contentious, there would nonetheless be insufficient soot and smoke available at altitude to render nuclear winter a credible threat.[82]

Thus, both nuclear winter and ozone depletion follow the same paradigm: (1) the initial prediction of extinction-level consequences not previously thought of by Department of Defense scientists; (2) followed by an initial flurry of official and public concern and (3) subsequent (or even prior) research that casts doubt on the initial claims; and (4) ending with government lack of interest and a small group of scientists pursuing research that suggests continuing cause for concern. It is fair to contemplate why such important concerns—and what could be more important than conjectures that question the survival of the entire human race?—seem to come into and then out of official focus. We are not psychologists or social scientists who have other insight into this pattern, but it seems that with the development of credible counters to an initially one-sided presentation, the Department of Defense and the general public seem content to ignore the "bad news" analyses, despite any persistent uncertainty. The key seems to be the development of scientifically credible rebuttal divorced from political agendas.

Trends and Other Patterns

By far, the most significant trend relevant to the consequences of nuclear weapons use is that no nuclear weapon has been used in anger since the bombing of Nagasaki some two-thirds of a century ago. This tradition of nonuse grew in parallel with the Cold War increase and post–Cold War decline of nuclear arsenals and survived several close calls of potential use. As this tradition extends further in time, it is generally assumed to strengthen. However, there are countervailing forces at work that would seem to undermine it. In particular, as the memories of Hiroshima and Nagasaki fade in the collective consciousness of humanity, the true human horror of nuclear war gravitates toward a theoretical abstraction. Whatever our understanding of consequences, there is a vast gap between abstract knowledge and actually experiencing or witnessing nuclear weapons used against real targets with real human casualties. Capturing this important difference in a risk assessment would be extremely challenging, if possible at all.

Another significant trend that affects consequences and their assessment is the slow but seemingly inexorable proliferation of nuclear weapons. In 1945, the only countries in the world with the understanding to build nuclear weapons were the United States and the United Kingdom, which worked together at Los Alamos to build the first bomb, and the Soviet Union, which followed progress at Los Alamos courtesy of its atomic espionage (Klaus Fuchs and perhaps others). The Soviet Union first tested a nuclear weapon in 1949, and the United Kingdom followed not long thereafter in 1952. In 1960 and 1964, respectively, France and China demonstrated nuclear weapons capability, and officially unconfirmed but widely assumed to be true published reports credit Israel with a nuclear arsenal as early as the late 1960s; in 1974, it was India, and in 1998, Pakistan. In 2006, 2009, and 2013, North Korea detonated devices with nuclear yields.

During this period, there have also been a few notable acts of both voluntary and involuntary reversals in proliferation and progress toward proliferation. South Africa, after having built (and possibly tested) a nuclear capability, voluntarily canceled its program and, under International Atomic Energy Agency supervision, dismantled the six warheads it had built. Libya, after actively seeking to develop a nuclear capability, voluntarily canceled its program, dismantling capabilities and equipment and returning research materials in 2004. After the collapse of the Soviet Union, Belarus, Kazakhstan, and Ukraine voluntarily transferred their nuclear weapons to Russia by 1996. In 1983, the Iraqi nuclear weapons program was abruptly and involuntarily terminated by the Israeli bombing of the Osirik reactor, and the Syrian nuclear program was derailed in 2010, again courtesy of Israeli intervention. More recently, in 2010, the Stuxnet worm apparently disrupted the Iranian uranium enrichment program for at least some period of time, and the pressure of ongoing international sanctions may yet have an influence on Iran's development efforts.

Notwithstanding these latter incidents of proliferation reversals, it is undeniable that the overall increase in nuclear weapon states and the spread of nuclear capabilities, through indigenous development, technology transfer, or outright sale, has continued to grow. It is also clear that more parties presently strive to join the increasingly less exclusive nuclear club, including, should we again credit published reports, terrorist groups.[83] This proliferation trend affects consequence assessment in at least two significant ways. First, it increases the importance and variety of small-yield scenarios. Our knowledge of effects is less well developed for small weapons, yet for consequence management and recovery purposes, it is more important to understand the consequences of those smaller attacks that we will survive. Second, every new nuclear-capable state needs to become educated about nuclear consequences so they act with appropriate caution.

