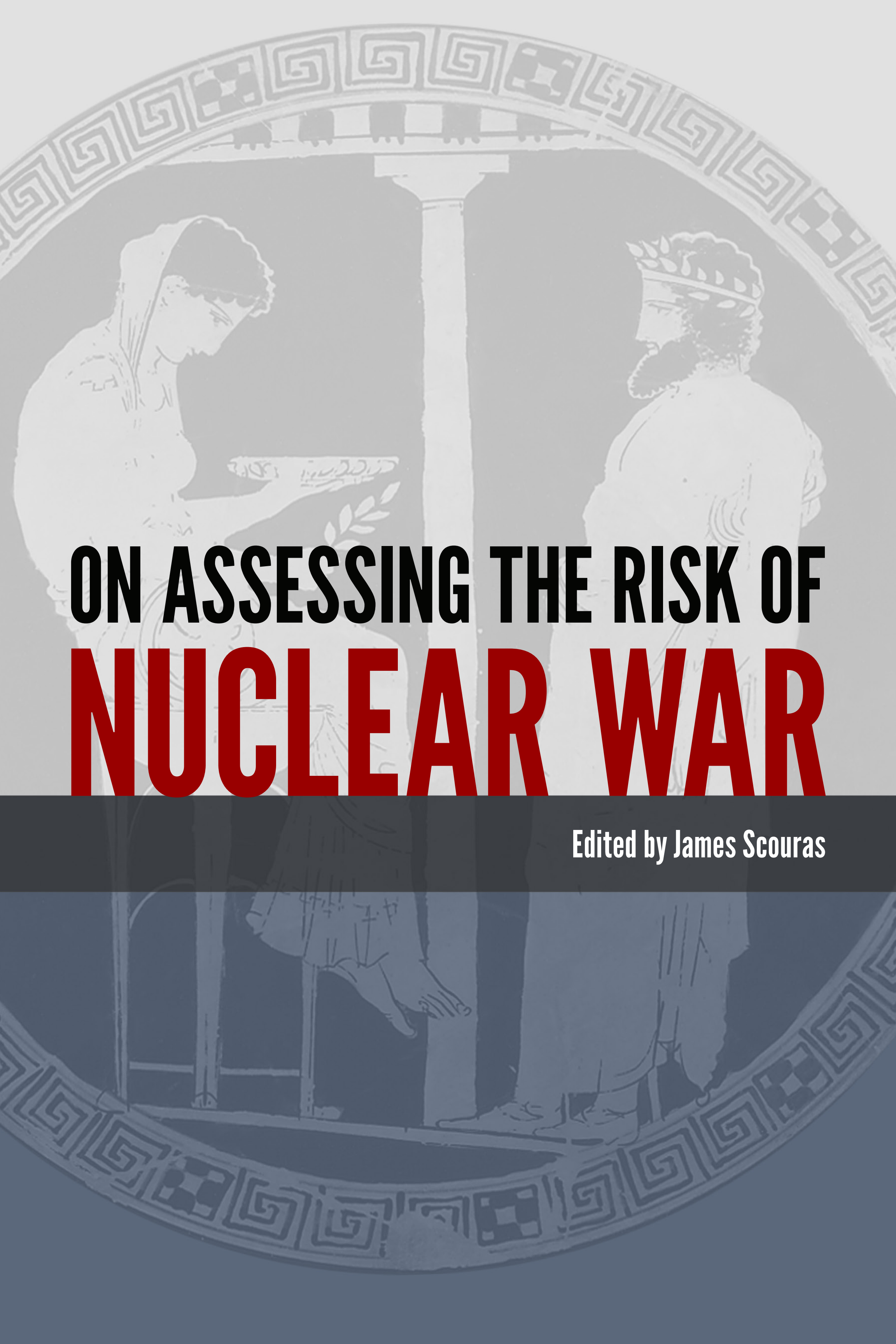

ON ASSESSING THE RISK OF NUCLEAR WAR

Edited by James Scouras

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To Kathy, the love of my life, without whose faithful support
this work would never have been completed.

The price we pay for maintaining nuclear weapons
is the gamble that the highly improbable
will not lead to the unthinkable.

—Eben Harrell, "The Nuclear Risk: How Long Will Our Luck Hold?"

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Preface

General perception of the risk of nuclear war has a strong influence on the broad directions of national policy. For example, arguments for both national missile defenses and deep reductions in nuclear forces depend in no small part on judgments that deterrence is unreliable. However, such judgments are usually based on intuition, rather than on a synthesis of insights from the most appropriate analytic methods that can be brought to bear. This book attempts to establish a methodological basis for more rigorously addressing the question, What is the risk of nuclear war? Its goals are to clarify the extent to which this is a researchable question and to explore promising analytic approaches.

This work had its intellectual origins in a series of conversations, beginning in June 2008, with Dr. Martin Hellman, professor emeritus of electrical engineering at Stanford University. At the start of these discussions, I was chief scientist of the Defense Threat Reduction Agency's Advanced Systems and Concepts Office. Dr. Hellman had been thinking, writing, and advocating for some time on the issue of assessing the risk of deterrence failure.[1] In particular, he had authored "Risk Analysis of Nuclear Deterrence," in which he discusses the criticality of estimating nuclear risk and the lack of existing analyses that attempt to do so. In this article he proposes "as a first step toward reducing the risk of a failure of nuclear deterrence . . . that several prestigious scientific and engineering bodies undertake serious studies to estimate its failure rate."[2] Dr. Hellman's proposal ultimately led to a congressionally mandated study, "Risk Analysis Methods for Nuclear War and Nuclear Terrorism," currently being undertaken by a National Academies of Sciences, Engineering, and Medicine committee of which I am a member.[3]

Many interesting insights came out of my conversations with Dr. Hellman. Among them was the notion that perhaps neither the scientific and engineering communities nor the national security and risk analysis communities are fully prepared to tackle this daunting challenge. Thus, the idea emerged that the first step toward a more comprehensive study should be a preliminary examination of the *feasibility* of assessing the risk of deterrence failure, focusing on the utility and limitations of some of the more promising approaches that could be used.

After I left the Defense Threat Reduction Agency to join the Johns Hopkins University Applied Physics Laboratory, the opportunity arose to pursue this idea. The Laboratory allocates a portion of its funding to a program of innovative research with the potential for significant impact on critical national challenges. This study, initially funded under that program, focuses on four diverse but complementary approaches to assessing the likelihood of deterrence failure: historical case study, elicited expert knowledge, probabilistic risk assessment, and complex systems theory. It also assesses the state of knowledge on both the physical and intangible consequences of nuclear weapons use. Finally, it examines the challenge of integrating knowledge obtained from these diverse disciplines and disparate approaches.

In addition to myself, the study participants are Andrew Bennett, Jane M. Booker, Dallas Boyd, Michael J. Frankel, Martin E. Hellman, Edward T. Toton, and George W. Ullrich. I am a senior scholar at the Johns Hopkins University Applied Physics Laboratory. Dr. Bennett is a professor of government and international affairs at Georgetown University. Dr. Booker, currently a consultant, was formerly group leader of the Statistics Group at Los Alamos National Laboratory. Mr. Boyd is an analyst whose work focuses on nuclear weapons policy and nuclear counterterrorism. Dr. Frankel, one of the nation's leading experts on effects of nuclear weapons, is a technology and national security consultant. Dr. Hellman is professor emeritus of electrical engineering at Stanford University and an eminent thought leader on nuclear risk. Dr. Toton, president of Toton Inc., is a theoretical physicist with a history of research in global catastrophic risk and quantification of uncertainty. Dr. Ullrich, formerly deputy director of the Defense Nuclear Agency, is senior vice president for strategy development at Applied Research Associates.

This book is the primary documentation of the Johns Hopkins University Applied Physics Laboratory study. It should be of interest to policy-makers, analysts, and citizens concerned with nuclear risk and the fragility of nuclear deterrence. The authors hope it will inspire others to tackle this critical issue.

Notes

1. See the Defusing the Nuclear Threat website, http://www.nuclearrisk.org, developed and maintained by Dr. Hellman, for a compendium of this work.
2. Martin E. Hellman, "Risk Analysis of Nuclear Deterrence," *The Bent of Tau Beta Pi* 99, no. 2 (2008): 14–22, https://ee.stanford.edu/~hellman/publications/74.pdf.
3. National Academies of Sciences, Engineering, and Medicine, "Risk Analysis Methods for Nuclear War and Nuclear Terrorism," https://www.nationalacademies.org/our-work/risk-analysis-methods-for-nuclear-war-and-nuclear-terrorism. While I am a member of the study committee, the views expressed in the chapters that follow are those of the authors and do not necessarily reflect those of the National Academies study committee.

Editor's Acknowledgments

I am grateful for the contributions of the authors, as well as numerous other colleagues, in advancing this book. In particular, I think Martin Hellman for providing the original inspiration for the topic; numerous nuanced discussions involving the intricate relationships among nuclear strategy, risk, and analysis; and detailed reviews of all chapters in their formative stages; Gregory Melcher, for providing the original funding under which this work was begun at the Johns Hopkins University Applied Physics Laboratory and for his continued support throughout the project; Andrew Bennett, for reviewing and significantly improving the first and final chapters; Jane Booker for alerting me to the importance of including a chapter on knowledge integration; and numerous reviewers who are individually acknowledged in the various chapters.

Chapter 1
Framing the Questions

James Scouras

> *What are the risks of nuclear war in all its potential manifestations? This is not an easy question to answer, and I do not propose to answer it here. Rather, the more tractable question is whether the process of studying it could yield policy-relevant insights even if it is unlikely to lead to a precise determination of the actual risks of nuclear weapons use. In this chapter, I summarize the current state of analysis regarding the likelihood of nuclear war, focusing on* The Lugar Survey on Proliferation Threats and Responses, *the* Bulletin of the Atomic Scientists' *Doomsday Clock, and a sampling of analysts' estimations of the likelihood of interstate nuclear war and nuclear terrorism. These estimations differ widely and are all of questionable validity because they are either fundamentally intuitive or based on very simple—even simplistic—analyses. Can we improve on this state of analysis by using more structured and more comprehensive approaches to provide a sounder basis for policies that will inevitably be based on imperfect analyses of the likelihood of nuclear war?*

What are the risks of the use of nuclear weapons? Through what paths might these risks arise? How best might these risks be reduced? Throughout the Cold War, American strategists seemingly had relatively clear answers to these questions, or at least a clear understanding of the policies we should follow to mitigate nuclear risks. During the near half-century between the end of World War II and the fall of the Berlin Wall, the United States and its allies were focused on the existential[1] threat posed by the Soviet Union. Broadly speaking, the overarching US national security policy was containment of Soviet expansionism, and the cornerstone of US strategy for preventing such expansion by military means was deterrence. Deterrence threatened "unacceptable consequences," code for nuclear devastation, to the Soviet Union should it attack the United States or its allies.

The capability to inflict unacceptable consequences was embodied in a nuclear weapons triad of intercontinental ballistic missiles, submarine-launched ballistic missiles, and long-range bombers. The adequacy of this capability was evaluated in the context of what was viewed as the most stressing scenario: a massive surprise attack on US nuclear forces and associated command and control. The redundancy embedded in both the US and Soviet nuclear triads, and the inability of either side to strike preemptively and simultaneously against all three legs of the other side's nuclear triad with confidence of success, even in the context of this so-called "bolt from the blue" scenario, was thought to provide robust deterrence for both sides and to nearly eliminate the incentives to be the first to use a nuclear weapon. Neither side would have the temptation to strike first because massive retaliation was virtually certain; nor did either side have to fear a disabling first strike by the other. The residual risk of nuclear weapons use, in this view, was best reduced through arms control agreements that further limited the incentives for a nuclear first strike, through reduced expenditures and dangers associated with an otherwise unconstrained nuclear arms race, and perhaps eventually through missile defenses should such defenses become technologically and economically feasible.

In contrast, the unanticipated and abrupt end of the Cold War initiated a period of additional uncertainty about the most likely paths to the use of a nuclear weapon and the best means of addressing them. One source of this confusion is the unresolved question of the extent to which Russia still did, or might once again, pose a mortal threat to the United States. In the decade-long afterglow following the end of the Cold War, the nuclear threat from Russia was largely dismissed as "Cold War thinking." This attitude was reinforced by the terrorist attacks of September 11, 2001, after which all things nuclear (except nuclear terrorism) took a back seat in national security planning. By the time of this writing, some two decades after 9/11, Russia has reemerged as a nuclear threat to be taken very seriously. Russia remains the one country other than the United States with a nuclear triad that under the latest arms control agreement will still have more than 1500 nuclear weapons of global range. Yet it is also true that the mutual hostility and mistrust that characterized much of the US–Soviet relationship are today far reduced, and the robustness of mutual deterrence that held during the Cold War still appears to apply.

In any event, the risk of nuclear war with Russia has clearly receded relative to the Cold War in terms of both its likelihood and potential consequences. As a result, there is a tendency to discount the residual Russian threat relative to other threats that appear to be more immediate, growing, or more likely to result in nuclear use, even if their consequences might be orders of magnitude less severe than those of an unconstrained nuclear war with Russia. The most significant examples of such threats include North Korea's nuclear and missile program, under which a nascent nuclear deterrent has been established, and Iran's uranium enrichment program, which by its scale and nature appears to be aimed at developing, or at least having the capability to develop, a nuclear weapon. Cascading regional proliferation, especially if Iran becomes a nuclear state, is not implausible. Meanwhile, China continues to increase its nuclear capabilities, extend the range of its missiles, and diversify its means of delivering nuclear weapons. India tested a nuclear weapon in 1998, after having foregone any additional tests since its first in 1974, and Pakistan followed suit with its first nuclear test shortly thereafter; both states are considered to have dozens of nuclear weapons or more. Israel is widely believed to possess scores, if not hundreds, of nuclear weapons, and many more states have the technological ability to produce nuclear weapons should they decide to do so. The present number of nuclear weapons states is not as large as President Kennedy and others predicted in the early 1960s, but it has grown, and each additional nuclear power, including long-term US allies Britain and France, presents an added set of risks that nuclear weapons will be used someday against someone. One singular concern is the possibility that terrorist organizations willing to carry out mass-casualty attacks will eventually get their hands on a nuclear weapon by buying, stealing, or building one. The present and future number of such organizations and the likelihood of their obtaining a nuclear weapon are even harder to assess than the future number of nuclear weapons states.

In retrospect, the apparent simplicity and robustness of nuclear deterrence during the Cold War were neither as simple nor as robust as they seemed at the time. The gradual release of historical evidence has made clear that the actual risks of nuclear weapons use during the Cold War, and the most likely paths through which nuclear use could have been realized, were quite different from the scenario of large-scale and intentional use of nuclear weapons that preoccupied American and Soviet leaders and national security analysts. The considerable number of close calls, accidents, incidents, misunderstandings, and false alarms that we now know arose during the Cold War were arguably more likely to have resulted in the use of nuclear weapons than the intentional calculation that the use of such weapons could advance some strategic purpose (and presumably there were additional close calls that are not publicly known). Indeed, perhaps the most serious incident was revealed only in 2002: during the Cuban missile crisis, Captain Valentin Savitsky, commander of a Soviet submarine, reportedly ordered his crew to prepare to launch a nuclear-armed torpedo against the American ships that were dropping depth charges to force his submarine to the surface. Fortunately, Soviet procedures required the consent of three top officers on the submarine for a nuclear weapon to be used, and another senior officer, Vasili Arkhipov, succeeded in convincing Savitsky to surface for orders from Moscow instead of launching a nuclear-armed torpedo without higher authorization.[2]

The divergence between contemporary impressions of nuclear risks and the accumulating historical evidence on actual close calls regarding nuclear weapons warrants caution in the assessment of current risks and humility in estimating future ones. Yet while precise and confident estimates of nuclear risks are not possible, the task of assessing and addressing the most pressing risks of nuclear weapons use is too important to forgo.

Objective

The nuclear threat space is clearly more complex today than during the Cold War. Interrelationships, obvious and obscure, abound among the myriad facets of the nuclear threat and policies intended to address them. A systems perspective, currently lacking, would help clarify how various aspects of nuclear policy affect all elements of the nuclear threat and thereby reduce the likelihood of unintended consequences. But even more basically, we need to establish policies informed by the risks of the various dimensions of the nuclear threat. What are the risks of nuclear use in all its potential manifestations?

This is clearly a difficult question to answer. In fact, it might not be answerable at all with a useful degree of certainty or consensus, and I do not propose to answer it here. Rather, my more limited purpose is to address whether the question is or is not analytically tractable and whether the process of studying it would yield policy-relevant insights even if it is unlikely to lead to a precise determination of the actual risks of nuclear weapon use. As President Eisenhower often said, "Plans are worthless, but planning is everything." In other words, although we cannot fully anticipate our adversaries or the future, the attempt to do so will leave us in a better position than if we failed to plan at all. More specifically with regard to the question of nuclear risks, what analytical approaches have been or could be utilized, and what are their prospects for providing a degree of enlightenment on the risk of nuclear use?

Risk Terminology and Analysis

Risk is exposure to danger due to the likelihood and consequences of an adverse event. In our case the adverse event is nuclear weapon use, which is defined as the detonation of one or more nuclear weapons, except for nuclear weapons tests, whether intentionally or accidentally, anywhere in the world. The reason for such an expansive definition is that any nuclear use could directly or indirectly cascade to involve the major nuclear states.

Likelihood can be described in qualitative terms (e.g., unlikely, highly likely, a remote possibility) or quantitatively, such as in probabilistic terms. To be meaningful, a time frame must be specified (e.g., "There is a moderate likelihood of nuclear use within the next ten years.") In some risk assessments, frequency is used to portray likelihood ("We can expect two attacks over the course of the next decade."). However, this is not appropriate for nuclear attacks, because the original nuclear use and the reaction to it can be expected to significantly affect the likelihood of a subsequent use.

Consequences include fatalities, injuries, physical and economic damage, social and psychological impacts, and all other forms of harm. They can be immediate or can unfold over the course of decades. As with likelihood, a time period should be specified. Important, but often overlooked, consequences include those that would result from the reaction to nuclear weapon use.[3] Because its consequences would be extreme, even the remote likelihood of nuclear weapon use may well motivate policy changes because remote possibilities can accumulate to worrisome levels when aggregated over the long term. Put another way, if there is a nonzero constant risk of nuclear use each year, given enough time, the probability of eventual nuclear use will approach 100 percent no matter how small the risk is in any given year.

For both likelihood and consequences, it is important that an uncertainty be associated with any estimation. Research in psychology suggests that humans are not very good at estimating "confidence levels" for their estimations.[4] For example, people are generally poor at tasks like the following: "Set the upper and lower bounds on the probability that a nuclear weapon will be used in the next ten years, in such a way as to be 90 percent confident that the actual probability will fall between your lower and upper bounds." Yet if we fail to press experts to associate a confidence level or uncertainty with their estimates, we can easily fall into the trap of assuming that the uncertainty is negligible.

Finally, the common practice of multiplying likelihood and consequences, which would result in an expected risk, is inappropriate for characterizing the risk of nuclear war. There are policy-relevant differences between the combination of low likelihood and high consequences (perhaps interstate nuclear war) and the combination of high likelihood and low consequences (perhaps terrorist nuclear weapon use). This critical distinction is lost when the product is used.

The Influence of the Perceived Risk of Deterrence Failure on Policy

Detailed consideration of the likelihood and consequences of nuclear war is not usually explicit in developing national security strategy. Yet implicit assumptions on these questions have a strong influence on nuclear policy, and explicit generalizations of them have been invoked to justify major new directions in policy. The entire nuclear arms control enterprise—from the "hotline" memorandum of understanding through the Anti-Ballistic Missile Treaty and Strategic Arms Limitation Treaty (SALT), the Intermediate Nuclear Forces (INF) Treaty, the Strategic Arms Reduction Treaty (START), the Strategic Offensive Reductions Treaty (SORT), and the current New START Treaty—was motivated principally by fear of nuclear war. In the 1950s the dominant theoretical concern involved a disarming surprise attack, but fear of nuclear war was made all too tangible by the Cuban missile crisis of 1962 and has been reinforced throughout the Cold War by the nuclear arms race and nuclear posturing.

Similarly, arguments for national missile defenses depend in no small part on the judgment that deterrence is unreliable. As expressed by President Reagan in his oft-quoted Strategic Defense Initiative speech of 1983:[5]

> Tonight . . . I am directing a comprehensive and intensive effort to define a long-term research and development program to begin to achieve our ultimate goal of eliminating the threat posed by strategic nuclear missiles. This could pave the way for arms control measures to eliminate the weapons themselves. We seek neither military superiority nor political advantage. *Our only purpose—one all people share—is to search for ways to reduce the danger of nuclear war.* [Emphasis added.]

President George W. Bush invoked the inadequacy of deterrence and the consequences of nuclear use by "rogue" states and terrorists to justify preemptive attack as a critical element of national security strategy:[6]

> It has taken almost a decade for us to comprehend the true nature of this new threat. *Given the goals of rogue states and terrorists, the United States can no longer solely rely on a reactive posture as we have in the past.* [Emphasis added.] The inability to deter a potential attacker, the immediacy of today's threats, and the magnitude of potential harm that could be caused by our adversaries' choice of weapons, do not permit that option. We cannot let our enemies strike first.