It is significant as well that these developments are taking place against the background of a trend of decreasing US domestic nuclear capability and expertise. Funding for nuclear effects research in the United States has been on a downward spiral since the fall of the Soviet Union in the early 1990s, and despite some minor funding upticks in recent years, the present Department of Defense capability to execute an authoritative consequence assessment lacks credibility.

Certainly not independent of the loss of funding for nuclear effects research is loss of the subject-matter experts who might perform such research. The cadre of scientific experts who grew up professionally in the nuclear testing era has not been replaced by a new generation of experts. Without confidence in the future availability of financial support or the psychological rewards associated with supporting one of the nation's top national security priorities, there is little to attract talented scientists to study the problem of nuclear effects. This ongoing loss of US nuclear effects expertise, which has been remarked for the better part of twenty years at this point, does not inspire confidence in a future effort to reduce uncertainties to the point that comprehensive consequence assessments might be performed.

Uncertainties in our nuclear effects knowledge base are also likely to grow with time because of a confluence of factors. The cessation of testing precludes opportunities to gather data on the impact of potential undetected aging-related defects in stockpile weapons or the effects of new advanced designs, both foreign and domestic.[84] Targeting policy has also changed significantly. There are now far fewer targets that are out of reach by conventional means or require prompt delivery, and minimization of collateral effects is a far more significant issue than it was during the Cold War. There are also new classes of targets, such as nonnuclear weapons of mass destruction, to which scant attention was paid in the past. For example, a nuclear weapon's ability to neutralize all biological agents in storage facilities—while simultaneously minimizing the collateral damage that would be inflicted by the explosive dispersion of any surviving part of the target—entails uncertainties that will be difficult, if not impossible, to reduce without any future opportunity to test. As states introduce newer chemical and biological agents in the future, these uncertainties will only grow.

In addition to these proliferation trends, the characteristics of the major powers' nuclear arsenals have evolved over time. Most notably, the quantity of weapons has decreased dramatically since peak stockpile levels of some thirty-one thousand for the United States in the mid-1960s and some forty-one thousand for the Soviet Union in the mid-1980s.[85] Current stockpiles number approximately five thousand to eight thousand for both sides and may decrease more as the New Strategic Arms Reduction Treaty (START) Treaty is implemented and with the potential for new arms control agreements and unilateral initiatives. The trend toward highly accurate modern weapons allows the dismantlement of numerous high-yield weapons and restriction of deployed weapons to available low-yield options, or even conventional explosives, to achieve the same level of expected target damage. However, with fewer weapons of smaller yield comes an enhanced interest in understanding more accurately what such weapons are likely to accomplish in actual use, as well as the regrets should this understanding prove wrong. The enhanced interest in understanding nuclear effects implied by these trends is as yet unmatched by any national effort to accomplish it.

Emblematic of the brain drain and loss of US nuclear expertise, it is ironic that there is a diminishing number of Americans who have witnessed a nuclear test in contrast to the growing cadre of young Indians, Pakistanis, North Koreans, potentially Iranians, and perhaps others, who have done so. However, subcontracting effects testing questions to others may not prove as simple as outsourcing to offshore call centers.

Conclusions and Recommendations

Our principal conclusion is that the existing knowledge base, while completely inadequate to support an all-consequences assessment, may, in a subset of scenarios associated with large exchanges, provide a useful lower bound to a consequence assessment that includes only physical effects.

Certainly, a Cold War scenario with an unlimited strategic exchange easily fits that description. Conversely, the same knowledge base seems inadequate for even such limited assessment purposes as the scenario shifts to smaller yields and numbers in the sorts of terrorist, rogue state, or even regional scenarios that have become more urgent matters of concern in the twenty-first century.