More recently, the prospect of nuclear use motivated President Obama's call for a nuclear-free world:[7]

> Today, the Cold War has disappeared but thousands of those weapons have not. In a strange turn of history, the threat of global nuclear war has gone down, but the risk of a nuclear attack has gone up . . . So today, I state clearly and with conviction America's commitment to seek the peace and security of a world without nuclear weapons.

Clearly, quite different policies have been motivated by the concern that deterrence might fail. However, assertions that deterrence cannot be relied on are based on intuition and limited perspectives rather than syntheses of the broadest expertise and most appropriate analytic methods that can be brought to bear.

The State of Analysis

Consider the current state of analysis. In 2005 the office of Senator Richard Lugar published *The Lugar Survey on Proliferation Threats and Responses* (hereinafter, the Lugar survey),[8] which addresses the risk of nuclear use and has been widely cited on the internet and in the academic literature. Among the questions asked in the survey was, "What is the probability (expressed as a percentage) of an attack involving a nuclear explosion occurring somewhere in the world in the next ten years?" The distribution of replies from seventy-nine respondents is shown in Figure 1.1.

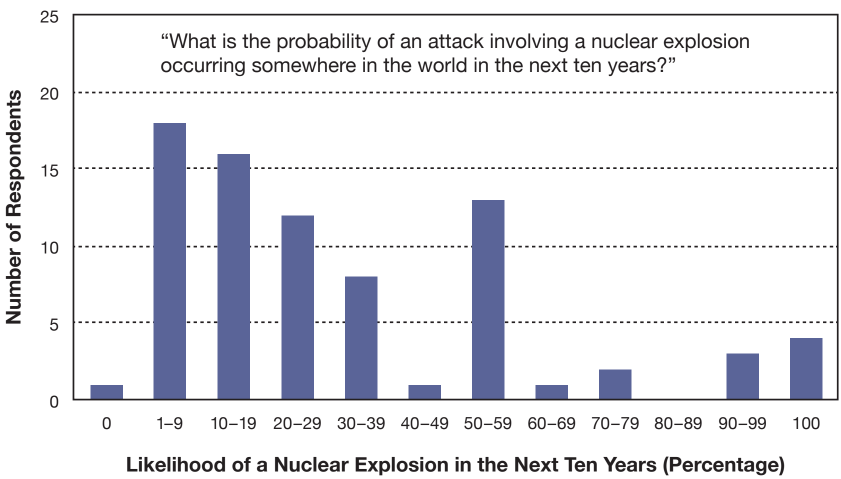

Figure 1.1. The Lugar survey, question 5.

What is most striking about Figure 1.1 is the breadth of opinion, which spans the full spectrum from 0 to 100 percent. From a classical statistics perspective, the true probability lies in only one bin. The fact that most experts' answers missed that value, whichever bin it lies in, means that most experts must necessarily be wrong. There are a number of possible explanations for this. One reason for the wide variation could be the lack of control of biases in the elicitation of the answers. Without bias control, experts can interpret and think differently about how to answer the question, resulting in wide variability. Even if biases are controlled, wide dispersion can still occur because of high uncertainty in the current state of knowledge. In any event, the most significant conclusion to be drawn from Figure 1.1 is that there is no consensus on the answer to the question. In contrast, the Lugar survey report highlights the mean (29 percent) of these data as the most relevant finding. If it had also reported the standard deviation (which is approximately 26 percent) with this mean, then the high variability in Figure 1.1 would have been more apparent.

In other respects as well, the Lugar survey did not make use of best practices in elicitation and analysis.[9] While each survey respondent was an expert in some aspect of nuclear policy, arguably no single person is truly an expert on *all* the factors that must be considered when answering broadly phrased questions such as that depicted in Figure 1.1.[10] Additionally, the survey provides no information about the experts' assumptions, reasoning, and uncertainties. Such information could, for example, be useful in understanding the apparently anomalous peak at 50–59 percent. The cumulative impact of these and other deficiencies is that the survey falls short of what could be achieved through a survey using best practices in expert elicitation. Yet references to the Lugar survey are almost uniformly uncritical, even in the academic literature, and policy advocates have used its results to argue for important decisions. Clearly, a more scientific survey could be conducted that would improve on the reliability of the Lugar survey. Nevertheless, the fact that the survey was undertaken and that it was extensively cited demonstrate that the question of the likelihood of deterrence failure is relevant to policy-makers, analysts, and the public.

Another exercise in characterizing the likelihood of nuclear war has been ongoing since 1947, when the Doomsday Clock first appeared on the cover of the *Bulletin of Atomic Scientists*.[11] The setting of the clock is intended to represent how close the world is to nuclear war, metaphorically midnight. The clock was originally set at seven minutes to midnight and has been reset periodically every several (one to seven) years. As shown in Figure 1.2, the time of greatest danger, two minutes to midnight, was set in 1953 after the US and Soviet hydrogen bomb tests, while the time of least danger, seventeen minutes to midnight, was set in 1991 after the START Treaty was signed and unilateral initiatives on both sides removed many nuclear weapons from "hair-trigger" alert.[12]

There are multiple problems with taking the clock seriously as an assessment of the likelihood of nuclear war. There could be motives in setting the clock beyond accurately characterizing the nuclear threat, such as to promote certain policies, especially with respect to arms control treaties, or simply to draw attention to the *Bulletin of the Atomic Scientists*. The process by which the clock is set is obscure, although brief summaries of the reasons for changing the clock's setting have been provided.[13] No attempt has been made to define the clock's scale, which is almost certainly nonlinear. Does ten minutes to midnight indicate half the probability of five minutes to midnight? And finally, the clock is unable to reflect the risks associated with short-duration, high-risk episodes, such as the Cuban missile crisis of 1962 and the coup attempt against Gorbachev in August 1991.[14] Ironically, the former occurred during a period of reducing risk, according to Figure 1.2, and the latter occurred during the period of least risk.

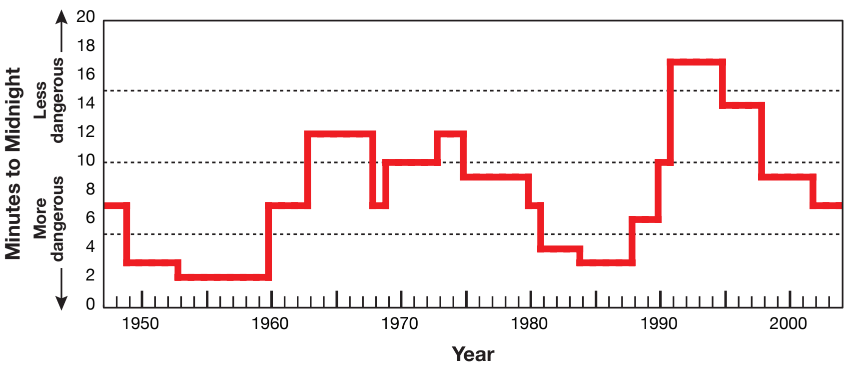

Figure 1.2. The Doomsday Clock, 1947–2004. The clock indicates then current perspectives of the *Bulletin of the Atomic Scientists* on the dangers of nuclear war. Since 2007, dangers associated with climate change and developments in the life sciences have been added.

Notwithstanding these points, the Doomsday Clock does seem to have captured the broad trends in the nuclear threat as it derives from the international political climate. Gaining a better understanding of the processes by which the clock has been set could prove useful in developing more scientific approaches. Unfortunately, the clock's future utility as an indicator of the risk of nuclear war has been diminished since 2007 by the inclusion of climate change and developments in the life sciences as additional harbingers of doomsday.

Several individuals have also estimated the likelihood of interstate nuclear war or nuclear terrorism. These estimates are summarized in Table 1.1. Most are subjective judgments (Kennedy,[15] Bundy,[16] Allison,[17] Perry,[18] Albright,[19] and Garwin[20]) without a formal underlying analysis, while others are based on a specific analysis (Hellman,[21] Bunn,[22] and Mueller[23]).

Arguably, the most compelling assessments are those of crisis managers who experienced a nuclear close call firsthand: President John F. Kennedy and his national security advisor, McGeorge Bundy. Not long after the Cuban missile crisis, Kennedy told Ted Sorenson, special counsel to the president, that he believed during the crisis the chances that the Soviets would go to war were between one in three and even, while Bundy, reflecting twenty-six years after the crisis, came to the dramatically lower estimate of up to one in one hundred. Of course, the crisis occurred almost a half-century ago, and even with the additional information now available it is hard to estimate its risks retrospectively. For example, depending on one's interpretation of the probabilities associated with the Soviet submarine incident discussed above, and the risks one should attach to other "close-call" incidents during the Cuban crisis,[24] one could argue for either Kennedy's estimate or Bundy's. Moreover, neither Kennedy nor Bundy knew at the time they made their estimates that a Soviet submarine had come close to launching a nuclear torpedo, but they could have imagined this and other scenarios as part of their risk estimates, so it is unclear whether either of them would have raised or lowered their estimates if they had known at the time of their estimates everything we know now. Of course, beyond the question of what the actual risk was at the time of the Cuban crisis is the problem of the relevance of that information to the assessment of future risks.

Recently, Martin Hellman assessed the risk of a future "Cuban missile-type" crisis that results in nuclear use as between two in one thousand and one in one hundred per year. Note that this is only one of three estimates in Table 1.1 that provides a range, a useful approach to addressing uncertainty. Hellman also points to a dearth of analyses of the risk of deterrence failure and proposes that "several prestigious scientific and engineering bodies undertake serious studies to estimate its failure rate."[25]

Table 1.1. Individual estimates of the probability of nuclear war

	Question	Estimate	Author	Year
War	Probability that the Cuban missile crisis could have escalated to (nuclear) war?	Between 1 in 3 and even (war)	John F. Kennedy	1962
		As large as 1 in 100 (nuclear war)	McGeorge Bundy	1988
	Probability of a future Cuban missile-type crisis that results in at least one nuclear weapon being used?	2 in 1,000 to 1 in 100 per year	Martin Hellman	2008
Terrorism	Probability that terrorists will detonate a nuclear bomb?	More likely than not (on America)	Graham Allison	2004
		50–50 odds within the next decade	William Perry	2004
		Less than 1 percent in the next 10 years	David Albright	2005
		29 percent probability within the next decade	Matthew Bunn	2007
		10–20 percent per year against a US or European city	Richard Garwin	2007
		Less than 1 in 1,000,000 (per attempt)	John Mueller	2008

Not surprisingly, a number of post-2001 estimates have focused on the probability of nuclear use by terrorist organizations. Of the subjective estimations (i.e., those not based on a specific analysis), Richard Garwin's estimate of 10–20 percent per year against a US or European city is the highest; it equates to a probability of approximately up to 90 percent within a decade assuming that the probability remains constant over that period. In the middle of the range of subjective estimates are Graham Allison and William Perry, who independently judge this probability to be 50 percent within a decade. At the low end is David Albright, who estimates less than 1 percent over ten years. These subjective assessments span almost the complete range of possibility from near 0 to 90 percent.

Two estimates in Table 1.1 are based on specific analyses. Matthew Bunn estimates 29 percent within the next decade and John Mueller estimates less than one in one million per attempt. This large difference in estimates is not an encouraging indicator that analysis will facilitate convergence on a consensus estimate, but at least it provides valuable insights into the basis for each estimate.

In summary, the principal insights I take from the estimates in Table 1.1 are the same as for the Lugar survey: (1) they differ widely, and (2) they are all of questionable validity because they do differ widely and because they are fundamentally either intuitive or based on simple analysis. Also, subjective judgments appear to gravitate to either 1 percent or 50 percent as an estimate, which suggests that the resolution of human intuition is relatively coarse on this question.

Study Scope

Based on this review of the current state of analysis, two alternative courses of action are apparent. The first is to make the case that the risk of nuclear weapon use is so analytically intractable that even the most careful and comprehensive assessment of this risk would not be relevant to policy-making. The other option is to improve current approaches to assessing nuclear risk in order to provide a sounder basis for policies that will inevitably be based on imperfect analyses of such risks. Either course of action would represent an improvement over the current state of analytic affairs in which individual judgments are offered, usually without a clear trail of assumptions and reasoning, and simple analyses and surveys are undertaken that rely on unsound elicitation practices.

As a first step toward both of these ends, this book tackles the somewhat more modest objective of addressing whether assessing the risk of deterrence failure is *feasible*. We have examined the potential utility and limitations of four of the more promising approaches to the question of likelihood. Case studies of nuclear weapon use and historical close calls in which nuclear weapon use was contemplated or could have occurred, discussed by Andrew Bennett in chapter 2, provide a unique window into past nuclear risk. Jane M. Booker addresses challenges and best practices for utilizing elicited expert knowledge, which underpins almost all analytic approaches, in chapter 3. Probabilistic risk assessment, which has been ever more successfully applied to complex engineered systems including those with human components, is assessed by Martin Hellman in chapter 4. Edward T. Toton analyzes the potential applicability of complex systems theory to the question of the risk of deterrence failure in chapter 5.

In chapter 6, Michael J. Frankel, George W. Ullrich, and I address the consequence dimension of the risk, focusing on the state of knowledge and tools to support anticipation of the physical consequences of nuclear weapon use. Dallas Boyd provides a complementary analysis of the intangible consequences of nuclear use in chapter 7. The challenge of integrating knowledge from these disparate approaches to both likelihood and consequences is discussed by Jane M. Booker in chapter 8. In the final chapter, I conclude with some thoughts on the fundamental questions, Is a risk assessment of deterrence failure worth pursuing, and, if so, what is the most promising path forward?

Other approaches to assessing the risk of deterrence failure also hold promise but have not been included in this study. For example, for likelihood assessments, we have not examined the utility of statistical analyses of the historical record of warfare and terrorism. Nor have we studied the potential contributions of the humanities, particularly human psychology, or the social sciences, notably organizational psychology, anthropology, and the emerging discipline of strategic culture.[26] Perhaps our work will motivate others to pursue these omissions.

Notes

1. Existential to the United States as a constitutional republic, not to the human race.
2. Aleksandr Mozgovoi, *Kubinskaya Samba Kvarteta Fokstrotov* [Cuban Samba of the Foxtrot Quartet] (Moscow: Voennyi Parad, 2002). See also William Burr and Thomas Blanton eds., "The Submarines of October: U.S. and Soviet Naval Encounters During the Cuban Missile Crisis," *National Security Archive Electronic Briefing Book No. 75* (Washington, DC: National Security Archive, GWU, October 2002), https://nsarchive2.gwu.edu/NSAEBB/NSAEBB75/; and Svetlana V. Savranskaya, "New Sources on the Role of Soviet Submarines in the Cuban Missile Crisis," *Journal of Strategic Studies* 28, no. 2 (2005): 233–259, http://dx.doi.org/10.1080/01402390500088312.

3. Dallas Boyd and James Scouras, "The Dark Matter of Terrorism," *Studies in Conflict & Terrorism* 33, no. 12 (2010): 1124–1139, https://doi.org/10.1080/1057610X.2010.523863.
4. Mary A. Meyer and Jane M. Booker, *Eliciting and Analyzing Expert Judgment: A Practical Guide* (Philadelphia: Society for Industrial and Applied Mathematics, 2001).
5. Ronald Reagan, "Address to the Nation on Defense and National Security," March 23, 1983, http://www.reagan.utexas.edu/archives/speeches/1983/32383d.htm.
6. George W. Bush, *The National Security Strategy*, September 2002, http://georgewbush-whitehouse.archives.gov/nsc/nss/2002/index.html.
7. Remarks by President Barack Obama, The White House Office of the Press Secretary, April 5, 2009, http://www.whitehouse.gov/the_press_office/Remarks-By-President-Barack-Obama-In-Prague-As-Delivered/.
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9. Meyer and Booker, *Eliciting and Analyzing Expert Judgment*. See also Bilal M. Ayyub, *Elicitation of Expert Opinions for Uncertainty and Risks* (Boca Raton, FL: CRC Press, 2001).
10. According to the Lugar survey report, "Many of these men and women have dedicated their professional careers to the study and practice of preventing weapons of mass destruction and materials from falling into unauthorized hands. Others have been national security leaders within their countries. As a group, they possess enormous experience in the fields of non-proliferation, counter-proliferation, diplomacy, military affairs, arms inspection, intelligence gathering, and other national security fields relevant to the questions asked." The fault of the survey is to confuse the expertise of the group as a whole, if it could be brought to consensus, with the sum of individual expertise within the group.
11. "Doomsday Clock Overview," *Bulletin of the Atomic Scientists*, http://thebulletin.org/overview.
12. "Doomsday Clock Overview," *Bulletin of the Atomic Scientists*.
13. "Timeline," *Bulletin of the Atomic Scientists*, http://www.thebulletin.org/content/doomsday-clock/timeline.
14. Peter Vincent Pry, *War Scare: Russia and America on the Nuclear Brink* (Westport, CT: Praeger Publishers, 1999).
15. Theodore C. Sorensen, *Kennedy* (New York: Harper & Row, 1965), 705. The exact date of Kennedy's estimate is not specified in this source, but the estimate appears to apply to Kennedy's belief in the midst of the crisis. According to Sorenson, "The odds that the Soviets would go all the way to war, he [Kennedy] later said, seemed to him then 'somewhere between one out of three and even.'" Note that Kennedy's estimate refers to the likelihood of war but does not explicitly specify *nuclear* war. Nevertheless, it seems clear that if the Soviets

initiated a conventional war (in Berlin, perhaps), the likelihood of escalation to nuclear conflict was high.

16. McGeorge Bundy, *Danger and Survival: Choices about the Bomb in the First Fifty Years* (New York: Random House, 1988), 461. See also p. 453 for a discussion of Kennedy's estimate.
17. Graham Allison, *Nuclear Terrorism: The Ultimate Preventable Catastrophe,* 1st ed. (New York: Times Books/Henry Holt and Company, 2004), 15.
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Chapter 2
Historical Case Study

Andrew Bennett

Case studies are useful in analyzing infrequent events because they can assess "close calls" in which such events could have occurred, as well as those instances in which they actually occurred. Nuclear weapons have been used twice, but there have been many more close calls. This chapter outlines an agenda for using case studies to assess the risks of nuclear weapons use. First, it identifies twelve cases in which leaders used, seriously contemplated using, or might have considered using nuclear weapons. Second, it notes thirteen cases of close calls of accidental or unauthorized detonation of a nuclear weapon. Third, it assesses three possible paths toward the use of nuclear weapons by non-state actors, none of which as yet has had any known close-call incidents. The chapter then briefly assesses how the historical risks of nuclear weapons use might change as the world evolves toward a larger number of nuclear weapons states. Finally, the chapter develops policy-relevant questions on the risks of nuclear weapons use that can be addressed through case studies, including the behavior of new nuclear weapons states, the likelihood of nuclear weapons use by field commanders versus that by national command authorities, the safety trade-offs of dispersed versus centralized nuclear weapons sites, and the differences between contemporaneous and historical evaluations of nuclear risks. These contributions are unlikely to lead to clear point estimates of nuclear risks, but they may help identify which paths toward possible nuclear weapons use deserve more attention and how risks on these paths can be reduced.

The challenges of assessing the risks of nuclear weapons use are unique in many ways, but they are similar in important respects to the difficulties of analyzing the likelihood of other rare but high-consequence events. Like nuclear weapons use, medical mistakes, airplane crashes, nuclear power plant accidents, space shuttle disasters, and wars are hard to study because they are infrequent relative to their opposites (successful medical operations, uneventful flights, etc.). All are also difficult to predict because they can arise through many combinations of factors, some of which have unknown base rates and failure modes and some of which may not be identifiable even after the fact. A third commonality is that all involve "close calls" whose frequencies and seriousness are difficult to assess because the actors involved have incentives to underreport (or occasionally to exaggerate) near misses.

These shared features of relatively infrequent, high-consequence, and complex events make it both exceedingly difficult and unusually important for the organizations and scholarly communities concerned with preventing them to study not only instances in which they have happened but also close calls in which they could have happened. Such studies can help assess the overall risks of such events, identify the different pathways to their occurrence, and reduce the likelihood that they will take place.[1] In the areas of airline safety and medical anesthesia, where there are sufficiently frequent and identifiable outcomes and near misses to study, and where the risks of actors intentionally bringing about bad outcomes are either small or mostly preventable at acceptable cost, the study of "incidents and accidents" by professional associations, regulators, and businesses has led to considerable success in reducing the frequency of bad outcomes.[2]

Assessing less frequent and more intentional potential disasters is more difficult. Potential nuclear weapons use is perhaps the most difficult to study of all the possible disasters noted above because nuclear weapons embody the most challenging features of other potential disasters. Actors have very high incentives to hide nuclear close calls and everything related to them, such as how nuclear warning and launching procedures work. Drawing the right conclusions on the risks of nuclear weapons use is even more imperative than for most potential disasters because the use of even one nuclear weapon would be more costly than all the other disasters noted above save a large-scale conventional war. Finally, nuclear weapons use and nuclear close calls are, thankfully, as small in number as space shuttle flights and crashes, but this makes it exceedingly difficult to assess their likelihood.

Because of this "small *n*" nature of nuclear weapons use and risks, although scholars have usefully applied statistical methods to questions related to the likelihood of nuclear weapons use—such as nuclear proliferation[3] and how the acquisition of nuclear weapons affects the frequency of interstate crises and militarized disputes[4]—standard frequentist statistical techniques face sharp data limitations in assessing the risks of nuclear weapons use. Case studies are not a panacea for these inferential challenges, but they do have several advantages in the study of nuclear risks. Case studies do not require large numbers of cases to proceed, they draw on Bayesian rather than frequentist logic, and the number of actual and close-call uses of nuclear weapons is small enough that scholars have already intensively studied most of the known cases. Some, such as the Cuban missile crisis, are the subject of numerous studies.

A second advantage of case studies is that they can get closer to the mechanisms through which outcomes arise.[5] Case studies can use process tracing to identify the paths through which nuclear weapons use has happened or nearly happened in the past, providing important clues to potential future risks even if some as-yet-nonexistent failure modes are not subject to historical study. Case studies of the 1962 Cuban missile crisis and the 1983 Able Archer exercise, for example, have clarified the paths through which nuclear weapons might be used as a result of accidents or misunderstandings, and have revealed these risks to have been much higher than top-level decision-makers understood them to be at the time.[6]

Third, study of cases that researchers judge to be analytically similar to current cases or emerging risks can provide insights into current policy dilemmas, so long as due attention is given to differences between the current case and the historical case to which analogies may be drawn.[7]

Fourth, case-study researchers can apply rigorous criteria to identify the relevant populations of "negative cases,"[8] such as cases in which nuclear weapons might have been used but were not, and those in which leaders could have considered using nuclear weapons but did not seriously contemplate doing so. These cases can usefully be compared to those in which leaders came much closer to considering or using nuclear weapons, in order to develop insights on the factors that make the use of nuclear weapons likely. The population of close-call cases will remain biased and incomplete because of classified data, but it is possible to improve on extant lists of such cases, and a more complete population of close calls can help establish a lower bound on nuclear risks (the actual population of close calls is presumably higher than the population identifiable via public sources).

Fifth, case studies of efforts to reduce nuclear risks, such as the Washington–Moscow Direct Communications Link, or "hotline," established after the Cuban missile crisis, may be relevant to ongoing risk-reduction efforts, such as recent or planned hotlines among Pakistan, India, and China.

Finally, although it is not possible to use case studies to arrive at precise estimates of past nuclear risks, careful analysis of both the events that happened and the counterfactual events that could have happened, such as assessment of contingency plans or standing orders that were in place, can give some sense of the magnitude of these risks.

This chapter outlines an agenda for using case studies to assess the risks of nuclear weapons use. It is not a history of all the instances in which nuclear weapons might have been used, nor does it aspire to offer the definitive bottom line from among contending views of this history; rather, it touches on existing nuclear histories to identify patterns and gaps for future research. First, it draws on existing case studies and data sets in a preliminary attempt to identify the full set of cases in which leaders seriously contemplated (as defined below) the possible use of nuclear weapons, as well as negative cases in which leaders might have contemplated nuclear weapons use but there is not (as yet) convincing evidence that they did so (the actual cases of nuclear weapons use, Hiroshima and Nagasaki, are of course well identified). Second, it categorizes these cases along three general paths toward possible nuclear weapons use—intentional use by state leaders, accidental or unauthorized use, and use by non-state actors or terrorists—and along more specific sub-paths within each of these three general categories. Third, it provides some preliminary observations on the frequency and seriousness of these close calls and potential close calls, and it identifies ongoing trends and potential future developments that will affect the ways in which future risks and path frequencies might differ from historical ones. Most obviously, for example, the frequencies of different potential paths to nuclear weapons use in a world of many nuclear powers with small nuclear arsenals might be quite different from what they have been in a world that until 1990 was characterized by two superpowers with large arsenals and a small number of other nuclear-armed states. Fourth, the chapter develops policy-relevant questions pertinent to the risks of nuclear weapons use that can be addressed through case studies, and it identifies the cases that might be studied to assess these questions as well as the cases that deserve closer study because they most closely resemble current policy dilemmas or represent the potential paths to nuclear weapons use that might be more common in the future. These contributions are unlikely to lead to clear point estimates of nuclear risks, and may not lead to convincing confidence intervals on the different potential paths to nuclear weapons use, but they may help identify which paths deserve more attention and how risks on these paths can be reduced.

Defining the Population of Cases in Which Nuclear Weapons Were Used, Contemplated, or Could Have Been Contemplated

It is important at this stage of the research agenda to define close calls of potential use of nuclear weapons broadly, and to err on the side of including possible cases that might later prove irrelevant rather than risk leaving out relevant cases. I define cases of potential use of nuclear weapons along each of three general paths: intentional use by state leaders, accidental or unauthorized use by military organizations, and intentional use by terrorist organizations.

Cases of Actual or Potential Intentional Use by State Leaders

Cases of Actual Use of Nuclear Weapons

The cases of actual use of nuclear weapons, by the United States against Hiroshima and Nagasaki in 1945, have been intensively studied, and, for present purposes, only a few very general observations are in order.[9] In particular, these uses of nuclear weapons were by a nuclear-armed state against a state lacking nuclear weapons, and in a context in which the state that used nuclear weapons saw them as an alternative to costly conventional conflict (although debate remains regarding whether Japan might have surrendered, and on what terms, even without the use of nuclear weapons[10]). The key point for present purposes is that this general situation—nuclear asymmetry in the midst of an ongoing or anticipated costly conventional conflict—has been one of the recurring contexts in which state leaders have contemplated most seriously the use of nuclear weapons.

Cases of Potential Intentional Use by State Leaders

I define cases of serious consideration of intentional nuclear weapons use by state leaders to include those in which any of the following took place: (1) a top leader (including high-level military officials as well as top political leaders) advocated the possible use of nuclear weapons in a high-level meeting in which the use of force was discussed; (2) a top political or military leader authorized study of the costs and benefits of nuclear weapons use, or of contingency plans for such use, in the context of an ongoing crisis or militarized confrontation (as opposed to general contingency planning in noncrisis contexts); (3) a top leader approached or authorized an approach to a third state to request assistance, cooperation, or approval with regard to the use of a nuclear weapon (this includes asking third states to use their nuclear weapons or seeking aid or approval in using one's own nuclear weapons); (4) a top leader authorized the specific use of a nuclear weapon, perhaps under defined contingent circumstances in a crisis context, even if this authorization is later reversed; or (5) a top leader ordered putting nuclear forces on heightened alert in the context of a crisis, even if this was viewed solely as a measure to make a preemptive strike by an adversary more difficult. A negative case of consideration of nuclear weapons use is one in which top leaders did none of these things in a situation that is closely analogous to those in which leaders have most frequently contemplated the use of nuclear weapons, such as a costly or losing conventional conflict against an adversary that lacks nuclear weapons or a nuclear-armed patron.

Cases in Which Leaders Contemplated the Possible Use of Nuclear Weapons

There are twelve well-documented contexts in which top leaders contemplated the use of nuclear weapons by the definition above:

1. **1948 Berlin crisis.** Defense Secretary Forrestal recommended a preventive strike on the Soviet Union.[11]
2. **1951 Korean War.** General MacArthur repeatedly requested authorization to use nuclear weapons.[12]
3. **1953 Korean War.** President Eisenhower considered possible use of nuclear weapons to bring the war to an end.[13]

4. **1954 Vietnam.** French and US officials discussed the possible use of US nuclear weapons to relieve the siege of French forces at Dien Bien Phu.[14]
5. **1954–1955, 1958 Quemoy-Matsu crises.** Eisenhower and Secretary of State Dulles publicly threatened the use of nuclear weapons, and the United States deployed nuclear capable forces to the Taiwan Strait.[15]
6. **1961 Berlin crisis.** During the crisis, President Kennedy was briefed on a contingency plan for a nuclear first strike on Soviet forces, and Kennedy followed up with specific operational questions on a possible strike.[16]
7. **1962 Cuban missile crisis.** Kennedy and Khrushchev contemplated nuclear options.[17]
8. **1961–1964 United States–China.** The United States studied the possibility of preempting China's nuclear capability, including possible use of a tactical nuclear weapon.[18]
9. **1968 Vietnam War, siege of Khe Sanh.** General Westmoreland convened a secret study of nuclear options.[19]
10. **1969 Korea:** The Nixon administration prepared a range of options, including an option for nuclear strikes, for possible retaliation against North Korea after it shot down a US reconnaissance plane.[20]
11. **1969 Soviet–Chinese border clash.** A Soviet KGB official probed the possible US response if there were a Soviet attack on Chinese nuclear facilities.[21]
12. **1973 Middle East crisis.** The United States raised the DEFCON alert status of its nuclear forces, and Israeli prime minister Golda Meir rejected a request by Defense Minister Moshe Dayan to authorize preparations for a nuclear demonstration blast should one become necessary.[22]

These twelve incidents, together with the two borderline cases of US conflict with Iraq in 1991 and 2003 discussed below,[23] can be divided into five potential paths toward the intentional use of nuclear weapons. Each path is useful in identifying analogous situations in which nuclear-armed states might have considered the use of nuclear weapons, but for which there is no reliable public evidence that they did so. These might be "negative cases," in which nuclear weapons never received serious consideration, or they could be cases in which nuclear weapons were actually given serious but secret consideration. I analyze each of these five paths or contexts in turn and provide a list of possible negative cases for each.

Path 1: A nuclear state faces a costly conventional conflict with a non-nuclear state or a conventional conflict in a theater in which it lacks conventional superiority over a nuclear or non-nuclear rival. This path covers the two actual uses of nuclear weapons (Hiroshima, Nagasaki) as well as several instances in which top leaders gave the most serious and detailed consideration to using nuclear weapons: the 1948 Berlin crisis, the Korean War, and the Vietnam War.

Other analogous cases in which a nuclear state may have considered using nuclear weapons by the definition above, but in which there is no credible public evidence that they did so, include Israel in 1967 (it is unclear whether Israel had by then achieved a usable nuclear weapon), Britain in the Falklands War in 1982, India during its crises with Pakistan in 1987 and 1990 (depending on when one thinks Pakistan attained a usable nuclear weapon), and Israel when it was under attack by Iraqi Scud missiles in 1991.

Path 2: A nuclear state contemplates or carries out a preemptive strike on a rival's small or emerging nuclear weapons capability. A preemptive strike could use a nuclear weapon, or if it is against a state that has a small number of nuclear weapons, it could provoke a nuclear strike. This path includes the US consideration of an attack on China's nuclear facilities in the early 1960s, and the Soviet contemplation of an attack on these facilities in 1969.

There have been many other cases in which nuclear-armed states considered or carried out attacks on other states' nuclear weapons programs but in which there is no public evidence that they considered using nuclear weapons to carry out such attacks.[24] These may deserve study to try to classify them as either actual or negative cases of contemplated nuclear weapons use. These include the Israeli attack on Iraq's Osirak nuclear reactor in 1981; US decision-making on North Korea's nuclear program in 1994; Israeli consideration of attacks on Pakistan's nuclear program in 1983–1987 (Israel sought help from India for possible conventional attacks on Pakistan); Soviet contemplation of possible attacks on Israel's nuclear program in 1967; Soviet requests for US assistance in attacks on South Africa's nuclear program in 1976; US conventional strikes on Iraqi capabilities from 1990 to 2003; US consideration of preemptive strikes on Pakistan's nuclear capabilities in 1978–1979; Israeli consideration of (and request for US assistance with) strikes on Iran's nuclear program in 2008; and Israel's strike on a Syrian nuclear reactor in 2007. It is unlikely that nuclear states gave serious thought to using nuclear weapons in any of these instances, but these cases may still deserve study on whether states may have considered this, and why they did or did not do so.

Path 3: Crisis instability between two nuclear weapons states, especially if they lack large, secure second-strike forces, leads to consideration of preemptive nuclear strikes. This characterizes the 1961 Berlin crisis and the Cuban missile crisis to some degree, although it is unlikely that either side could have preemptively struck all the nuclear weapons of the other side. Crises between India and Pakistan in 1999 and 2002 fit into this category as well. Here again, it is unlikely that either side could have mounted a disarming first strike, not because their adversary's weapons were numerous or able to withstand a first strike but because the storage and potential launch points of their nuclear weapons (including those deliverable by aircraft) were secret.

Path 4: A non-nuclear state asks a nuclear ally to threaten or use nuclear weapons against an adversary. This path includes discussions between French and American officials about possible nuclear strikes against Vietnamese forces surrounding the French at Dien Bien Phu in 1954. Fidel Castro also urged the Soviet Union during the Cuban missile crisis to strike the United States if it invaded Cuba.[25] It is also possible, although less well documented, that Chinese leaders probed the Soviet Union's willingness to threaten to use or actually use nuclear weapons in defense of China in the in 1950s crises in the Taiwan Strait.

Path 5: A nuclear state considers the use of nuclear weapons to preempt or punish chemical and biological weapons use by a non-nuclear state. Two cases that came close to the criteria herein for leaders having contemplated the possible use of nuclear weapons are the 1990–1991 Gulf crisis and war and the 2003 US intervention in Iraq. In both cases, the

US president and top administration officials refused to rule out publicly the possibility of using nuclear weapons if Iraq used chemical weapons against American soldiers. In neither case, however, is there evidence that the president authorized contingency planning for such an eventuality or even seriously considered the possible use of nuclear weapons.[26] In addition, the Obama administration pledged that it would not use nuclear weapons against a non-nuclear state that is in compliance with the Nuclear Nonproliferation Treaty, even if that state attacks the United States with biological or chemical weapons.[27] Nonetheless, the active discussion of this issue by reporters and experts during the two Iraq crises suggests that it remains a possible path to the use of nuclear weapons by other countries or by the United States if it should reverse or fail to follow the Obama administration's policy pledge.

Cases of Potential Accidental or Unauthorized Nuclear Weapons Use

Depending on how one defines them, the list of cases of potential accidental or unauthorized use of nuclear weapons is much longer because presumably many low-level alerts and near accidents are not publicly known. Top leaders may not have been aware of near accidents as they arose or even later, and some close calls are presumably not known to the nuclear weapons operators who nearly caused them. I define these cases to include any of the following: (1) false alerts or warning indicators, whether by radars or intelligence operators, that were communicated to high-level military or political leaders; (2) false alerts that led to heightened alert status of nuclear forces, whether authorized by top political or military leaders or not; (3) change of control or loss of control of nuclear command authority in the context of a coup or attempted coup; (4) heightened alert status of nuclear forces or contemplated use of nuclear weapons by military units in a tactical military engagement in the absence of orders from high-level military or political leaders; or (5) use of dual-capable ships, aircraft, or artillery carrying nuclear weapons in tactical conventional combat, or deployment of dual-capable weapons systems to a crisis zone where they could be used. This last category, deployments of dual-capable weapons systems, embodies some elements of both potential intentional use of nuclear weapons and potential unintended escalation. It could arguably be placed under the intentional paths to nuclear weapons use, but for present purposes, this analytical choice makes little difference.

There are thirteen well-documented contexts of close calls of accidental or unauthorized use by this definition. There are more than thirteen incidents because some contexts involved several close calls. Indeed, the Cuban missile crisis alone included twelve incidents that could have led to unintended or unauthorized escalation to the use of nuclear weapons.[28] The overall list of contexts in which close calls of accidental or unauthorized use took place includes the following:

- **1956.** Suez crisis[29]
- **1961.** US Ballistic Missile Early Warning System communication failure[30]
- **1962.** Cuban missile crisis: multiple incidents[31]
- **1962.** The Penkovsky false warning[32]
- **1965.** US power failure and faulty bomb alarms[33]
- **1968.** B-52 crash near Thule, October 24–25[34]
- **1969.** Nixon orders a nuclear alert to try to convince Soviet leaders he might take radical steps in the war in Vietnam[35]
- **1973.** US false alarm during Middle East crisis[36]
- **1979.** US computer exercise tape mistakenly inserted[37]
- **1982.** Britain in the Falklands, ships carried nuclear weapons
- **1983.** Soviet alert over NATO Able Archer exercise[38]
- **1991.** Transfer of nuclear codes to coup plotters in attempted coup against Gorbachev[39]
- **1995.** Russian radar alarm of Norwegian scientific rocket launch[40]
- **1995.** United States deploys a nuclear-armed aircraft carrier to the Taiwan Strait during a crisis[41]

A key point here is that most of the known close calls involve the United States not just because it has had nuclear weapons longer than any other state but because it has declassified more of the relevant documents than any other state. The second-most-frequent cases come from the Soviet Union and are known as a result of US intelligence efforts and Soviet participants' memoirs after the Soviet Union collapsed rather than because of declassified Soviet or Russian documents. Presumably there are some unknown Soviet and Russian close calls. The least is known about close calls in other nuclear weapons states with more limited detection and alert systems, and in many instances shorter decision times before an adversary's weapons might strike, including France, Britain, China, North Korea, India, Pakistan, and Israel. The lack of evidence on potential accidental or unauthorized nuclear weapons use by these countries is one of the biggest data gaps in assessing the historical risks of nuclear weapons use.

The known close calls of accidental or unauthorized use embody five potential paths to nuclear weapons use:

Path 6: False alarms in the absence of an ongoing crisis or war. False alarms in noncrisis contexts are unlikely to lead to nuclear weapons use themselves, but they can indicate the kinds of failure modes that, were they to occur during crises, could be much more dangerous. The cases of such false alarms include the 1961 US Ballistic Missile Early Warning System communication failure,[42] the 1965 US power failure in the Northeast that led to two faulty bomb alarms,[43] the mistaken insertion into US warning systems of a computer tape simulating an incoming nuclear missile attack in 1979,[44] and a 1995 Russian missile warning radar alarm set off by a Norwegian scientific rocket launch.[45] These incidents point to the importance of learning about and reducing the failure modes of the early warning systems of new nuclear weapons states that lack the redundant warning systems deployed by the United States.

Path 7: False alarms, misinterpretations, and dual-capable deployments in ongoing crises or wars. False alarms in crises are clearly more dangerous than those during peacetime. In crises, especially when alert levels are raised, warning and decision systems become more tightly coupled, redundancies and safeguards are lowered, decision times are shortened, and decision-makers' mindsets are more oriented toward interpreting any warning indicators as real signs of imminent threats rather than false alarms.[46] Four crisis incidents from the list above illustrate these dangers: the intersection of several incidents in the 1956 Suez crisis,[47] a false alarm at a US B-52 air base during the 1973 Middle East crisis, an elevation of the alert status of Soviet nuclear forces during the 1983 NATO Able Archer military exercises (a time of high tension[48]), and, perhaps most dangerously, a series of incidents that could have led to misinterpretations and nuclear weapons use in the Cuban missile crisis.[49]

One incident during the Cuban missile crisis illustrates a potentially important sub-path toward nuclear weapons use in a crisis. During the Cuban crisis, the Soviet Union captured Oleg Penkovsky, a colonel in the Soviet Military Intelligence organization (the GRU) who had been acting as a spy for the United States. Penkovsky had been given a special code to transmit to warn of any impending Soviet nuclear attack on the United States, and after his capture this code was transmitted (whether by the intention of Penkovsky himself or unwittingly by his captors remains unclear). This incident draws attention to the more general possibility that a state or non-state actor intent on creating a nuclear crisis or even a nuclear war between two of its adversaries might try to create a false alert during a crisis.

Another sub-path involves the deployment of dual-capable weapons systems carrying nuclear weapons to an ongoing conflict or potential conflict zone. Britain's deployment of nuclear-armed ships to the Falklands in 1982 and the US deployment of a nuclear-armed aircraft carrier to the Taiwan Strait during a crisis in 1995 illustrate this sub-path. Such deployments might be seen by an adversary as advance preparation for actual nuclear weapons use, or they can lead to unintended escalation if the deployed forces are attacked or captured by an adversary's conventional forces.

Path 8: Close calls of potential use by local commanders without explicit national command authority orders. Because of concerns over possible communication disruptions in a crisis or war, US and Soviet leaders gave their submarine commanders the technical ability to use nuclear weapons without first having to receive an enabling code from national command authorities, so long as two sailors simultaneously turned launch keys (it is unclear whether this capability to initiate launch even without an authorization code continues). This creates the risk that commanders will use nuclear weapons should they come under direct attack and be unable to receive communications from national leaders indicating whether the attack they are experiencing is localized or part of a global or even nuclear conflict. In one of the most dangerous incidents in the nuclear age, this risk came close to being realized during the Cuban missile crisis. To enforce the naval quarantine of Cuba ordered by President Kennedy, American ship commanders began dropping small "practice" depth charges to force

Soviet submarines to the surface. The commander of one such submarine, Valentin Savitsky, believing his submarine was under attack and unsure whether a global war had started, ordered his crew to prepare a nuclear-armed torpedo for launch against the American ships. Fortunately, the second officer on the Soviet sub, Vasili Arkhipov, whose concurrence was needed for such a decision, convinced commander Savitsky to surface instead and seek orders from Moscow before taking further action.[50] Pry argues that Soviet and later Russian command and control procedures have allowed not only submarine commanders but also nuclear weapons operators at the level of colonel and above to have the technical capability of launching nuclear weapons without first having to receive an enabling code from national command authorities.[51] More generally, delegation of independent launch authority to local military commanders can create great risks because these commanders may be acting under intense pressure, limited information, and immediate threats to their own lives and those of the soldiers in their units.