We underestimate consequences by concentrating on selected physical phenomena that cause calculable damage to targets of interest to military planners. Yet, even when assessment is restricted to the immediate physical damage in the aftermath of a nuclear explosion, there remain very large uncertainties, in no small part because many of the questions, such as what might be the larger impacts on the infrastructures that sustain society, were never previously asked or investigated. Other physical effects that have proven too intractable to calculate with confidence, such as fires and EMP, have been effectively neglected in consequence assessments. Potential damage from these phenomena (in the case of US use of nuclear weapons) has been treated as a bonus effect except in those scenarios in which minimizing collateral damage is an important consideration. Some of those consequences that are even more difficult to quantify, such as social, psychological, political, or long-term economic effects, have never been on any funding agency's radar screen. As a result, the actual effects of a nuclear conflict tend to have been underestimated, and a full-spectrum, all-effects consequence assessment is not within anyone's grasp now or in the foreseeable future.

That we have been surprised more than once (e.g., EMP, the destruction of satellites in low-Earth orbits due to the injection of high-energy electrons into Earth's radiation belts, atmospheric ozone depletion, and nuclear winter) suggests that a degree of humility is in order in any assessment of the state of our knowledge about the consequences of nuclear weapons use. We do not know what we do not know. Yet, all these surprises have subsequently revealed anticipated consequences by uncovering previously unrecognized physical damage phenomena. Based on this history, it is doubtful that we are in any great danger that some future surprise will result in lowering our estimates of the consequences of nuclear weapons use.

In addition, effects on the atmosphere that might result in catastrophic worldwide consequences have proved difficult to model. Disagreements among scientists about key assumptions and modeling limitations, a collapse of communication between academic scientists and Department of Defense policy-makers, and the lack of sustained interest by the public have allowed the Department of Defense to dismiss the possibility of major worldwide temperature declines that could lead to mass starvations in belligerent and nonbelligerent countries alike.

While there are large uncertainties in just how bad any nuclear weapons use will be, for some purposes, we may be insensitive to these uncertainties. For example, the difference between one hundred million and two hundred million casualties is large but may not affect any policy or crisis management decisions, whereas the difference between five thousand and one million casualties is far smaller but may be more likely to affect such decisions, so it can be more important to get the fine details correct in the latter case. This simple example suggests that scenarios of potential nuclear weapons use might be usefully characterized by the fidelity with which nuclear consequences need to be known to support decision-making and that the required level of detail decreases as the nuclear intensity of the event increases. Nonetheless, there remain key uncertainties that, if resolved, could affect policy even in larger-scale events. It matters greatly if EMP from high-altitude nuclear explosions will turn off the lights for a few days and kill a few toasters or if it will instantaneously thrust the United States back into an eighteenth-century preindustrial state. It will matter even more if the most dire predictions of nuclear winter are proven true.

In light of these findings on the current state of knowledge and practice in nuclear weapons consequence assessment, we offer several recommendations. First, a set of formal consequence assessments that consider a handful of well-chosen scenarios of differing intensity should be commissioned, and adequate resources made available to conduct them. The analysis in the "Scenarios" section of this chapter should be considered only a start to a more complete and resourced investigation that would bring to the task all available information and computational tools. The results are likely to be illuminating, identifying with some precision what is lacking in our current knowledge base and available tools and just where the greatest leverage lies in different uncertainty reduction investment strategies. Scenarios of greatest utility for such closer examination include: (1) a small nuclear detonation in an urban center and one in a major port; (2) both a high-altitude EMP attack by an advanced nuclear-weapons-capable state (Russia or China) and one by a newly emergent or prospective nuclear-capable state, such as a North Korea or Iran, within foreseeable reach of intercontinental ballistic missile capability; (3) an Indian–Pakistani general nuclear war; and (4) both a counterforce nuclear "exchange" and an unlimited US–Russian nuclear war. The objective of these consequence assessments should not be to determine the most likely outcomes or to find lower bounds, although both results would be useful, but rather to capture the range of possible outcomes with full consideration of all known effects—prompt and delayed, proximate and distal, direct and indirect, and quantifiable or unquantifiable. We suggest that a scientific body independent of the Department of Defense conduct any such study and that it issue both unclassified and classified reports.