In addition, before US nuclear weapons were equipped with authorization codes or managed with dual-key arrangements, it was possible that US military commanders could have used nuclear weapons in crises or combat without explicit presidential authorization. For example, General Curtis LeMay, who headed the US Strategic Air Command, told a member of the Gaither Committee studying US security policy that his plan was to use nuclear weapons preemptively if he received intelligence indicating that Soviet forces were amassing for an attack. When told this contravened US policy, LeMay responded "It's my policy. That's what I'm going to do."[52]

Path 9: Disruption of national command authority chain of command in a civil war or coup. The most dangerous disruption of national command authority of a nuclear-armed state to date was the coup attempt against Soviet General Secretary Gorbachev on August 18–21, 1991. This incident amply demonstrates the dangers inherent in any such violent regime transition in a nuclear weapons state. One of the coup plotters' first acts was to take the Soviet nuclear "football" from Gorbachev. This device may not be analogous to the American nuclear "football," which is a device with the secret codes necessary to unlock the Permissive Action Links (PAL) or safety devices on all US nuclear weapons other than those on submarines. There are reports that the Soviet "football" does not contain codes for unlocking Soviet nuclear weapons and only has communications equipment.[53] In any event, for two days, the coup plotters had some element of control over Soviet nuclear weapons, a worrisome prospect given that these individuals were operating under high stress and on little sleep. One indication of their unbalanced state of mind is that several committed suicide when the coup attempt failed.

A second close call along this path occurred in October 1993, with a split in the Russian government between President Yeltsin and vice president and former general Aleksandr Rutskoy. Forces backing Rutskoy managed to knock out Moscow's main television station, but they failed in their attempt to seize control of the Defense Ministry, and Rutskoy's coup attempt ultimately failed when military forces armed with tanks shelled and took over the parliamentary building in which he was holed up, capturing him and his key supporters.

Path 10: Accidental detonation of a nuclear weapon. US nuclear weapons involve redundant safety devices and procedures and are unlikely to detonate accidentally. Despite thirty-six accidents classified as "Broken Arrow" incidents, or accidents involving nuclear weapons, there have been no accidental nuclear detonations.[54] Most of these incidents involved airplane crashes, and several included detonation of the nuclear weapons' conventional explosives. Perhaps the most serious such incident, for present purposes, was the 1968 crash of a nuclear-armed B-52 near the Thule Air Base, which detonated the conventional explosives of the nuclear weapons on board. Had it led to a nuclear detonation so close to a US base, it could have triggered a false alarm of a nuclear attack.[55] More worrisome are the nuclear forces of emerging nuclear weapons states, which may lack safeguards as effective as those on US weapons.

Contexts of Close Calls by Non-State Actors

Nuclear weapons use by non-state actors such as terrorist groups would require three conditions to be jointly met: (1) existence of a terrorist group willing to carry out mass casualty attacks, (2) ability of this group to deliver a nuclear weapon to a target site, and (3) acquisition of a nuclear weapon by this group. As several groups, including not just al-Qaeda but also Lashkar-e-Taiba (a Pakistani group), have demonstrated a willingness to carry out mass-casualty attacks, and as the delivery of a nuclear weapon to a port city by boat is a much easier condition to achieve than acquisition of a nuclear weapon, this section focuses on the third condition and examines paths through which a terrorist group might acquire a nuclear weapon.

There have been no known close calls of acquisition of a nuclear weapon by a terrorist group, but some of the steps toward such acquisition have been attempted, and the paths toward possible acquisition are easy to identify in their broad outlines. It may thus be useful to study the incipient attempts terrorists have made toward acquiring weapons of mass destruction[56] even if none have yet come close to fruition. Because it is far beyond the ability of terrorist groups to make the enriched uranium needed to produce a nuclear weapon, the present discussion focuses on the paths of buying or stealing an assembled weapon, buying or stealing enriched uranium and assembling a weapon, or acquiring a nuclear weapon from a state that backs the terrorist group.

Path 11: A terrorist group buys or steals an assembled weapon. States that have nuclear weapons typically keep them under sufficiently safe guard that it would be difficult for a terrorist group to steal an assembled weapon, and most nuclear-capable states have safety devices that would prevent their weapons from being used even if stolen. It cannot be ruled out, however, that insider assistance might enable a terrorist group to steal a weapon and circumvent its safeguards. This concern in part motivated the Nunn–Lugar program to increase the safeguards on Russian nuclear weapons, and nuclear scientists, after the Cold War.

Path 12: A terrorist group buys or steals enriched uranium and assembles a nuclear weapon. The huge Cold War nuclear arsenals of the United States and the Soviet Union generated large stockpiles of weapons-grade highly enriched uranium and plutonium. If terrorists were able to acquire highly enriched uranium, it might be within their technical capability to assemble a shotgun-style nuclear bomb.[57] From 1993 to 2012, the International Atomic Energy Agency confirmed sixteen cases of illegal possession of or attempts to move or trade highly enriched uranium or plutonium.[58] Also worrisome here is the possibility of nuclear scientists collaborating with terrorist groups. The network established by the Pakistani nuclear scientist A. Q. Khan, for example, provided nuclear assistance to other countries, and it is possible that a member of this network or one like it could cooperate with terrorist groups.

Path 13: A state sponsor of terrorism provides a nuclear weapon to a terrorist group. Several states have ties to well-organized terrorist groups: Pakistan and Lashkar-e-Taiba, Iran and Hezbollah.[59] Such a state might consider providing a nuclear weapon to a terrorist group. An important factor deterring such behavior is the fact that the radiological signature of any detonated weapon might allow identification of the country that was its source.

Preliminary Observations on Past Risks and Future Trends

Because of the relative infrequency of nuclear close calls along multiple different paths in the past, and the necessity of using counterfactual analysis to assess such "nonevents," it is not possible to develop precise estimates of past nuclear risks. For example, when Captain Savitsky ordered his crew to prepare to launch a nuclear torpedo during the Cuban missile crisis, his second in command, Arkhipov, was reportedly initially the only one of the three top officers on the submarine who argued against this. Does this mean the odds of nuclear weapons use were one in three, or did Arkhipov usually succeed in such arguments? How close did the other Soviet submarine commanders come to considering the use of a nuclear torpedo? Had a nuclear torpedo been used, how would the United States (or local naval commanders) have responded? Some questions of this nature are inherently counterfactual, and others involve information that we are unlikely to ever have.

Nonetheless, some general judgments about past risks are possible. Most importantly, it is likely that top leaders have underestimated the risks of nuclear weapons use, particularly those arising from the interaction of complex warning and alert systems and the dynamics of crisis decision-making. Perhaps the most famous estimate of nuclear risks is President Kennedy's statement that the odds of a nuclear war during the Cuban missile crisis were between one and three and even.[60] This seems to be in the ballpark of the risks evident in the Savitsky incident, but Kennedy could not have known of this incident, or of many of the other dozen or so close calls that arose during the crisis, at the time he made his observation. Perhaps Kennedy, having recently read Barbara Tuchman's account of World War I, was factoring such potential close-call pathways into his estimate, but in a later example—the Soviet alert during the NATO Able

Archer exercise—Western leaders were evidently unaware of how seriously Soviet leaders believed that the exercise might be a cover for a planned surprise attack.[61]

Just as it is impossible to make precise estimates of past nuclear risks, these risks cannot be estimated with confidence for the future. What is possible, however, is to combine knowledge of past potential paths toward nuclear weapons use with expert opinions on future trends that will affect the likelihood of alternative paths. Expert elicitation is discussed in depth in chapter 3, and although it is a separate task from the present chapter's focus on a research agenda for improving knowledge of past risks, it is useful to briefly review here possible future trends and how they might reshape the risks evident in past close calls.

Most obviously, the proliferation of nuclear weapons and missiles capable of carrying them may change future risks of nuclear weapons use. Less obvious is how they will change those risks; some experts argue that more nuclear weapons might mean stronger deterrence (Waltz), while others emphasize the potential increased risks of temptations to preemptive strikes and misinterpretations and false alerts in crises (Sagan).[62] Second, increased missile defenses might either deter first use or create incentives for preemption in either direction. Third, the generation of highly enriched uranium in a wider range of countries might create more opportunities for terrorists to buy or steal this material. Fourth, deep reductions in and de-alerting of US and Russian nuclear forces might reduce the risks related to these weapons along several different paths. Fifth, changes in enduring state rivalries among nuclear powers, or development of new ones, will affect the risks of both intentional and unintentional use. Sixth, increased dissemination of safety devices on nuclear weapons, or failure of new nuclear powers to use such devices, may affect nuclear risks. Seventh, the emergence or disappearance of terrorist groups willing to use weapons of mass destruction will affect nuclear risks. Eighth, the evolution of civil–military relations in new nuclear powers may affect which decision-makers have the authority or the ability to use nuclear weapons. Finally, cultural changes—most importantly, the strengthening or weakening of the "nuclear taboo" among existing and new nuclear weapons states—will affect nuclear risks.

Assessment of how past risks and future trends will intersect will require input from many experts, but for present purposes, this chapter builds on the general intuition that the kinds of risks and pathways to potential nuclear weapons use evident in the cases listed above are indicative of potential future paths to nuclear weapons use, but the frequency and severity of future close calls or the likelihood of future nuclear weapons use is more likely to reflect the risks attendant on new and emerging nuclear powers with small, dispersed arsenals; politically powerful military officers; and limited warning and safety systems than it is to resemble the US–Soviet nuclear standoff that generated the majority of the historical close calls noted above. A priority for studying past cases is therefore to identify those most similar to the likeliest future risks.

Researchable Questions and Cases in Which They Might Be Studied

Both the literature on the historical close calls above and the wider literature on the risks of nuclear weapons use suggest a number of policy-relevant questions that might be researchable through case studies:

- Are new nuclear powers more aggressive vis-à-vis either nuclear or non-nuclear adversaries? Do nuclear dyads experience more or less frequent, more or less severe conflicts and crises with one another? How are new nuclear powers such as North Korea and potentially Iran likely to behave given long-standing security rivalries and unsettled domestic political orders?

  The statistical literature on these questions is mixed. Horowitz argues that when states first acquire nuclear weapons, they are more likely to challenge adversaries and be challenged by them, but he argues that as time goes on from the date of acquisition, challenges in both directions become less likely.[63] Beardsley and Asal conclude that opponents of nuclear weapons states demonstrate restraint in using violence but that the overall incidence of crises is not affected.[64] Rauchaus argues that there is evidence for the "stability-instability paradox," or that major war between nuclear powers is less likely than for mixed or non-nuclear dyads, but that militarized interstate disputes are more likely in nuclear dyads.[65] Case studies of new nuclear weapons states, such as North Korea and Pakistan, and their adversaries might shed light on this question and might be relevant to the case of Iran's nuclear program. Civil–military relations in the 1991 Soviet coup attempt and the 1993 Russian civil conflict might also be relevant to North Korea and Iran, where military organizations play a large political role.

- Are field commanders more likely than national leaders to favor nuclear weapons use?

  Several of the historical cases noted above, including the 1948 Berlin crisis, the Korean War, the Cuban missile crisis, and the Vietnam War, suggest that military leaders have been more willing to use nuclear weapons than top civilian leaders. Study of these and other cases with a focus on this question can reveal whether this pattern holds up. This has important implications for countries that, to address surprise attacks and potential disruption of communications, devolve the technical capability to use nuclear weapons to top military leaders and especially those that allow weapons operators to have this ability.

- Has there been a trade-off between increasing the diversity and dispersion of nuclear weapons to deter preemption and the need for fewer weapons sites to limit accidental or unauthorized use?

  Anecdotal evidence suggests that US accident rates (particularly Broken Arrow incidents) have become less common as the United States has lowered alert rates of its bomber forces and modernized its nuclear weapons. This might be an actual trend, or it could be an artifact of the reality that more recent events could remain classified while older incidents have been declassified. In any event, study of the accident rates of states with fewer nuclear weapons (Britain, France, etc.) might provide closer analogies to the likely accident rates of recent and emerging nuclear weapons states.

- What do the answers to these questions suggest regarding new nuclear powers with different nuclear arsenals (smaller forces, reliance on aircraft or missiles for delivering nuclear weapons, reliance on secret locations to prevent preemption, etc.)?

- Have contemporaneous evaluations of the risk of nuclear weapons use differed from later historical assessments of that risk? In what circumstances were contemporaneous assessments higher and lower than subsequent assessments?

- Do states other than the United States have a "nuclear taboo?"

  Tannenwald argues that in the United States, at least, the use of nuclear weapons has become a "taboo;"[66] Paul argues that normative constraints on the use of nuclear weapons fall short of a taboo, even in the United States.[67] Case studies of other countries' nuclear doctrine, behavior, and ethical or religious frameworks with regard to nuclear weapons can help establish what degree of "taboo-ness," if any, there is in their attitudes regarding nuclear weapons. Countries that might be studied for this purpose include Russia, Pakistan, Israel, and China.

- How are the interactions of warning systems and decision-making processes in the past similar to and different from the likely interactions of such systems used by new nuclear powers with different technical capabilities and decision-making processes?

  Here, the performance of Indian and Pakistani warning and decision systems in the Kargil crisis may be more representative of future risks than that of US and Soviet systems in Cold War crises.

- What has been the experience of previous attempts to lower the risks of nuclear weapons use? How effective have reliability and accident-prevention programs been, such as the sharing of PAL technology? Has the Moscow–Washington hotline established after the Cuban missile crisis been a success? How might this experience be relevant to new or developing hotlines with China and between India and Pakistan?

Conclusions

A famous quote often attributed to Yogi Berra notes that "it is tough to make predictions, especially about the future." When it comes to assessing the risks of nuclear weapons use, even developing a confidence interval or an upper bound of past risks is difficult. Yet the dozens of past close calls give us clues to the lower bound of such risks, and to the paths through which they have arisen and might arise in the future. Also, although ongoing trends will affect which paths from the past are more or less likely in the future, assessing this relationship will require the input of many experts. What is clear is that the case-study research agenda and the most relevant cases for assessing future risks are different from what they were during the Cold War, an era that still characterizes most of the research on nuclear risks. A new research agenda on nuclear risks is needed, and an essential component of that agenda is closer study of those cases from the past that are most relevant to future risks.

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Chapter 3
Elicited Expert Knowledge

Jane M. Booker

Every decision and problem solution involves the use of knowledge gained from the experiences and thought processes of humans. Even for data-rich problems, humans influence how data are gathered, interpreted, modeled, and analyzed. For data-poor problems, such as those assessing risks of never-seen, rare, or one-of-a-kind events, knowledge from experts may be the sole available source of information. Assessing the risk of nuclear deterrence failure is an ill-posed problem that falls into the data-poor category. As a result, experts are needed (1) to supply the information and knowledge for the risk assessment and (2) to define and structure the deterrence problem. These two uses of elicited expert knowledge are discussed. For both, formal elicitation methods for bias minimization are recommended and briefly described. Formal elicitation also involves planning and the use of methods for obtaining the best-quality information from the experts' thinking and problem solving. This formalism includes the characterization of uncertainties, which are prevalent in the deterrence problem, and the analysis of the elicited information, which is necessary for assessing the likelihood and consequence constituents of risk.

Every decision and problem solution involves the use of knowledge gained from the experiences and thought processes of humans. For considering many problems of scientific or technical natures, observations, experiments, and tests provide useful data and insight into the physical world. For example, in meteorology, large amounts of data are continuously available for modeling and forecasting. In contrast, the problem of assessing the risk of the failure of nuclear deterrence is a data-poor problem. Historically, only two incidents of nuclear weapons use have occurred, both during World War II. There have also been other events relating to deterrence failure, such as the close call of the Cuban missile crisis in the 1960s. However, the limited historical data that exist on both actual use and close calls are subject to different interpretations. Theory or fundamental principles about the behavior of nations and groups of people are inadequate and lack sufficient validation to augment the sparse historical record with authoritative information. For such data-poor problems, analysts rely heavily on knowledge from experts.

While everyone can have an opinion, not everyone is an expert. Experts are recognized by their peers as knowledgeable in a subject-matter field and qualified to solve problems and to answer questions related to the subject matter.[1] Some use the terms *subject-matter expert* and *source expert*. The term *knowledge* is used in this chapter to distinguish the expertise formally elicited from peer-recognized experts from opinions that are asked of nonexperts or asked in an ad hoc manner. Examples of the latter would be a reporter asking a person on the street for their opinion about a current event or quoting a person's internet posting. In contrast, formal elicitation of knowledge involves careful planning and preparation of the subject matter, the selection of experts, the question formulation, the response format, the elicitation environment, the elicitation techniques to be used, and the analysis methods used to obtain results. A few scholars have published on these formal elicitation techniques,[2] with Meyer and Booker being the first.[3]

The primary goal of formal elicitation is to gather the best-quality knowledge, in as pristine a form as possible, from experts. This goal imposes a general tenet and approach: to design, implement, and analyze an elicitation that is expert oriented by using the terminology, practices, and cognition of the experts. Formal elicitation draws from many fields, including cognitive psychology, decision analysis, statistics, mathematics, anthropology, and knowledge acquisition. The elicitation and analysis methods are designed to detect, counter, or minimize biases arising from human cognition and behavior and to add rigor, defensibility, and ability to update ever-changing knowledge.[4]

Because knowledge is constantly changing, it is important to understand that an elicitation captures the current state of knowledge, no matter how poor or uncertain it may be. In rare-event subject areas such as nuclear deterrence failure, expert knowledge carries a heavy burden, perhaps being the sole source of information for long periods of time. Such reliance on expertise in these cases makes the goals of formal elicitation even more important.

Formal elicitation serves two purposes in considering the problem of assessing the risk of nuclear deterrence failure:

1. Elicited knowledge is necessary to provide information for any of the techniques and methodologies used for assessing the risk of nuclear deterrence failure.
2. Elicited knowledge can also prove useful in structuring the problem and selecting methods for assessing risk.

The first section of this chapter outlines topics related to and methods for conducting formal elicitation and analyzing elicited knowledge for use in the first purpose. For the second purpose, the second section of this chapter describes how formal elicitation can be used as a methodology for structuring a problem with an unknown structure, such as the ill-posed, data-sparse, multifaceted assessment of the risk of nuclear deterrence failure.

Formal Elicitation and Analysis of Expert Knowledge

The use of expert knowledge is central to all approaches to assessing the risk of deterrence failure because of the shortage of data, information, and knowledge. Regardless of the approach, methods, or models used to structure and represent this problem, data, information, or knowledge is required to characterize its features, issues, components, and conditions. A primer on formal elicitation provides guidelines designed for data-poor problems, such as this one, and covers the highlights of bias minimization and analysis methods.[5] More detail about planning, designing, implementing, and analyzing the elicitation is available in Meyer and Booker's book.[6]

Elicitation Topics

Some of the topics in eliciting expert knowledge most important to the problem of assessing the risk of nuclear deterrence failure are briefly described here. Additional topics relevant to analyzing elicited knowledge are discussed in the "Analysis Topics" subsection.

Biases

Biases are a slanting, adjusting, or filtering of an expert's thinking and original knowledge due to their needs (motivation) and through cognitive processing. Biases degrade the quality of elicited knowledge through distortion. To counter these deleterious effects, formal elicitation includes bias minimization methods for monitoring and/or controlling common biases.

Table 3.1 lists names and descriptions of common biases. While names of biases may vary in different subject areas, their descriptions and effects are common across problems. For example, near-miss bias can be described as a combination of overconfidence and availability biases.[7]

Nuclear war and deterrence are highly emotional topics, and factions exist on multiple sides of associated issues. Experts tend to place undue importance on the few facts available to them, be wishful about outcomes that support their views and agendas, and anchor to their own experiences. Availability bias is strong because experts may not have been alive when nuclear weapons were used in Hiroshima and Nagasaki, and many were children during the Cuban missile crisis. Other events may never have been widely publicized (e.g., the Norwegian meteorological rocket launch in 1995 and the Russian reaction to the NATO Able Archer 83 exercise in 1983).[8]

Wishful thinking bias manifests itself in experts with strong personal or emotion-based agendas that filter or change their expertise to fit a desired result about the success or failure of nuclear deterrence. Waltz and Sagan exhibit this bias; each uses the same historical record as evidence for his own case.[9] Waltz assesses that deterrence has been and will be a successful policy and interprets history to fit that assessment. Likewise, Sagan assesses that deterrence is prone to failure and interprets the same history to fit his view. As another example of wishful thinking bias, experts may exaggerate the risk of deterrence failure to support their favorable view of missile defenses.

Experts often anchor to their initial assumptions, conditions, or responses even when presented with opposing or new, indisputable information. Anchoring bias is detectable, and experts can be made aware of this bias. However, it is easier for anchoring to go undetected or unchallenged when there is uncertainty about whether the new information is valid; therefore, anchoring bias is difficult to detect and to overcome for the deterrence failure problem.

Another anchoring bias is that humans inherently assume that others think and behave in the same way they think and behave. The close call in the NATO Able Archer 83 exercise is one such example. From the Soviet perspective, and consistent with its military doctrine, a nuclear exercise was a useful pretext for a nuclear surprise attack. Soviet leaders, assuming that US leaders think like they do, surmised that a US surprise attack could be the true purpose of Able Archer.[10]

These biases require monitoring and understanding through formal techniques such as probing the experts for explanations, clarifications, and thought processes. Likewise, these techniques aid in distinguishing bias effects from expertise and experience.

Table 3.1. Common biases

	Name	Definition
Cognitive Biases	Anchoring	An expert's failure to sufficiently adjust from their first, long-held, or unchallenged impression in solving a problem—the expert anchors to first, long-held, or unchallenged impression. Sometimes this bias is explained in terms of Bayes' theorem as the failure to adjust knowledge in light of new information as much as it should be adjusted using Bayes' mathematical formula.
Cognitive Biases	Availability	A bias that results from how easily an expert can retrieve particular events from memory. This affects how accurately frequencies (and probabilities) are estimated. Because memory by its nature is selective, a strong agenda will affect retrieval.
Cognitive Biases	Inconsistency	Inability to maintain the same problem-solving heuristic, definitions, or assumptions through time because of the limited information-processing capacity of the human mind.
Cognitive Biases	Overconfidence	The tendency to underestimate the true amount of uncertainty in giving an answer. For example, experts are frequently asked to estimate ranges around their answers to reflect their uncertainty. If experts are requested to put a range around their answers such that they are 90 percent sure that the range encompasses the correct answer, they will tend to underestimate the uncertainty by providing a range that is as much as two or even three times too narrow.

Table 3.1—*continued*

	Name	Definition
Motivational Biases	Group think	The tendency to modify knowledge and/or information so that it agrees with that of the group or of the group leader. Individuals are generally unaware that they have modified their thinking and responses to be in agreement. This bias stems from the human need to be accepted and respected by others. Individuals are more prone to group think if they have a strong desire to remain a member, if they are satisfied with the group, if the group is cohesive, and if they are not a natural leader in the group.
	Impression management	Resulting from social pressure, this bias occurs when the expert responds to the reactions of those not physically present. For example, the expert answers survey questions in a way that maximizes approbation either from society in the abstract or from the administrator of the elicitation in particular.
	Misinterpretation of the expert	The altering of the expert's thoughts as a result of the methods of elicitation and documentation.
	Social pressure	An effect that induces individuals to slant their responses or to silently acquiesce to the views that they believe the interviewer; their group, supervisors, organization, or peers; or society in general will accept. This altering of an individual's thoughts can take place consciously or unconsciously. The social pressure can come from those physically present or from the expert's internal evaluation of how others would interpret their responses. People's need to be loved, respected, and recognized induces them to behave in a manner that will bring affirmation. Political correctness is an example.
	Training bias	The tendency of the data gatherer, analyst, or both to misinterpret data/information from others for their own purposes (for example, choosing quotations, references, or events that suit the interviewer's purposes).
	Wishful thinking or conflict of interest	A tendency that occurs when individuals' hopes influence their thinking and responses. For example, people typically overestimate what they can produce in a given amount of time. In general, the greater the experts' involvement and the more they stand to gain from their answers, the greater this bias.

Elicitation Setting

The quality of elicited knowledge depends on the interviewer's ability to question experts about the assumptions they use, the heuristics and cues involved in their thinking, and their problem-solving processes. These details are best elicited in face-to-face elicitation sessions, making a personal interview the preferred setting for eliciting knowledge on the deterrence failure problem. Modern teleconferencing may provide a convenient alternative. Ideally, two interviewers conduct the elicitation: one who has subject-matter expertise and one who has elicitation expertise. As necessary, each should train the other before the interview.

Because of the multidisciplinary nature of this problem, some group elicitations may be necessary for different experts to interact. Group elicitation sessions suffer from biases different from those typical of individual interviews. For example, experts may be prone to agree with an influential member in the group. Group-related biases can also be minimized with proper use of elicitation methods. The setting that provides the least opportunity for the interviewer to understand the expert's thinking and the most opportunity for biases is the mail-in questionnaire.

A common language and terminology may not exist among the different subject areas involved in assessing the risk of nuclear deterrence failure. Thus, for group elicitations and the subsequent analysis, the interviewer must provide experts with background, assumptions, and definitions of terminology from different subject areas. Even with a single expert, the interviewer may have to remind the expert of changes in terminology.

Question Phrasing and Response Mode

One of the most important bias minimization techniques is proper phrasing of questions. Avoiding "loaded" questions such as "When did you stop beating your wife?" requires only minimal effort. However, asking unbiased questions is difficult, especially when the subject is sensitive or emotional, such as might be the case when discussing nuclear weapons use or war. It is helpful to use terminology consistent with the expert's common practice and to repeat the expert's own words back to them. For guidelines on question phrasing, Payne's book is the classic reference[11] and its guidance is used in conjunction with formal elicitation methods.[12]

Response mode refers to the format the interviewer choses for the answers to questions posed to the experts. Examples of response modes include multiple choice, open-ended essay, continuous numerical scale, odds ratio, range of values, comparison, ranking, and likelihood. Some of these are described in the next section on structuring. Likelihood may be a concept consistent with the way many experts think, and it is general enough to encompass definitions used by specific communities of practice. In contrast, probability is only rarely appropriate to very specific communities.

Uncertainty

All knowledge, data, and information have uncertainty associated with them. Uncertainty can be defined as that which is not precisely known. Examples particular to the issue of nuclear deterrence include uncertainty in the number and nature of nuclear close calls, uncertainty about whether a state leader's statements in a speech are true, uncertainty about how a potential adversary views the use of nuclear weapons, and uncertainty about whether a group can construct a nuclear weapon.

More often than not, uncertainties are ignored or assumed negligible because it is difficult to recognize and treat them. When addressed, uncertainty is often measured quantitatively, such as by using a range of values or a probability. However, uncertainty can also be expressed qualitatively when knowledge and information are also qualitative.

The qualitative nature of the knowledge and information associated with the question of nuclear deterrence failure is conducive to qualitative uncertainty representation. The deterrence literature is filled with phrases such as *not impossible*, *possible but not probable*, *plausible*, and *belief*. These words express a degree or measure of uncertainty regarding the subject under consideration. For example, an expert stating that something "is possible but not probable" implies that possible is less likely than probable. The words themselves have an uncertainty inherent in their interpretation. For example, how unlikely is "possible"? Experts expressing qualitative uncertainties should be asked to provide definitions or examples to illustrate the meanings behind their words. This clarification aids in comparing uncertainties between issues and between experts.

General information theories can be used to quantify uncertainties, and they provide standards or yardsticks by which uncertainties can be compared.[13] One general information theory differs from another based on the types of uncertainties it characterizes and the properties (axioms) it follows. For example, Zadeh fuzzy sets and logic have properties designed to turn qualitative linguistic information into quantitative uncertainties.[14]

However, mathematical theory is lacking for combining uncertainties characterized using different general information theories, making it difficult to mix the use of different theories within a problem. This is one reason why probability theory is often chosen for a problem even though it characterizes only one type of uncertainty: the uncertainty of the outcome or result of an indeterminate event.[15] Once that event has occurred, and its outcome determined, there is no uncertainty and the probability of that event is either 1.0 if the event occurred or 0.0 if not. This basic meaning of probability is not readily practiced even by scientific and technical experts.

Quantitative, experimentally derived data are subject to uncertainties from measurement, experimental conditions, initial conditions, environmental or system controls (or lack thereof), and unexplained random variations. Most scientists are taught to characterize these uncertainties by using probability theory. Probability has a mathematical definition based on measure theory and crisp sets. Unfortunately, the reasons for using probability get lost in its common usage—one reason why probability is commonly viewed as the exclusive method for characterizing uncertainty.

Despite the common usage of probability for uncertainty, there are three difficulties in using probabilistic uncertainties for the risk of nuclear deterrence failure. First, not all uncertainties inherent in the deterrence failure problem fit into the probabilistic definition. Uncertainties relating to linguistic information or resulting from conflicting information, misclassification, lack of knowledge or theory, or lack of specific detail or its reverse—generalization—are not well characterized or quantified by probability. Some of the other general information theories are designed to characterize these uncertainties. Regarding linguistic uncertainty, previous attempts have been made to equate or transform words to numbers. One of the most common is the Sherman Kent scale.[16] Weiss developed another scale based on legal standards of proof.[17] The disadvantage of using predefined scales is that an expert's definition of words such as *likely* may not match the definition in the scale. Ideally, each expert would define such a translation based on how they think about the term.

Second, experts tend to violate the axioms of probability theory when providing probability estimates. For example, an expert responding with a probability of 0.05 for a particular event to occur might later respond with a probability of 0.90 for that event to not occur. More difficult-to-detect violations of the axioms of probability include a sum of multiple mutually exclusive and exhaustive probabilities that is not 1.0 and improper estimates of conditional or dependent probabilities.

Often surveys interchange the terms *probability* and *percentage*. While a probability can be transformed into a percentage, a percentage cannot always be transformed into a probability because percentages can be greater than one hundred.

Third, humans (even statisticians) are not well calibrated for estimating probabilities. As a rule, they cannot accurately express their perceived likelihood or frequency of their experiences as probabilities.[18] For extremely rare events, poor calibration of probability estimation can be magnified. For example, it is difficult to distinguish between a probability of 0.000001 and 0.0000001. This is why in some subject areas, orders of magnitude (e.g., the Richter scale for earthquakes) are used. However, if experts are not experienced in thinking in such scales, it is difficult to teach or train them. In general, it is difficult to train experts to accurately estimate probability.[19]

Unless an expert is used to dealing with and thinking in terms of probability, it is best to avoid asking for probability as a response. Other response modes and descriptions are advised, such as odds (betting odds), likelihoods, ratios, ranks, or other comparisons. The choice should be consistent with the expert's community of practice. At the very least, the interviewer should thoroughly define any unfamiliar response mode for the expert.

In those special cases in which probability is appropriate to characterize uncertainty, it should be noted that there are at least two modern interpretations of probability that are equally valid within its theory.[20] The first is what most are taught as probability—the number of event occurrences divided by the total number of outcomes. This is the frequentist or relative frequency interpretation of probability. For example, the probability of drawing a red marble from a jar containing one hundred marbles of which twenty are red is 20/100 = 0.05.

The second is the personalistic interpretation, often referred to as the Bayesian interpretation, the centerpiece of Bayesian analysis. Personalistic probability is an individual's assessed value based on their willingness to bet that they are correct.[21] For example, if an expert states that there is a 0.90 probability that the next terrorist attack on the United States will occur within three months, the expert should be willing to stake $0.90 in exchange for $1.00 if the attack occurs within three months. If the attack occurs within three months, the expert wins the $1.00, for a net gain of $0.10. If the attack does not occur, the expert loses $0.90. To prevent cheating, the expert should also be willing to make the opposite bet, where they are willing to stake $0.10 in exchange for $1.00 if the event does not occur. This two-sided bet is depicted in Table 3.2. In terms of betting odds, this example demonstrates odds of 9 to 1.[22]

Table 3.2. An example of a two-sided bet

Bet	Attack Occurs, p = 0.90	Attack Does Not Occur, p = 0.10
Expert stakes $0.90 in exchange for $1.00 if attack does occur	Expert's net gain is $0.10	Expert's net loss is $0.90
Expert stakes $0.10 in exchange for $1.00 if attack does not occur	Expert's net loss is $0.10	Expert's net gain is $0.90

An expert who believes the probability of attack is 90 percent should be willing to take either side of this bet.

Regardless of whether or not an uncertainty is probabilistic, the interviewer should elicit it along with the responses to the questions asked of experts during an elicitation. The form or format for noting uncertainties should be consistent with the way the experts think and the available knowledge.

One of the recommended forms for eliciting uncertainties is to request a range of answers after eliciting the expert's response. To avoid introducing ambiguous uncertainty in the analysis of experts' ranges, it is necessary to define what the requested range represents. For example, the range could represent absolute highest and lowest values. Unless experts are familiar with percentiles (and most are not), tying range limits to percentiles (e.g., 5th and 95th) is not recommended. To minimize anchoring bias, the expert should be encouraged to consider their range in conjunction with their response, making any necessary adjustments.

When eliciting uncertainty, the common bias of underestimating the real uncertainty should be monitored. Experts tend to be overly optimistic about what is known and to respond with uncertainty estimates that are too narrow relative to the state of knowledge. This is called overconfidence bias.

The word *confidence* is often used in relation to uncertainty. Too often *confidence* is used in a colloquial sense, as the dictionary definition of belief, without any technical, mathematical, or quantitative definition. To lend technical meaning to confidence, it can be defined as the complement or inverse of uncertainty.[23] For example, a commander might tell a general that they are confident the mission will be a success, using the colloquial definition. However, the general could ask for the uncertainty about the success, understanding that the larger the uncertainty, the smaller the confidence.

Neither of these definitions of confidence should be confused with statistical confidence intervals or confidence level. These terms have specific mathematical definitions in statistical inference and hypothesis testing that are not appropriate for the colloquial or technical definitions. Often decision-makers and experts confuse the colloquial definition of confidence with the statistical ones.

Decomposition Principle

Assessing the risk of nuclear deterrence failure is an extremely complex problem that cuts across multiple areas of expertise. It is unlikely that any single expert will have enough expertise to cover all aspects of the problem. Thus, experts from different and diverse subjects will have to participate in the assessment, and the problem will require decomposition into manageable parts.

Studies on human cognition have shown that experts provide more accurate knowledge when the problem is fully specified and broken down into basic constituents.[24] The more complex a problem, the more specification and decomposition is necessary. A simple example illustrates this concept: Estimate how much you spend on your home budget. Then consider all the items in the budget, and write down individual estimates for each: the groceries, utilities, rent/mortgage, clothes, education/business expenses, vacations, medical expenses, etc. The sum of these should differ from your first estimate, and the decomposed total should be more accurate.

The decomposition process includes specifying definitions, conditions, scenarios, assumptions, timelines, quantities, and parties involved. Usually, several preliminary questions that provide these specifications are asked to set the stage for the questions of interest. A structure or framework of the problem provides guidance on how to do the decomposition.

The decompositions and operating conditions of physical systems can be easily represented because of their structure. However, decompositions of complexities of human behaviors, timelines, or event sequences—all of which are applicable to assessing the risk of failure of deterrence—may not be so obvious or conducive to common structures such as fault trees. The nuclear deterrence failure problem currently lacks a systems perspective (and hence structure) or model, making decomposition difficult. Even establishing initial or boundary conditions may pose challenges because of all the facets and factors involved. It may be possible for experts to contemplate some specifically defined scenarios or special cases and begin decomposing the problem by using those.

Risk analysis has two aspects: likelihood and consequence. Risk studies usually address the likelihood first and then the consequences, even though there are interdependencies between them. Deterrence also has two aspects: capability and credibility. Both should be evaluated from the perspective of the party being deterred, and again, there are dependencies.[25] Because of the dual natures of both risk and deterrence, decomposition is a necessity for the problem of assessing the risk of nuclear deterrence failure. Other decompositions could be based on issues such as state versus non-state nuclear use; a single weapon attack versus multiple weapons; attack on US homeland versus elsewhere; unauthorized versus authorized use; and accidental versus intentional use.

Ill-Posed Problem Decomposition

The risk assessment of nuclear deterrence failure is an ill-posed problem because it is knowledge sparse, complex, and multifaceted and involves multiple subject areas and large uncertainties of various types. Thus, there is a temptation to elicit knowledge at a general level, ignoring decomposition and failing to capture specific expertise. An example of what can happen when a nonspecific question is asked of experts, consider question 5 from the Lugar survey.[26] Figure 3.1 is discussed in chapter 1 relating to biases and reprinted in this chapter for convenience. As noted in chapter 1, it shows the varied responses of seventy-nine experts to the question, "What is the probability (expressed as a percentage) of an attack involving a nuclear explosion occurring somewhere in the world in the next ten years?" While this question may sound specific, the geopolitical conditions leading up to such an event were not specified, assumptions about the attacker were absent, and what constitutes an "attack" was not defined, leaving each respondent free to decide what these factors might be. The wide variety of responses suggests that different experts answered differently based on their assumptions and what they were free to specify in their thought processes (but were not asked to report). As noted in chapter 1 and in the bias subsection above, such lack of specifics provided to the experts opens the door for biases to dominate, adding to the wide dispersion seen in Figure 3.1.

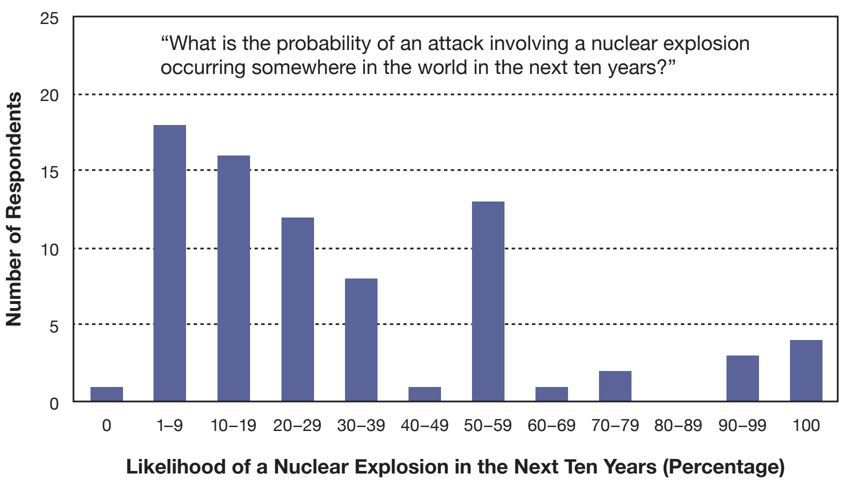

Figure 3.1. The Lugar survey, question 5.

While it is important to select a diverse group of experts to ensure the state of knowledge is represented, such a dispersion of responses could also indicate that some respondents did not know how to answer because of lack of expertise so they opted for the middle-percentage answers. However, even with expertise, experts may supply a middle response (e.g., 50 percent) to indicate their large uncertainty about the answer. It is not uncommon for experts who have strong biases regarding the probability of attack to respond with the extremes of 100 percent and 0 percent. Detecting such bias and getting experts to expand their thinking beyond their anchored views is what bias minimization elicitation is all about.

The nuclear terrorism and war literature contain some examples of decomposing the complex and ill-posed deterrence problem. Bunn,[27] Hellman,[28] and Mueller[29] decomposed the problem into separate events for evaluation. Each provided their own problem structuring for the conditions and assumptions of the events they chose. Each then provided their own estimates of the likelihoods of these events and descriptions of how to combine or propagate those estimates to obtain the final answers.

Their analyses of their versions of the problem could be called self-elicitations. Self-elicitations are very prone to biases when questions are not properly phrased and problem-solving is not monitored, as was the case in these authors' evaluations. The disadvantages of their analyses are that the authors' biased responses were driven by their personal agendas and that it is possible that not every author is an expert. The advantage of written self-elicitations is that authors tend to describe their thought processes, reasons for structuring the problem in a particular way, and reasons for their personal responses.

Decomposing a complex and/or an ill-posed problem into manageable parts and diligently defining the specifics of each question relating to those parts not only aids in eliciting pristine knowledge from experts, but it also helps determine whether different experts are answering slightly different versions of the same question. Differences in experts' assumptions, definitions, conditions, problem-solving processes, and interpretations of the question can result in different responses, such as those seen in Figure 3.1. Decomposing the problem and using formal elicitation methods helps the interviewer avoid those kinds of results.

Analysis Topics

After expert knowledge has been elicited, it must be analyzed. The analysis topics described in this section are part of formal elicitation design and implementation. The particular topics were chosen for inclusion because of their importance to the nuclear deterrence failure problem.

Selection and Motivation of Experts

For analysis results to have interpretive meaning about the current state of knowledge, the selected experts must be a representative subset of all such experts. To ensure proper representation, a random sample or other statistical sampling method should be used to select experts. However, there may be few experts in existence. In that case, the goal should be to get participation from as many as possible. If the entire set of experts is known to be composed of groups based on factors such as opposing views, varying levels of expertise or experience, and different backgrounds, the selected experts should represent those different groups. For example, a poorly designed selection would include only experts who work in Washington, DC, or only experts who hold strong anti–nuclear weapons views.

To avoid experts' nonparticipation or nonresponse, it is necessary to motivate their participation from the beginning. Motivations include flattery, compensation, and collaboration. Experts can be motivated and encouraged by reminders that their work is fundamental and is breaking new ground. Likewise, it is important to keep in contact with experts to encourage them to provide the requested knowledge in a timely manner. Motivation is difficult if a mail-in survey is the chosen elicitation setting. Lack of participation can undermine the care taken to obtain a representative selection of experts and can adversely affect conclusions drawn from the elicited knowledge.

Feedback: The First Analysis Step

After a representative set of experts is selected and the elicitation has been conducted, compiling and reviewing the experts' responses for clarity and errors is the first step in analysis. This step is likely to involve re-contacting the experts. At that time, they should be reminded of what analysis is planned for the knowledge they provided—of which they should have been informed when first interviewed. They can review their responses and reasons for them. This is the feedback process.

An analyst will be tempted to interpret the experts' responses in such a way as to make the analysis job easier. In doing so, the analyst introduces bias. For example, if the analyst wants to analyze the responses as average values, the experts should have been asked to provide averages. It is vital to plan ahead for the kinds of analyses anticipated so that proper questions and response modes can be provided to the experts. Response modes should be chosen based on how the experts think rather than for the convenience of the analyst.