Our second recommendation is that the Department of Defense, informed by the analyses and results of the first recommendation, develop and implement a serious plan to reinvigorate the nuclear effects research and analysis enterprise. Funding restoration should be accompanied by a new guiding framework focused on risk analysis and with a mandate to address emerging threats. The primary task of a reinvigorated nuclear effects community is then to reduce uncertainties that hinder prosecution of nuclear weapons consequence assessments. We recognize that this funding recommendation comes at a time of significant budgetary stress within the Department of Defense, especially for new initiatives. However, the risks attendant to the proliferation of nuclear threats in the new century warrant a reexamination of funding priorities.

Third, to establish priorities to broaden the scope of consequence assessments and reduce uncertainties, it would be useful to consider perspectives other than the ability to damage facilities on a target list in a war plan. In particular, to inform crisis management decisions, what would the president ask of the National Security Council and other advisors during crises with the potential to escalate to nuclear war? Other important perspectives are those of emergent nuclear powers lacking an indigenous nuclear weapons effects establishment. What information would be useful to provide such states about the consequences of regional nuclear wars, for example, as they consider the nuclear policies that will guide the use of their nascent arsenals? What research should be shared and which tools made available? Finally, we should consider the utility of accurate consequence assessments in the aftermath of nuclear weapons use to help mitigate the longer-term consequences that have not yet unfolded. Many uncertainties will have been resolved at that point, including quantity, locations, and heights of bursts; weapon characteristics; weather; and immediate damage from cratering, air blast, ground shock, and prompt radiation. What would be most useful to know about the propagation of effects and delayed consequences to help survivors and contain further damage?

Our final recommendation addresses particularly important gaps in our knowledge of consequences. As a guiding principle, we should focus research on scenarios with greater consequences or higher likelihood of occurrence. For both classes, the focus should be on indirect effects, cascading effects, social and psychological effects, and economic effects—areas traditionally given scant attention.

In terms of greater consequences, the two phenomena most in need of uncertainty reduction are nuclear winter and EMP. With respect to the former, the Department of Defense does not seem to consider any potential for long-term atmospheric effects in its consequence assessments or in its tools. At the same time, there is a small but persistent academic research community that continues to sound the alarm bell on nuclear winter, although not to the same degree as the original TTAPS study. We must clarify the science of nuclear winter and consider validated claims when developing nuclear targeting plans and managing crises.

Recently, we have noted increased awareness of the potential for catastrophic national consequences to our civil infrastructures due to a high-altitude EMP attack. The most serious potential outcome is the collapse of the electric power infrastructure over large areas for long times. However, there are very large uncertainties in the circumstances under which such a result would occur, and reminiscent of the nuclear winter saga, there has also been some hype concerning the threat, which could undermine long-term support for fixing real vulnerabilities. Thus, we need to better understand EMP phenomenology, predict damage to electrical devices, and model the cumulative effect across entire infrastructures and the entire society.

In terms of those threats with greater likelihood of occurrence, we suggest that crude weapon designs, rather than sophisticated designs, are more likely to be developed by terrorist organizations, and smaller weapons are more feasible both because they require less nuclear material and are easier to deliver to target. A ground burst in an urban center is more likely than a burst in the cornfields of Kansas because terrorists are motivated to terrorize. Ports may be more likely than other detonation points because terrorists may deem the probability of inland transport too risky, or US surveillance systems may detect a weapon's entry in a port and thereby provoke its detonation. Therefore, scenarios based on such considerations should be higher on the priority list for consequence assessments, notwithstanding the possibility of a sophisticated weapon exploding at altitude above the cornfields of Kansas.

Absent the actual use of nuclear weapons, tremendous uncertainties will inevitably remain in our understanding of the consequences of nuclear weapons use. However, a reinvigorated nuclear effects community with a refocused mandate as described above can far better inform our national leaders, which will, one hopes, help maintain these questions in the domain of theory.