Experts' Problem Solving and Cognition

Much of the wide dispersion (a type of uncertainty often measured by a variance) in the responses in Figure 3.1 could be understood if the experts had recorded their thoughts and problem-solving processes while answering the question. These activities are part of formal elicitation design. Querying the experts about their thinking and problem-solving processes is conveniently done in a face-to-face interview. It can also be done during the feedback process to clarify responses.

Probing into cognitive and problem-solving processes is important for determining whether an expert is answering the posed question or some modified or misinterpreted version. Often experts think about conditions, assumptions, cues, and experiences and use problem-solving methods that affect their responses, but these thoughts and methods may not be recorded. Changing one or more of these could significantly change an expert's response. If the analyst does not know details about how the experts answered a question, the analyst will not be able to draw proper conclusions or resolve disagreements among experts.

A simple example illustrates the importance of eliciting cognitive and problem-solving processes. Experts A and B both respond with high likelihoods of nuclear weapon use within the next ten years. However, after eliciting their problem-solving processes, it is discovered that expert A assumes a terrorist use while expert B assumes an interstate war. Further probing reveals that expert A considers the interstate war an unlikely situation for nuclear use and expert B considers nuclear terrorism unlikely. Thus, without knowing what the experts were assuming when responding to the nuclear use question, their apparent agreement is not the correct conclusion. Experts A and B were actually providing different answers based on different assumptions and cognitive processing.

The analyst is often faced with determining the degree of dependency among experts. This is important if experts' responses need to be aggregated (e.g., reporting an average response as done in the Lugar report). Experts who are highly dependent are expressing the same knowledge and cannot be counted as independent sources. It is difficult to determine the extent of overlapping or double-counted knowledge from a group of experts. Without details about how experts arrived at their responses, dependency determination becomes untenable. Experts who solve problems by using similar methods tend to produce similar responses, illustrating the importance of eliciting experts' cognitive processing for monitoring dependence.[30]

The analyst is a unique position to compare responses to multiple questions for each expert. Such analysis can check on the expert's self-consistency and understanding of the subject. It can also be used to indicate a change in a definition or assumption used by the expert and monitor biases.

Conditionality

Every piece of knowledge, model, answer, and problem is conditioned on things known and unknown, admitted and unaware. These conditions could be boundary conditions, scenarios, environments, settings, cases, domains, levels of detail (granularity), cues, rules, heuristics, or assumptions. A thorough, formal elicitation should uncover as many of these conditioning factors as possible, given constraints on time and budget. Different conditions considered in the expert's thinking often produce different responses. For example, two experts with the same experience, education, and viewpoints can produce different answers because one is using an assumption different from the other's. That assumption can be considered a different problem-solving process or a different model used by the expert.

Models applied to portions or the entire problem are also considered conditions because results may change if a different model is used. An example of such a model is Perrow's complexity theory, which describes the interaction of humans with technology.[31] Sagan's organizational theory uses a different conditional modeling—the interaction of humans with their environment (organization) and its influences (conditioning) on them.[32] Taleb (of black swan fame) recommends using expert knowledge but wisely warns about watching out for the assumptions and conditions found in modeling.[33]

An example of the importance of conditionality is found in probability theory. If conditional probabilities are not carefully and properly estimated, their combination can produce a result that violates probability axioms. This violation due to ill conditioning is the basis of Borel's paradox.[34]

Expert Resolution and Aggregation

Clarification gained by resolving differences in experts' responses by using their problem-solving processes is necessary for achieving a consensus of experts and for the analyst to aggregate experts' responses. An accurate consensus cannot be achieved if experts do not mutually understand the reasons behind their responses. An inaccurate consensus can arise because of biases, such as fatigued experts acquiescing just to end a meeting or following the party line in the presence of authority. The analyst could be inadvertently combining nonidentical responses if they do not know the experts' reasoning. Neither consensus nor aggregation may be necessary or practical (because they are too difficult to achieve) for the problem of assessing the risk of deterrence failure. A decision-maker would be better served by being given the full spectrum of responses (with uncertainties) from a diverse set of experts.

Aggregating experts' responses suffers from the same problem as any combination scheme: Should all experts' responses be considered equal? If not, how should experts be weighted? Recall that experts are identified by their peers; thus, those same peers are a reasonable source of weights. Self-identified weights are the next reasonable source; however, some experts can be overly modest, and some can be overly arrogant. The analyst or decision-maker should not determine weights for experts. Weights can differ from question to question, because some experts may be more knowledgeable than others in differing subject areas. Such determinations can be very complicated and time consuming. Assuming the experts are peer identified, then the simplest solution is to weight experts equally. This is the maximum entropy[35] solution and is recommended unless a good reason and a good method for discriminating among experts exist.

Cooke advocates aggregation of experts' responses through a process by which they are calibrated.[36] This calibration involves training and testing the experts—a time-consuming process. However, this approach is of limited use in subject areas in which data and experience are sparse and/or knowledge and theory are not well known. For calibration to be effective, feedback to the experts must be (1) immediate, (2) frequent, and (3) relevant to the subject. One of the few areas that meets these criteria is meteorology, which has theory, models, and huge amounts of data for forecasters to consult and improve their predictions. The nuclear deterrence problem is the opposite: it is data poor and theory poor. Thus, calibration is not recommended.

Drawing Conclusions

Usually the reasons for analysis are to summarize the elicited responses and to draw conclusions from them, often to inform decision- and policy-makers. Even though elicited expert knowledge is not a substitute for experimental, historical, or observational data, it can be analyzed and conclusions can be drawn from it. If there is ever a time when data might become available, elicited and analyzed expert knowledge can be considered a placeholder for those future data and can be compared and combined with the future data.

For highly qualitative responses, there may be little opportunity to analyze the information elicited by using statistical or data analysis methods. While qualitative knowledge can sometimes be grouped or categorized, this is subject to misinterpretation bias. If the responses are continuous numeric quantities, integers, ordinal, or categorical, then statistical analysis methods are useful for providing defensible conclusions inferred from experts' responses.

Decision-makers may be accustomed to seeing a central aggregated response from all the experts—a mean (the average of numerical values), median (the middle of the range), or mode (most frequent or common value). For example, the mean for the question in Figure 3.1 is 31 percent, which falls in the 30–39 percent bin. The median of seventy-nine values is the fortieth value, which falls in the 20–29 percent bin. The mode is the bin with the largest count, the 1–9 percent bin.[37] Because of how these three differ, the conclusion is that these data are not distributed symmetrically around a central value. Figure 3.1 visually confirms the lopsided loading of the data in the lower percentages. The wide dispersion of responses in Figure 3.1 is summarized by the large standard deviation—an uncertainty metric for dispersion—of 28 percent. Another common measure of dispersion uncertainty is the range, which is 100 percent.

Statistical methods can be used to determine whether the experts responded uniformly across the percentage scale as might be suspected in Figure 3.1. The answer here is no; significantly fewer than expected experts responded in the percentage bins labeled 0, 40–49, 60–69, and 80–89, and too many responded in the bins labeled 1–9, 10–19, 20–29, and 50–59.

It is anticipated that different experts may have different perspectives and perhaps strong personal agendas. Such differences can emerge from divisions or factions within a subject-matter community. For example, a discussion of nuclear war tends to divide viewpoints into factions based on the emotional response that concept evokes. That emotion translates to inducing bias as experienced from decades of elicitation efforts on sensitive and taboo topics, including nuclear weapons and war. The deterrence community also appears to be divided into factions regarding the effectiveness, or lack thereof, of nuclear weapons. The well-documented debate of two such factions can be found in the works of Sagan and Waltz.[38]

Analysts should be aware of such perspectives and should question experts about their preexisting (i.e., anchored) positions. Along with that, other questions about the experts' specific areas of research and experience provide information about how their responses may be biased. Statistical analysis may be able to determine whether or not these biases affect responses, by comparing responses among experts whose preexisting positions are established and whose problem-solving processes have been elicited.

Linguistic responses and qualitative descriptive answers are more difficult to analyze than quantitative responses such as those shown in Figure 3.1. However, the knowledge gained from these responses is more detailed than that obtained by forcing experts to collapse their knowledge into a single numeric response. Some linguistic responses can be categorized and category responses counted, permitting some analysis. The analyst must accept the fact that some responses cannot be graphed, counted, or analyzed in any manner. In such cases, thorough and unaltered documentation of responses accurately captures the current state of knowledge for that question.

Reviewing information from the nuclear deterrence and war literature illustrates some of the issues regarding drawing conclusions, uncertainty, and conditionality. Table 3.3 (discussed in chapter 1 and reprinted in this chapter for convenience) presents a set of estimates of nuclear war or terrorism from various authors who have written about the subject (and who may or may not be considered experts). At first glance, these authors appear to be estimating the same thing—the probability of nuclear war—but with widely different results. The table divides the sources into two different subjects (conditions), war and terrorism. Different response modes are used: some of the estimates are percentages, some are odds, and some are ratios (1 in *n* or *x* in *n*). In addition, the estimates have different time conditions: four estimates apply to the next decade, two are per year, one is per attempt, and two are specific to the time during the Cuban missile crisis. It should be noted that lack of specificity is a type of uncertainty because the analyst looking at this table faces the conundrum of how to compare results from unspecified conditions to the results from specified ones.

Table 3.3. Individual estimates of the probability of nuclear war

	Question	Estimate	Author	Year
War	Probability that the Cuban missile crisis could have escalated to (nuclear) war?	Between 1 in 3 and even (war)	John F. Kennedy	1962
		As large as 1 in 100 (nuclear war)	McGeorge Bundy	1988
	Probability of a future Cuban missile-type crisis that results in at least one nuclear weapon being used?	2 in 1,000 to 1 in 100 per year	Martin Hellman	2008
Terrorism	Probability that terrorists will detonate a nuclear bomb?	More likely than not (on America)	Graham Allison	2004
		50–50 odds within the next decade	William Perry	2004
		Less than 1 percent in the next 10 years	David Albright	2005
		29 percent probability within the next decade	Matthew Bunn	2007
		10–20 percent per year against a US or European city	Richard Garwin	2007
		Less than 1 in 1,000,000 (per attempt)	John Mueller	2008

The analyst might be able to resolve other response differences by determining each author's viewpoint, understanding what information the author used, discovering how the author structured or modeled the problem, and gaining insights into the author's cognition by reading the author's papers. Without such conditioning information, the analyst can only compare "apples to apples." The four estimates that terrorists will detonate a nuclear bomb in the next decade have a large, unexplained, range of 1 percent to 50 percent. The other estimates cannot be included with these unless and until the conditional factors inherent in them are known, putting them in the same terms as the first four. The Bundy and Kennedy estimates can be compared to each other but not the rest.

Informing Decision-Makers

Quantifying or summarizing results from elicitation and analysis should be done in a form useful for and understandable to decision- and policy-makers. Determining that format may involve an elicitation with the decision-maker. While top-level managers rely on executive summaries, details should be made accessible for their staff and for future updates as knowledge changes.

Returning to the data in Figure 3.1, quoting the mean response of 31 percent to a decision-maker without the uncertainty does not convey an adequate summary of these data. In this particular case, the histogram in Figure 3.1 does provide an appropriate summary. However, a decision-maker who is unfamiliar with histograms (or who is uncomfortable with graphs and bar charts) should be given verbal descriptions and explanations of the data, using that decision-maker's usual terminology, rather than shown Figure 3.1. Another disadvantage of Figure 3.1 is the choice of intervals for the bins. Of note is the large count in the bin for 50–59 percent. A reason for this may be that some experts opted for the 50 percent response. The decision-maker should be given the 50 percent count instead of mixing it with other responses in the 50–59 percent bin.

There are creative and informative visual displays for data and information available with apps, such as the word frequency generator, Word Cloud, from Microsoft. Most of these modern tools have their origins with those in Edward Tufte's seminal books.[39]

Eliciting Problem Structure

Assessing the risk of nuclear deterrence failure is an ill-posed, complex, multifaceted, knowledge-sparse problem spanning multiple subject areas. These characteristics make structuring this problem a challenge. A problem structure can be described generally as a recorded representation of a problem in the real world, organized into a useful format of pieces, facets, or aspects (often designated with boxes), which are interconnected according to some order, association, hierarchy, time flow, or logic. A problem structure:

- Defines the boundaries and scope of the problem (which facets and subject areas will be included and excluded)
- Defines the top-level or bottom-line question (what is the risk of deterrence failure?)
- Provides a logic flow that cohesively connects all aspects of the problem to answer the top-level question. Such a flow could be a timeline (e.g., an event sequence), a hierarchy (e.g., general to specific parts), or specified relationships (e.g., dependencies, influences and conditions, and mathematical models), to name a few possibilities.
- Guides the formation of questions about smaller problem aspects or parts
- Provides a mechanism for capturing and recording experts' thoughts and problem-solving processes in an elicitation
- Guides the use of the decomposition principle for an elicitation
- Provides the relationships, connections, and associations of problem parts and aspects for analyses
- Provides a framework or skeleton on which all the available and applicable data, information, and knowledge are attached

For purposes here, the term *framework* refers to the general problem outline, concept, and scope, while *structure* refers to establishing order, organization and arrangement, logic flow, and connections and interrelationships of problem aspects and parts. A framework is part of the structure and is related to it like a skeleton is to a body.

Applicability of Established Structures

Determining problem structure for an ill-posed, knowledge-sparse, multifaceted problem, such as the risk of nuclear deterrence failure, is challenging because many of the established structuring methods may not be applicable. Established structures from risk and reliability analyses include fault trees, reliability block diagrams,[40] and event trees[41] and are designed to represent physical systems. Such systems have definite structure and are designed for specific modes and environments for operation. Complex or ill-posed problems involving human behavior, such as the problem of nuclear deterrence, may not be so easily decomposed into discrete parts the way a physical system can be. Defining what constitutes the whole—the "system" and its boundaries—for this problem is also a challenge. Even determining what constitutes success or failure may not be clear, precise, or crisp in the deterrence "failure" problem.

Other established structures follow timelines and logic flow sequences in operations and processes. Examples indicating the wide variety of such structures include computational algorithms, flowcharts, manufacturing processes, communication networks, PERT charts,[42] Gantt charts, electrical circuit or wiring diagrams, blueprints, chemical and physics reaction sequences, and assembly processes. The structures for these problems usually involve human interaction with physical systems and physical processing, so the physical system supplies the structure. Again, these structuring methods do not readily apply to the nuclear deterrence problem, which is not a physical system. In addition, it may be difficult to define and prescribe predominantly human processes or sequences because of unknown behaviors, politics, etc. Multiple parallel activities may cease and restart for unknown reasons.

Established structures from decision sciences may be somewhat applicable because they deal with human thinking and actions in decision-making and problem solving. These structures include decision trees[43] and influence diagrams.[44] Because of these structures' popularity, many software packages exist to allow users to create them. Decisions, actions, and causalities are specified in the structuring of a decision problem. Connections between these are limited to specific relationships according to the mathematics used. The mathematical framework is utility theory, which has its origins in game theory.[45] However, it is difficult for humans to think and behave in accordance with this mathematics. Thus, while the diagrams and interrelationships (e.g., influencing factors) may be useful for the nuclear deterrence problem, the mathematics used to perform the analysis and glue the structure together to arrive at the top-level answer may not be appropriate.

For the reasons mentioned (and others), established structures may not be applicable to assessing the risk of nuclear deterrence failure. The goal for structuring this problem is to take the ill out of the ill-posed problem or at least understand the difficulties and what knowledge would be needed to overcome them. An alternative to applying established structures for the assessment of the risk of deterrence failure is to elicit problem structure consistent with the way the experts think about the problem. Reasons why this alternative is attractive for the nuclear deterrence problem follow.

Reasons for Eliciting Problem Structure

Expert knowledge will be the primary source of knowledge for the nuclear deterrence failure problem, and the structure should be consistent with experts' thinking about the problem, according to elicitation principles. However, experts from the different subject areas involved may not agree on how their portions of the problem should be structured. If those differences are not resolvable, then reasons for those differences can be documented.

Experts may think about their portions of the problem using relationships and connections not easily accommodated by established structures. These relationships include feedback loops, complex associations spanning or crossing different facets or dimensions, partially or ambiguously defined influences, vague or indeterminate conditions and dependencies, and complicated networks. Network structures (e.g., Bayesian networks) permit conditional probability types of dependencies with a hierarchical structure, but the logic flow defined by the mathematics is cumbersome and is not easily understood by experts (or analysts) outside of the Bayesian analysis community. Experts should be permitted to define whatever conditional relationship or network necessary without being forced to fit them into a prescribed mathematical rule set or axioms.

When encountering problems with relating poorly known, interacting, continuous processes not suited for established structures, experts do not think of problem features as discrete boxes with definitive connections. For example, a physicist or chemist resists structuring the kinetics of an explosion into sequences of well-defined boxes. This is because of the lack of detailed fundamental knowledge required to "box" and because of the complexities (some poorly known) of the processes involved. The problem of assessing the risk of nuclear deterrence failure may suffer from the same difficulties.

However, even for difficult, amorphous, or ill-posed problems, experts tend to think in terms of some sort of problem structure or framework based on the logic behind their understanding. That structure may be loosely defined, choppy, disjoint, approximate, general, vague, and difficult to record on paper, a whiteboard, or a computer pad/tablet. Detailed probing into the expert's thinking may be required to elicit a rough draft that mimics the expert's thoughts about their portion of the problem. During the elicitation reasons for the "ill" nature can be discovered, investigated, and documented. As more knowledge becomes available in time, that understanding and documentation can be updated.

For the nuclear deterrence failure problem, it would be interesting to determine whether any expert has a structure and logic flow in mind for the whole problem. If such organization exists in an expert's thinking, it may be at only a general level, oversimplified, or beyond the expert's subject proficiency. Examples of this in the literature include Bunn's general structure cutting across multiple areas of expertise without eliciting from different experts[46] and Hellman's acknowledgment that his structure, a mathematical model, is not formulated from any expertise and is for illustration purposes (see chapter 8). Instead, it is anticipated that experts may have only structural ideas about their particular subject-matter portion of the whole problem. Different experts can work together to construct the whole problem during a group elicitation. Utilizing the decomposition principle goes a long way toward understanding aspects of an ill-defined problem structure.

Structure in the Knowledge

Whether an expert-supplied or an established structure is used, the data, information, and knowledge used to populate the structure may have internal patterns, association structures, and redundancy or dependency relationships. In other words, the knowledge can have a structure that is worth understanding and using.

Understanding and using any structure in the knowledge is a separate exercise from structuring the problem. Knowledge structuring is more of an analysis activity than an elicitation activity. Nonetheless, experts must work closely with analysts in seeking understanding of the knowledge structure. Neural networks, factor analysis, cluster analysis, statistical covariance, and correlation structures are some commonly used techniques to uncover data structures. Although many of these require large amounts of numerical data, some can still be used for smaller amounts of more general knowledge.

For example, an expert examining the results of a neural network or factor analysis of historical events data might be able explain the data structure found from this analysis by seeing an association or reason that was previously not considered. That reason or association would then be an added feature to the problem structure.

Analysis for structure in the data, information, or knowledge (e.g., historical record) is recommended, when possible, because understanding the data/knowledge structure often provides insights into the problem structure. Even organizing all the available data, knowledge, and information into files, spreadsheets, or perhaps databases reveals problem structure. For the nuclear deterrence problem, it is unlikely that much analysis would be possible because of the sparse amount of data, information, and knowledge available. However, some collection and organization of the applicable data, information, and knowledge will be necessary for simple bookkeeping. This effort can reveal structure in the knowledge, which might, in turn, be useful for considerations about the problem structure. If the structure in the knowledge is inconsistent with the problem structure, the reasons for this conflict should be understood.

Eliciting a Structure

The formal elicitation principles from the first section of this chapter have been applied to eliciting a structure from experts.[47] Eliciting a problem structure is an iterative process; it is common to start, stop, restart, redo, and rework. What follows is a brief description of how to elicit a problem structure and some of the difficulties involved relating to the problem of assessing the risk of deterrence failure.

Elicitation can be done with each expert or with a group of experts. The former is advantageous for understanding how each expert views their portion of the ill-posed problem. The latter is advantageous for the deterrence problem because different experts will be needed for different aspects of the problem. In a group setting, these experts can discuss how their different areas fit together to complete the whole problem structure.

Such interactions often reveal new understandings that cut across different aspects of the problem.

The first step in eliciting problem structure is to ask the expert(s) to simply write down some of the fundamental components, issues, or aspects of the problem. For nuclear deterrence experts, this would include eliciting their areas of expertise and experience. Defining the problem scope—what may or may not be included—also starts here. Usually this first set of items supplied is at a very general level of detail, representing the basic problem features, facets, subject areas, and historical record. For the deterrence problem, these items could include a time frame (past and future), participants involved (states, groups, leaders), sociopolitical perspectives and agendas, technologies available at the time (including communications, manufacturing, transportation, and detection), scenarios or sequences, and intelligence-gathering capability. Many iterations and refinements might be needed just to get the fundamentals listed down on paper, with no particular organization. Using the decomposition principle helps experts clarify their thinking about the problem while drilling down to the level of detail of their knowledge.

The interviewer should continuously record the expert's verbalizations as the expert works and encourage the expert to think out loud. Elicitation probing methods should be used to get the experts to supply reasons behind their thinking. The interviewer may have to encourage experts to think about the unthinkable (e.g., nuclear war), to think beyond their experience (e.g., the use of nuclear weapons), and to go outside their comfort zones, countering anchoring bias.

It may or may not be appropriate to instruct experts to "box" their supplied information. Whether to do so is the experts' choice. It is appropriate to permit experts to separate or group some items even at this early stage. For example, an expert may be recording multiple activities and events that can be organized into different scenarios leading to potential nuclear weapon use.

At any point, the expert may want to begin denoting associations, sequences, relationships, influences, causalities, or dependencies among items recorded on paper. Again, these relationships should be identified and designated in whatever form or format the expert desires. Colors, shapes, lines, arrows, highlighting, using different pages, or cutting and pasting are a few helpful methods. For example, an expert may have listed several socioeconomic and political factors necessary for any state or terrorist group to consider when committing to the acquisition of a nuclear weapon. The expert now wants to distinguish and organize these factors according to which particular state and which particular group.

Connections or associations among items may be difficult to define and characterize because of the uncertainty in their relationships. The difficulties and uncertainties expressed by the expert should be recorded. To aid the expert in these determinations, some common relationships among two generic items, A and B, include:

- **Cause and effect (A causes B).** For example, a 9/11 terrorist-type attack (A) causes Americans to become incensed (B).
- **Dependence (A is conditioned on B).** For example, a country will not impose economic sanctions (A) unless the United Nations agrees (B).
- **Implication (A implies B).** For example, Israel's past policy of preemptive strikes (A) implies it will strike preemptively again (B).
- **Subset (A is included in B).** For example, an attack on a NATO nation (B) is an attack on the United States (A).
- **If–then rule (if A, then B).** For example, if the United States determines who originated the attack (A), then it will retaliate against them (B).
- **Series or intersection (A and B).** For example, the Joint Chiefs will transport troops (A) and send a carrier group (B) to the area.
- **Redundancy or union (A or B).** For example, the Army will either deploy special forces (A) or use drones (B).
- **Correlation (A behaves like B or the opposite of B with or without known causality).** For example, as world economics gets worse (A) the likelihood of attacks (B) increases.
- **Inference (A is inferred by B).** For example, examining the debris and isotopes from a nuclear blast (B) provides evidence to infer its country of origin (A).

During the initial portion of the elicitation for problem structure, the expert should be thinking freely and freely recording aspects, features, and issues of the problem, including the first round of relationships and associations. Any difficulties in formulating or recording these should be noted and completion should be postponed. Likewise, focus on organization or logic flow is not necessary yet and may still be too ill posed. Organization and flow may become clearer as the elicitation progresses.

To distinguish details from general items, an iterative course in the elicitation is helpful. Start with the most general level of detail and then elicit more specific issues, facets, ideas, etc. However, getting specific can quickly burden and complicate the expert's thinking, resulting in inconsistency and in reaching knowledge voids or gaps. An alternative strategy is to stop drilling down in detail and generalize once more. Guide the expert, without fatiguing them, to iterate between thinking about the general to the specific and back again as often as required. The reason for this is to aid the expert in keeping the bigger picture in mind while decomposing the problem into details. For example, the bigger picture might be a particular assumed political environment, affecting the detailed issues, events, and outcomes within it.

Permit the expert to leave holes, blanks, and question marks as placeholders for things not easily characterized or known. These voids can be addressed in a later iteration or after the expert has had a chance to ponder, calculate, or research. Other experts may have to be used to fill in these gaps. Alternatively, these holes, blanks, or questions may never get completed because the knowledge simply does not exist. This lack of knowledge is part of the uncertainty inherent in the problem. The same is true of describing associations. Some may remain vague or ill defined. A simple notation suffices such as "I know A is somehow related or important to B, but I just don't know what that relationship is."

The experts should not try to complete the structure in one elicitation session or even one day. Time between sessions gives the experts a chance to rethink and reorganize, preventing cognitive overload. It is not uncommon for the expert to return to the next elicitation session and completely start over. However, the previous work should not be discarded.

It may be possible to establish some major general features in one session and then develop the structures for each of these in subsequent sessions. The level of detail may not be the same for all features of the problem. Some aspects of the problem may be known in great detail. Others may be listed at only the most general level, with nothing known in detail. For example, the actions of some newly formed terrorist faction would difficult to detail.

An expert may designate some issues, relationships, or portions of the problem for other experts to structure. Bringing in new experts brings in new knowledge, but it can also bring in disagreements about how to structure the problem. Resolution of disagreements between experts takes time; however, it usually provides valuable insights for the interviewer, analyst, and the experts. Some disagreements may not be resolved. Those unresolvable differences reflect the large uncertainty in the state of knowledge for that issue.

Some Difficulties in Eliciting a Structure

A few difficulties involved for ill-posed problems such as the risk of nuclear deterrence failure are described below.

Experts may run into dead ends where their thoughts cannot be depicted because of complexities or lack of knowledge or because they have not thought about how to structure aspects of the problem before. Dead ends are legitimate. There is a difference between forcing experts to supply knowledge that does not exist and asking them to use their expertise beyond their personal experience or comfort zone. The former results in biased, fictitious responses, whereas the latter minimizes anchoring bias. For example, asking experts to consider circumstances according to their knowledge for when a state leader might detonate a nuclear weapon on US soil may be uncomfortable but can be within the expert's capability. Demanding that the experts read the leader's mind is unreasonable.

The unknown or little known details (high uncertainty issues) can hinder thinking and even contribute to cognitive overload. The same is true for poorly understood relationships, such as degrees of association or dependency. For example, an expert may state something like "I just don't know why country A nearly always votes like country B in the United Nations, but it just does."

The expert may have to explore various ways of depicting the problem, which can be frustrating and time consuming. The expert may find it difficult to think aloud or record on paper their thoughts about the structure. These difficulties are not necessarily due to some inability of the expert, but they stem from the complexity, knowledge-poor nature, and high uncertainty inherent in the problem.

The elicited structure may make sense only to a single expert, reflecting their way of thinking about the problem. Their structure is conditioned on the way that expert thinks. That conditioning makes it difficult to combine structures from different experts or to combine substructures of parts of the problem elicited from different experts. After the structuring elicitation(s), it is permissible and often beneficial for experts to see how others view the same problem or parts of it. Facilitated group elicitations can accomplish this as long as bias minimization techniques are used.

Because the elicited structure is personal and expert specific, experts may request that their names be kept anonymous or not associated with specific details. Honoring such requests is part of good formal elicitation practice.

At the end of the elicitations of problem structure, there may be multiple versions from multiple experts. Each may have holes, blanks, and unresolved questions. For the problem of assessing the risk of nuclear deterrence failure, if this is not the result, something went wrong with the elicitations. High uncertainty, especially from lack of knowledge, manifests itself in what appears to be an inconsistent mess (or even a waste of effort) for problem structure. Getting the experts to think deeply and deliberately is necessary to understand and capture the current state of knowledge about the problem—as poor as that current state of knowledge may be.

It is possible that the final expert-supplied structure(s) may not completely specify how all the pieces of the problem go together so that the likelihood and consequence constituents of risk can be assessed. Even with this situation, the risk constituents can be determined conditioned on the fact that pieces are missing or aspects are temporarily removed. A conditional risk assessment is better than no assessment. Those conditions made to assess risk should be noted as the focus for future investigation and understanding when or if the required knowledge becomes available. Only then can an unconditional risk assessment be completed.

Alternatives to Established Approaches

Eliciting problem structures from experts is one of the alternative approaches for problem structuring. Other approaches could prove useful for the risk of nuclear deterrence failure. Some suggestions follow, including enhancements to established methods and new, untested ideas.

Fuzzy Sets and Logic

Since 1965, when Zadeh published his landmark paper,[48] many mathematical and logic-based applications, based on crisp sets and binary logic, have been enhanced by using fuzzy sets and logic. For example, probability-based decision analysis, reliability, and risk analysis have become fuzzy decision analysis, fuzzy reliability, and fuzzy risk analysis. Fuzzy sets and logic accommodate a different type of uncertainty than probability theory does. That uncertainty is called by many names: an imprecision uncertainty, the uncertainty of classification, linguistic uncertainty, and rule-based relationships (e.g., if–then rules) uncertainty. Uncertainty of classification is found in formulating the "boxes" and in determining their connections in problem structuring. Linguistic uncertainty is applicable to the quantification and interpretation of words (e.g., *better*, *not likely*, *maybe*). These uncertainties, along with rule-based relationships, could be prevalent in the risk of the nuclear deterrence failure problem.

While it is doubtful that an expert would have experience with fuzzy sets, their elicited thinking may be conducive to its use. It is the job of the interviewer and/or analyst to make the expert aware of fuzzy constructions when the expert appears to be thinking about the kinds of uncertainties and relationships best handled with Zadeh's fuzzy mathematics.

Structuring methods (including established ones) need not be restricted to binary outcomes (e.g., failure or success) or crisp logic. Actually, human thinking, decisions, and actions tend to follow fuzzy logic better than crisp logic. This is because fuzzy logic permits degrees of performance, likelihood and consequence, and partial decisions and actions. For example, an expert having difficulty deciding how several events are related can describe multiple connections of varying strengths and degrees. Many connections listed in the "Eliciting a Structure" section contain words that lack binary meaning. Fuzzy connections are not restricted to sum to 1.0 as in probabilistic event trees.

Fuzzy structures are potential alternatives to established structures based on crisp logic.[49] Using fuzzified versions of established structures requires more elicitation time because of the different types of uncertainties involved in characterizing degrees of associations and many rules governing those.

It is common practice to characterize the constituents of risk using green, yellow, and red shading to indicate low, medium, and high levels, respectively, for likelihood and consequences, as shown in Figure 3.2. However, this representation actually depicts fuzzy sets for the risk constituents. For instance, the risk denoted by the X has degrees of both yellow and green but is mostly green. Thus, X partially belongs to the yellow (medium) set and more to the green (low) set. The risk at X cannot be precisely assigned to either the low or the medium sets. The same is true of the risk denoted by the asterisk, which has most membership in the red (high) set but some in the yellow (medium) set.

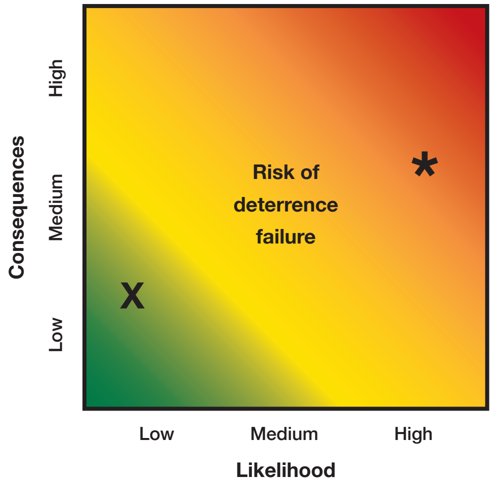

Figure 3.2. Fuzzy shades for the constituents of risk.

Uncertainty Perspective

Recent developments in risk assessment have included the use of possibility theory instead of probability theory because of the type of uncertainty that possibility addresses (which probability does not) and because humans are poor probabilistic thinkers.[50] Established problem structuring approaches (e.g., trees) used in probabilistic risk assessments can be modified for using possibilities instead of probabilities.

Because the deterrence problem has such a high degree of uncertainty attributable to lack of knowledge, one could imagine a structure for the problem based on these uncertainties. The exact form or nature of this uncertainty-perspective structuring is speculation at this point; however, experts could again be called on to determine it. The idea is that experts would be asked to view the problem and its aspects in terms of uncertainties instead of the event/issue perspective. The challenge would be that experts should be comfortable with thinking about uncertainties, and most experts are not.

Regardless of the problem structure used for assessing the risk of deterrence failure, managing the different types of uncertainties will be a challenge.

Information-Gap Structure and Triad Principles

The JASON study correctly concluded that rare events could not be predicted because of the lack of data and the lack of specific information about such events.[51] This conclusion actually is based on a type of uncertainty called nonspecificity.

Nonspecificity is the uncertainty from relying on the general to determine the specific. For example, with so few and so varied kinds of attacks (events), the best an expert could predict for the future would be a rate or average time until the next attack but with no specification about what, where, or how it would happen. As the JASON study concludes, predictive capability suffers from this uncertainty. This conclusion is one of three important principles composing the triad.[52]

The triad involves three dependent concepts: predictability, robustness to uncertainty, and fidelity of models or theory to data. Simply stated, for any given problem with an information-gap structure, all three cannot be simultaneously optimized.[53] Trade-offs or sacrifices must be made for one or two to improve the third.

The information-gap structure is a decision-making and an uncertainty-structuring approach. It is general enough to permit the use of general information theories (including probability) to characterize the different types of uncertainties. The information-gap approach focuses on the relationships in the triad, and their trade-offs could prove useful for structuring the conclusions and results of a risk assessment for presentation to decision- and policy-makers.

Structuring Knowledge Sources

Research is currently in progress focusing on the uncertainty involved in structuring the data, knowledge, and information available for populating a problem structure.[54] For knowledge-poor problems, additional knowledge is sought from similar and relevant problems. Using other knowledge sources induces additional uncertainty based on how close these other sources are to the problem of interest. For example, an important issue in the deterrence problem is assessing close calls. Another knowledge source that could be useful for understanding nuclear close calls would be to understand close calls in historical military attacks (see chapter 2). Knowledge source structuring can be considered a knowledge-integration-structuring approach and is described in chapter 8.

Assessing Risk with Expert Knowledge

Regardless of the structuring approach for the problem or for the knowledge, the high uncertainty and knowledge-poor nature of the risk of deterrence failure problem necessitates eliciting knowledge from multiple subject-area experts. There is a long history of using expert knowledge in risk assessment. Perhaps the best-known and earliest use of expert knowledge in data-sparse applications was the WASH-1400 study, also known as the reactor safety study, considered the birth of probabilistic risk assessment.[55] Experts contributed their knowledge and expertise for this study but did so without formal elicitation. To remedy this, the US Nuclear Regulatory Commission sponsored research into the development of formal elicitation and analysis techniques. WASH-1400 was replaced in 1991 with NUREG-1150, which used formal elicitation.[56]

Evaluating Likelihood

As shown in Figure 3.2, the first constituent of risk is determining the likelihood, which is often (perhaps too often) expressed as a probability. When data, history, or models are available, they can produce estimates for likelihood or probability. When they are lacking, expert knowledge becomes the source for estimating likelihood. Recall, it is best to avoid asking experts for probabilities, especially if they are not accustomed to thinking in those terms. However, it is often reasonable to elicit general likelihoods.

Likelihoods are estimated or elicited for the many issues, items, and parts of the problem in a risk assessment. Hence, they are common to the entire problem structure. The problem structure specifies how these likelihoods are to be combined together, resulting in the overall likelihood required for calculating risk. Uncertainties attached to these likelihoods must also be combined through the structure. Again, the source of these uncertainties may be solely from the experts' experience and knowledge.

Evaluating Consequences

The second constituent of risk is determining the consequences, as shown in Figure 3.2. A common form, quantity, or standard of these is less obvious because consequences stem from different subject areas: loss of life, damage to property, cost, time, and perception. A utility or utility function is often formulated to transform these different consequences to a common scale or measure of value or worth.[57] Sometimes a dollar value is used as a common measure of utility.

Consequences of deterrence failure are particularly devastating—nuclear weapons exchange or nuclear war. While these are difficult to evaluate and estimate, comparative techniques, such as Saaty's Analytic Hierarchy Process, and formal elicitation techniques aid the expert in thinking about the unthinkable.[58]

Summary

Assessing the risk of nuclear deterrence failure is a complex problem covering multiple subject areas. Common to these subject areas are sparse or lacking data, lacking theory or models, high uncertainty, and involvement of human behaviors and decisions. Because of these difficulties, analysts must rely on the use of experts and formally elicited expert knowledge. Established problem structuring and framework methods (e.g., logic or block diagrams) may not be appropriate and may be inconsistent with the way experts think about the problem or their portions of it.

An alternative approach for structuring, framing, and/or organizing the ill-posed deterrence problem is to elicit the structure from the experts. The same formal elicitation techniques briefly described in the first part of this chapter also apply to eliciting problem structure described in the second section. These bias minimization techniques help ensure that the knowledge gathered is of the best quality.

Qualitative or quantitative knowledge can be accommodated, permitting some analysis and drawing of conclusions. Elicited uncertainties can also be qualitative or quantitative. There are theories that characterize these various kinds of uncertainties consistent with experts' thinking; however, these theories present some analytic difficulties when used together.

For the challenging problem of assessing the risk of deterrence failure, an analyst should rely on an expert-oriented structuring of the problem and should use all available sources of data, knowledge, and information. The integration approach necessary to analyze such a structured problem and to draw conclusions is discussed in chapter 8.

In summary, assessing the risk of nuclear deterrence failure relies on the existing state of knowledge of the experts in its subject areas. Eliciting that knowledge with established formalism for minimizing biases is feasible, as outlined in this chapter. What is described is an expert-oriented, expert-driven methodology. Because knowledge is constantly evolving, it is necessary to periodically elicit experts to update how their understanding and cognitive processing has changed with new information and knowledge. For this updating, it is vital to retain all material gathered in all the elicitation sessions.

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Chapter 4
Probabilistic Risk Assessment

Martin E. Hellman

Probabilistic risk assessment (PRA) can provide a quantitative estimate of risk for catastrophes that have not yet occurred by analyzing sequences of events that can lead to that event—in our case a major nuclear war. PRA is also useful for reducing that risk by identifying potential paths to nuclear weapons use that otherwise might escape attention. While PRA has been embraced in nuclear power, spaceflight, and other engineering fields, there are significant challenges to transferring that experience to the risk of nuclear deterrence failing. In-depth PRA of nuclear deterrence holds promise but requires significant further research. Fortunately, a simple approach can be used to show that the risk of nuclear deterrence failing currently appears to be on the order of 1 percent per year. It is hoped that this surprising result will cause society to invest in the larger efforts required for in-depth analysis, both to estimate and to reduce the risk of a major nuclear war.

The debate over our nation's nuclear posture has been carried out largely in a fashion inconsistent with the issue's importance. On the one hand, former secretary of defense James Schlesinger stated that we will need to depend on nuclear deterrence "more or less in perpetuity," while former secretary of defense Robert McNamara claimed that doing so "will destroy nations."

This chapter addresses the role that probabilistic risk analysis, or PRA, can play in the nuclear posture debate.

Can Probabilistic Risk Analysis Be Applied to Nuclear Deterrence?

By fostering a culture of risk awareness, PRA (also known as quantitative risk analysis, or QRA) has improved safety and illuminated previously unforeseen failure mechanisms in areas as diverse as nuclear power reactors, space systems, and chemical munitions disposal.[1] In a more embryonic form, it also has been applied to nuclear proliferation[2] and nuclear terrorism.[3] It is therefore surprising that PRA has only recently been applied to nuclear deterrence[4] and has not yet been seriously considered when formulating US nuclear strategy.

Of course, PRA as applied to a nuclear power plant cannot be directly applied to a potential failure of nuclear deterrence. A cooling pump in a nuclear power plant can usually be assigned a binary value: either it is functioning properly or it has failed. In contrast, the crises that are part of many accident chains leading to nuclear war take on a continuum of values, and it is often difficult to assess which of two crises created more risk. Another difficulty in applying the standard PRA approach to nuclear deterrence is the large number of human factors affecting the risk of a nuclear war.

Even so, PRA is very useful for deciding whether McNamara[5] or Schlesinger[6] was right, and this chapter illustrates how to use PRA to do just that.

The problem becomes more manageable when it is recognized that even crude estimates, to just one or two orders of magnitude, can be useful. If the failure rate of nuclear deterrence were 1 in 100,000,000 per year—comparable to the probability of an extinction-level asteroid hitting Earth—then that level of risk would be acceptable. But, if the failure rate were 1 percent per year, there would be worse-than-even odds that a child born today would experience a nuclear war over their expected lifetime of approximately eighty-five years. As this extremely wide range of possible failure rates shows, even an order-of-magnitude estimate might be useful for refining the debate.

Definitions and Models

Before proceeding, a few definitions and comments on modeling are in order.

First, for ease of exposition, this chapter will use the terms *failure of nuclear deterrence*, *nuclear war*, *major nuclear war*, and *full-scale nuclear war* interchangeably, even though a nuclear war could stay limited.

Second, risk is usually defined as a function of both consequences and probability, whereas this chapter will use *the risk of a major nuclear war* to mean its annualized probability. While the latter phrase is more correct from a technical perspective, it is a bit cumbersome. Further, the consequences of a full-scale nuclear war would be so catastrophic that, for its risk to be at an acceptable level, its annualized probability would have to be acceptably small. While this chapter uses *the risk of a nuclear war* as an abbreviation for its annualized probability, it will never use the imprecise phrase *the probability of a nuclear war.* That phrase makes no sense unless it is referenced to a specific period of time, such as one year in the case of the annualized probability.