Notes

1. Early concerns that a nuclear detonation might "ignite" the atmosphere were largely dismissed based on a detailed analysis by the time of the test. See E. Konopinski, C. Marvin, and E. Teller, *Ignition of the Atmosphere with Nuclear Bombs*, Technical Report No. LA-602 (Los Alamos, NM: Los Alamos National Laboratory, 1946), https://sgp.fas.org/othergov/doe/lanl/docs1/00329010.pdf.
2. K. T. Bainbridge, *Trinity*, Scientific Laboratory Report No. LA-6300-H (Los Alamos, NM: Los Alamos National Laboratory, 1976), https://doi.org/10.2172/5306263.
3. US Department of Energy, *United States Nuclear Tests: July 1945 through September 1992*, DOE/NV-209-REV 15 (Las Vegas: US Department of Energy Nevada Operations Office, 2000,) https://www.nnss.gov/docs/docs_librarypublications/doe_nv-209_rev16.pdf.
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5. The shape of the dust skirt is generally attributed to an oblique precursor shock propagating ahead of the main shock in a channel of hot (higher sound speed) air adjacent to the fireball-heated surface. Some have argued that for lower heights of burst, such as with Trinity, the thermal layer has not yet formed at the time of shock reflection, and the scouring effect of the strong reflected shock wave alone is sufficient to create a supersonic dust jet that catches up and propagates ahead of the main shock.
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47. E3 is generated by expulsion of magnetic flux from the ionized, expanding nuclear fireball and by the additional displacement of flux due to the rise ("heave") of a heated and ionized patch of atmosphere directly under the detonation point.
48. The E2 component of EMP immediately follows E1 and is dominant in the time domain from about one microsecond to one second. It is of significantly lower intensity than the E1 component and is generated by late-arriving neutrons and scattered gamma rays. It has the electrical pulse characteristics of lightning, and because standard lightning protection also offers protection against E2, this component is often neglected in discussions of high-altitude EMP. There are circumstances, however, in which E2 may assume importance, such as in a scenario where an E1 pulse first damages electronic circuit breakers and other lightning controls.
49. SREMP is generated by an asymmetric current of Compton electrons.
50. This trend is most prominent at overpressure levels below about one hundred pounds per square inch. The optimum height of burst is often referred to as the "knee" in the overpressure curves, represented as iso-pressure contours plotted in height-of-burst versus range space.
51. The Regular Reflection region starts at ground zero and is characterized by an incident shock wave followed by a reflected shock wave, which intersect at the ground surface. At a range approximately equal to the height of burst, the reflected shock wave, which is traversing shock-heated air, catches up and begins to merge with the incident shock wave to form a single shock wave known as the Mach stem. This is the start of the Mach Reflection region. In the Regular Reflection region, an above-ground structure will experience two shock waves; in the Mach Reflection region, such a structure would see only one shock wave, provided the Mach stem has grown to a height that is taller than the structure at that ground range.
52. As an example, Sedan, the peaceful nuclear explosion conducted in desert alluvium at the Nevada Test Site in 1962, achieved an optimal depth of burst at 635 feet for a 104-kiloton device, forming a crater that was 320 feet deep with a diameter of 1,280 feet.
53. The Allied strategic bombing campaigns during World War II attempted to achieve similar incendiary effects through patterned laydowns but, according to the US Strategic Bombing Survey quoted in the 1983 National Academy of Sciences report *The Effects on the Atmosphere of a Major Nuclear Exchange* (https://doi.org/10.17226/540), succeeded only on four occasions, in Dresden, Hamburg, Kassel, and Darmstadt, where the dense fuel loadings of wood-constructed buildings and the closely spaced and near-simultaneous ignitions over a large target area produced an extreme fire phenomenon. Loss of life was similarly horrific—cumulative estimates vary widely, ranging from 167,000 to

300,000 for the four events—with similar reports of victims' inability to escape the burning zone.

The conditions that define a firestorm and whether those conditions are met in individual instances remain matters of scientific controversy. Thus, for example, Nagasaki is not categorized as a firestorm by some assessments that point to hilly terrain, among other things, that may have impeded ignition and coalescence to the degree experienced in Hiroshima. Darmstadt and Kassel, which suffered devastating fire damage and many thousands of casualties, are nevertheless left off some lists of World War II firestorms.

54. A. Saint-Venant was a nineteenth-century elasticity theorist who formulated the principle bearing his name that the difference between the effects of two different but statically equivalent loads on an extended solid body rapidly diminishes with increasing distance from the loaded segment.
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