Third, this chapter defines the era of nuclear deterrence as starting in 1955, when it is estimated that the Soviet Union had almost 3,300 warheads and the United States over 2,400.[7] A slightly earlier or later date could be chosen but will not change the substance of the arguments that follow. With that convention, we have lived in the nuclear deterrence era for the last sixty-six years, a figure that will be used henceforth.

Fourth, this chapter uses a time-invariant model. Looking to the past reveals significant variations in the risk of nuclear deterrence failing, with the worst month of the 1962 Cuban missile crisis likely encompassing more than 10 percent of all the risk over the last sixty-six years, even though that one month accounts for only 0.13 percent of that era. But, looking to the future, we have little or no idea when such periods of high risk might occur, necessitating a time-invariant model. Even so, past history is useful for estimating future risks. For example, the events in appendix A indicate that the risk associated with a major crisis, comparable to the one in 1962, is such that the world would have to be extremely lucky to survive more than a few such crises, a possibility that will be treated later in this chapter.

Fifth and last, models can only approximate reality and that caveat applies to everything said here. But models are still useful for resolving whether McNamara or Schlesinger was right about the risk of nuclear deterrence failing. A reasonable model is a much better guide for developing our nuclear strategy than a guess or a gut-level reaction.

A Teetering Nuclear Coin

At first, it might seem that there is inadequate information for estimating the risk of nuclear deterrence failing since nuclear weapons have not yet been used in a war in which more than one nation possessed them. However, PRA can glean more information from the available data than might first appear possible.

One can think of each of the sixty-six years in the nuclear deterrence era as a coin toss, with tails meaning that a nuclear war did not occur that year and heads meaning that one did occur. To date, we have seen sixty-six tails in a row, making it difficult to estimate the probability of heads—the annualized probability or risk of a nuclear war.

But it is possible to reclaim valuable information by looking not only at whether each toss showed heads or tails but also at the nuances of how the coin behaved during that toss. If all sixty-six tosses immediately landed on tails without any hesitation, that would be evidence that the coin was more strongly weighted in favor of tails and, thus, additional evidence that Schlesinger was right. Conversely, if any of the tosses teetered on the coin's edge, leaning first one way and then the other before finally showing tails, that would be evidence in favor of McNamara's position.

In 1962, the nuclear coin clearly teetered on its edge, with President John F. Kennedy later estimating the odds of war during the Cuban missile crisis at somewhere between one in three and even.[8] Other nuclear near misses are less well known and had smaller chances of ending in a nuclear disaster. But even a partial hesitation before the nuclear coin lands on tails provides useful information. Appendixes A, B, and C enumerate a number of times that the nuclear coin hesitated before landing on tails, with appendix A listing events during the Cuban missile crisis; appendix B, other events during the Cold War; and appendix C, events that occurred after the Cold War ended.

PRA Explained via the Concorde SST Crash

While, as noted above, there are major differences between PRA as applied to physical systems and as applied to nuclear deterrence, the July 2000 crash of the Concorde SST (short for supersonic transport) is useful for demonstrating some similarities. Just as the success to date of nuclear deterrence might be used to justify Schlesinger's belief that we will need to depend on that strategy "more or less in perpetuity," before its fatal crash the Concorde appeared infinitely safer than the subsonic fleet, with absolutely no fatalities. But, because there were so few Concorde flights, a *Washington Post* article noted that the one fatal crash, "transformed the supersonic aircraft from the safest plane on earth to the most dangerous, statistically speaking."[9]

Of course, hindsight is 20-20, and the real question is whether the Concorde's risk could have been foreseen before the crash. As intimated in the previous section, PRA gleans information from the available data by looking not only at catastrophic failures but also at partial failures—excursions into accident chains that have the potential to result in catastrophe. The fatal Concorde crash involved a four-step accident chain:

1. A tire blew out after striking debris on the runway.
2. The exploding tire ruptured a fuel tank.
3. The leaking fuel caught fire.
4. The fire led to the crash.

Although no Concordes had crashed before July 2000, the fleet had experienced tire failures at a rate between one and two orders of magnitude greater than that of the subsonic fleet, and more than 10 percent of those tire failures resulted in the penetration of a fuel tank.[10] While the above accident chain had never led all the way to a crash, this high rate of excursion down its first two steps should have been a red flag. If a PRA had been performed, it might well have resulted in grounding the Concorde before the crash.

Of course, a PRA would have included other accident chains that could have resulted in a crash, with some examples given in an *Air & Space* magazine article:

> The very day before the crash, Air France discovered cracks in the wings of four of its six aging Concordes. . . .
>
> . . . Aircraft belonging to both companies [Air France and British Airways] had lost parts of their elevons and rudders several times in flight but were able to land safely. In 1998, the Olympus 593 engines were found to have 152 problems in hardware design or other factors, 55 of which were considered "significant risks," and BA and Rolls-Royce initiated a plan to remedy them.[11]

The union of all the accident chains that can result in the catastrophe is called an *event tree*. As the Concorde's example shows, there is often significant, valuable, empirical data about excursions down various accident chains, even before any one of them is traversed all the way to a catastrophe, and a similar situation currently exists for a major nuclear war.

Using PRA to Estimate the Risk of a Nuclear War

The Concorde crash illustrates how the probabilities of steps in an accident chain that have not yet occurred might be approximated from related data. For example, before the fatal crash, the probability that a fuel leak would cause a fire on the Concorde could have been approximated from data from the subsonic fleet or from supersonic military aircraft. Those estimates could be improved by analyzing airflow and ignition sources for those aircraft as well as for the Concorde, and then modifying the first approximations to account for the differences.

A similar approach could have been used to estimate the probability that step four in the accident chain would be traversed if reached, namely that a fire would lead to a crash.

Similarly, we have traveled significant distances into accident chains with the potential to produce a nuclear war, and some of those events are described in the appendixes.

For example, during the Cuban missile crisis, American destroyers attacked Soviet submarines that, unbeknownst to them, were armed with nuclear torpedoes. In the case of one submarine, it was reported (but not until 2002) that the captain gave orders to arm the nuclear torpedo, but was talked down by another officer on board. While it is impossible to assign a precise probability to those events resulting in the use of the nuclear torpedo, if these reports are correct, a number in the 25 percent range would not be unreasonable since one of the two Soviet officers involved wanted to use the weapon.[12] While the nuclear torpedo was not used, the 25 percent estimate is useful for estimating the probability that the Cuban crisis could have gone nuclear due to this one accident chain.

A second major risk was that American decision-makers who advocated invading Cuba did not know—or even give much thought to the possibility—that the Soviets had battlefield nuclear weapons on Cuba to repel such an attack.[13] This was not revealed until 1992[14] and Secretary of Defense Robert McNamara later said, “If the president had gone ahead with the air strike and invasion of Cuba, the invasion forces almost surely would have been met by nuclear fire, requiring a nuclear response from the United States.”[15]

While, again, it is impossible to assign a precise probability to a hypothetical American invasion being repelled by Soviet tactical nuclear weapons, the following factors should be included when formulating an estimate.

- Early in the crisis, most of the participants, including President Kennedy, favored air strikes on the missiles to be followed by an invasion of Cuba. Fortunately, Kennedy was able to keep the crisis secret for a week by pressuring newspapers to keep stories from running. As he and his advisors thought things through without public pressure "to do something," some of them, including the president, recognized the danger inherent in military attacks and instead moved to supporting a naval quarantine or embargo. Would today's much more diffuse media bow to such pressure?
- On November 16, 1962, more than two weeks after Khrushchev had agreed to remove his missiles from Cuba, the Joint Chiefs of Staff (JCS) sent a memorandum to President Kennedy stating that they were "glad to report that our Armed Forces are in an optimum posture to execute CINCLANT OPLANS 312-62 (Air Attack in Cuba) and 316-62 (Invasion of Cuba)."[16] Earlier, during the crisis, the JCS had met and recommended air strikes to be followed by an invasion of Cuba.[17]
- There are two versions of Kennedy's televised speech in which he told the American people of the crisis and his response. Having eventually chosen a naval quarantine or embargo of Cuba, his speech as delivered[18] told of that action. But another version[19] of the speech also was prepared, which told the nation that air strikes had been carried out and intimated that an invasion of Cuba was imminent to prevent new missiles from being deployed. It read in part:

  > With a heavy heart, and in necessary fulfillment of my oath of office, I have ordered—and the United States Air Force has now carried out—military operations, with conventional weapons only, to remove a major nuclear weapons build-up from the soil of Cuba. . . . Further military action has been authorized to ensure that this threat is fully removed and not restored.

Another Cold War example of an accident chain that could have led to nuclear war is the October 1961 Berlin crisis. A US Army history states that, "tensions . . . nearly escalated to the point of war."[20]

Appendix C shows that we continued dangerous excursions down such accident chains even after the Cold War ended. During the 1999 Pristina Airport crisis in Kosovo, a British three-star general refused to follow an order from an American four-star that he feared might lead to combat between NATO and Russian troops. Their accounts agree that a heated argument ended with the British general telling the American, "Sir, I'm not starting World War III for you."[21]

A PRA would also consider nuclear wars with smaller, though still catastrophic, consequences. For example, India and Pakistan combined have approximately three hundred nuclear weapons,[22] which some studies[23] have indicated could kill up to a billion people through ash and dust interfering with photosynthesis for an extended period of time on a worldwide basis. India and Pakistan have traversed the early steps of accident chains repeatedly, fighting wars in 1947, 1965, 1971, and 1999; India suffered a major attack by Pakistani-based terrorists in November 2008; and Kashmir is experiencing a renewed wave of violence.

Further, a nuclear war between India and Pakistan would create an international crisis that would increase the risk of a war involving the United States and either Russia or China. This illustrates yet another advantage of applying PRA to the risk of a major nuclear war. It would highlight the coupling between that risk and lesser risks such as a limited nuclear war, nuclear terrorism, and conventional war. Yet, many Americans think that our conventional superiority would allow us to prevail in a war with Russia or China. President Obama even referred to Russia as "a regional power."[24]

Another similarity between the PRA that could have been performed before the Concorde disaster and the one that could be performed now concerning nuclear deterrence relates to estimating the probabilities of accident chain steps that have not yet been traversed.

Just as subsonic and military fires and crashes due to fuel leaks could have provided some information about the probability of the last two steps in the Concorde's fatal four-step accident chain, a nuclear deterrence PRA could look at how frequently non-nuclear deterrence failed, with one possible example being the start of World War I. (Some elements within Russia wrongly thought that backing Serbia would deter the kaiser from coming to Austria-Hungary's aid.) While that occurred before the nuclear era, the effect on the czar and his family was equally catastrophic.

War games that ended badly also could be used to provide data for estimating the probabilities of the last, as yet untraversed steps of accident chains leading from a crisis or conventional war to nuclear war. Appendix A lists one such war game (Proud Prophet in 1983), while appendix C includes several such unintended escalations. Most recently, in 2018, then USSTRATCOM commander US Air Force General John Hyten described a war game that ended badly, "meaning it ends with global nuclear war."[25] It would help if the results from more of these war games were declassified, either directly or through a Freedom of Information Act request.

Accident chains that stopped short of a full-blown crisis can sometimes be used to estimate the risk of such a crisis or of a conventional war. For example, during the 1999 Pristina Airport crisis described in appendix C, the British three-star refused an order that risked combat with Russian troops. Given that the American four-star giving the order thought the risk was worth taking, one might assign an initial rough estimate of 50 percent to the probability that the three-star would have thought similarly to the four-star. (Of two high-ranking NATO officers, one thought that way, which is 50 percent.) Additional analysis would be needed to estimate the probability that taking that action would have resulted in combat and a full-blown crisis.

Using PRA to Reduce the Risk of a Nuclear War

The Concorde provides another lesson for nuclear deterrence: even without estimating the probability of a catastrophic failure, accident chains can highlight risks that are currently being overlooked or inadequately considered. Using PRA to reduce the risk of a nuclear war is at least as important as using it to estimate the risk of that catastrophe.

In the case of the Concorde, the high failure rate of tires should have attracted more attention than it did, with or without an estimate of the overall risk. Similarly, we should be working harder to detect and correct misinformation about adversaries, especially those with nuclear weapons or which might acquire them. For example, in 2008, vice presidential candidate Sarah Palin said that we should be prepared to go to war with Russia over its invasion of Georgia, even though it was later established that Georgia fired the first shots.[26] A more recent example is Timothy

Morrison's testimony at President Trump's first impeachment trial, where he said, "The United States aids Ukraine and her people so that they can fight Russia over there, and we don't have to fight Russia here."[27] The risk of having to fight Russians on American soil seems remote, yet there has been little questioning of Morrison's statement. Worse, it has been repeated as if it were an established fact.

There are a number of other risks that a PRA would highlight that should be reduced if possible, including the following.

Alliances. Alliances played a major role in escalating the 1914 assassination of Archduke Ferdinand from a relatively minor incident into a catastrophic world war. NATO has the same potential; the former head of the policy and planning staff in the German Ministry of Defense, Vice Admiral Ulrich Weisser, warned in 2007 that, "Moscow also feels provoked by the behavior of a number of newer NATO member states in central and Eastern Europe. Poland and the Baltic states use every opportunity to make provocative digs at Russia; they feel themselves protected by NATO and backed by the U.S."[28]

A careful analysis should be undertaken to strengthen aspects of America's alliances that reduce risk while curtailing those that increase it.

Delegation of authority. In the 1964 dark comedy *Dr. Strangelove*, a rogue American Air Force general orders his bomber wing to attack the Soviet Union. When the president learns of this, he objects, saying "I was under the impression that I was the only one in authority to order the use of nuclear weapons." He is told that, while he is the only one with the *authority* to launch a nuclear strike, the *ability* to do so is possessed by others further down the chain of command "to discourage the Russkies from any hope that they could knock [you] out . . . and escape retaliation." That decapitation-strike dilemma still exists today.

The delegation-of-authority problem is present in conventional conflicts as well. During the 1961 Berlin crisis, when Soviet and American tanks faced off at Checkpoint Charlie, each tank commander had the ability to start a firefight that would have increased the risk of war, including escalation to nuclear war. And, during the 1999 Pristina Airport crisis mentioned earlier, a three-star general refused an order from a four-star because he feared following the order might start World War III. In both cases, conventional actions that could be taken by a military officer had some risk of escalation to nuclear war.

Domestic politics. On October 16, 1962, the first day that President Kennedy and his advisors learned that Soviet nuclear missiles were being deployed to Cuba, Secretary of Defense Robert McNamara admitted that, "I don't think there is a military problem . . . This is a domestic, political problem."[29] President Kennedy said much the same thing that day: "It doesn't make any difference if you get blown up by an ICBM flying from the Soviet Union or one from 90 miles away."[30]

Similar problems exist today, and their associated risks should be minimized.

Lack of critical thinking. Also on October 16, 1962, President Kennedy expressed shock at Khrushchev's recklessness in deploying nuclear-armed missiles so close to our shores. Forgetting that he had deployed similar missiles in Turkey just months earlier, JFK argued, "It's just as if we suddenly began to put a major number of MRBMs in Turkey. Now that'd be goddamn dangerous." Kennedy's national security advisor, McGeorge Bundy, had to remind him that we had done exactly that. Then, instead of seeing Khrushchev's move in a new light, Kennedy and his advisors used tortured logic to portray the Soviet's nuclear missile deployment in Cuba as fundamentally different from ours in Turkey.[31]

A 1995 USSTRATCOM report, *Essentials of Post-Cold War Deterrence*, even recommended that

> it hurts to portray ourselves as too fully rational and cool-headed. The fact that some elements may appear to be potentially "out of control" can be beneficial to creating and reinforcing fears and doubts within the minds of an adversary's decision makers. This essential sense of fear is the working force of deterrence. That the US may become irrational and vindictive if its vital interests are attacked should be part of the national persona we project to all adversaries.[32]

Mental instability in leaders. Potential instability in leaders of nuclear-armed nations has a long history; for example, James Forrestal died of an apparent suicide on May 22, 1949, less than two months after he stepped down as secretary of defense.

Along with a number of other celebrities, President Kennedy received massive doses of amphetamines from Dr. Max Jacobson.[33] Potential side effects of amphetamine use include euphoria, anxiety, aggression, grandiosity, and paranoia. In chronic or high doses, such as Kennedy received, amphetamine psychosis is also possible. In 1969, a Jacobson patient died of "acute and chronic intravenous amphetamine poisoning," according to the medical examiner. Jacobson's medical license was revoked in 1975.[34]

President Nixon had a drinking problem. For example, on October 11, 1973, British prime minister Edward Heath requested a phone conversation with Nixon during the crisis produced by the Yom Kippur War. A formerly secret telephone conversation shows Nixon's national security advisor, Henry Kissinger, telling his assistant, "Can we tell them no? When I talked to the president, he was loaded."[35]

In his memoirs, Tony Blair admits that while he was prime minister of Great Britain his daily alcohol consumption was "definitely at the outer limit. Stiff whiskey or G&T before dinner, couple of glasses of wine or even half a bottle with it."[36] Boris Yeltsin also had a drinking problem.[37] Someone who could not legally drive a car should not be able to start a nuclear war.

Appendix C's entry for January 8, 2021, details actions that Bob Woodward and Robert Costa's book, *Peril*, claims were taken by General Mark Milley, chairman of the JCS, to ensure that President Trump could not launch a nuclear war as part of an effort to stay in power. As noted in that entry, a spokesman for Milley confirmed most of what is disclosed in the book. Currently the president of the United States has the sole authority to order an American nuclear strike, a power that has been questioned by former secretary of defense William Perry among others.[38]

Preexisting orders. At the height of the Cuban missile crisis, US Air Force Captain Chuck Maultsby became disoriented on a U-2 mission over the Arctic and accidentally strayed deep into Soviet airspace. Soviet MiGs were scrambled to intercept him, while American F-102s from Alaska were sent to protect him. Because of the heightened DEFCON condition, the F-102s' only air-to-air missiles were Falcon missiles with nuclear warheads.[39] Fortunately, Maultsby was able to exit Soviet airspace before he and the nuclear-armed F-102s came in contact with the MiGs.

The risk of preexisting orders can be seen twice in this incident: first, from Maultsby's mission proceeding despite the heightened tensions as a result the crisis; and second, from the F-102s being armed with Falcon missiles out of a concern that they might have to shoot down Soviet aircraft on nuclear bombing missions aimed at our nation.

Some First Steps For Risk Analysis of Nuclear War

A simple, but very useful, first step in applying PRA to a potential failure of nuclear deterrence is to estimate the risk only to an order of magnitude, rather than trying for greater precision. A paper I published in the March 2021 issue of the *Bulletin of the Atomic Scientists*[40] outlines why I estimate that probability is on the order of 1 percent per year.[41]

This order-of-magnitude estimate of 1 percent per year includes a range from a third of a percent to 3 percent per year, but the risk is likely to be upper bounded by 10 percent per year since we have survived sixty-six years of nuclear deterrence without any use of nuclear weapons in war, much less a major exchange.[42]

Similarly, 0.1 percent per year is likely to be a lower bound on the risk since that would imply that current policies could be continued for approximately one thousand years before there would be a significant probability of civilization being destroyed.[43] Over that time period, a simple statistical argument would predict fifteen major crises since there has been one in the last sixty-six years,[44] namely the Cuban missile crisis of 1962, and 1,000/66 = 15 after rounding. In light of the risks during that crisis that are detailed in appendix A, it is likely that at least one of fifteen such crises would result in a nuclear war.

If 10 percent per year is too high and 0.1 percent per year is too low, then the order-of-magnitude estimate for the risk of a major nuclear war is 1 percent per year. As noted above, this incorporates a range from approximately a third of a percent to 3 percent per year, but even a risk of a third of a percent per year would correspond to a 25 percent lifetime risk over the approximately eighty-five-year life expectancy of a child born today. And 3 percent per year would subject that child to a 92 percent lifetime risk.

Several refinements to the above approach are possible.

First, expert elicitation, discussed in detail in chapter 3, could be used to estimate a probability distribution on the rate of occurrence of major crises as opposed to the simple statistical argument used above.

Second, expert elicitation could be used to estimate the probability that such a major crisis results in a nuclear war.

Third, lesser crises could be incorporated into the model. Looking at the past two decades, we had crises in

- 2016, Russian meddling in the US election, resulting in very tense Russian–American relations down to the present day;
- 2014, Ukraine, again extending to the present day;
- 2008, the Georgian War;
- 2011, NATO's attack on Libya;
- 2003, the invasion of Iraq; and
- 2001, al-Qaeda's September 11 attack.

Expert elicitation could be used to estimate the relative severity of these crises, their risk of escalation to major crises, and their expected rate of occurrence.

However, all by itself, the order-of-magnitude approach seems adequate for concluding that McNamara was right when he said that "the indefinite combination of human fallibility and nuclear weapons will destroy nations."[45]

How My Approach Has Evolved

The approach suggested in the last section for estimating the risk of a major nuclear war has much in common with that used in my 2008 paper, "Risk Analysis of Nuclear Deterrence,"[46] but there have been several changes in my thinking that should be highlighted.

One change involves using more complex probability estimates than just intervals—for example, probability distributions derived by expert elicitation.

Another change is that, in my 2008 paper, I estimated the rate of occurrence of potential initiating events for a major crisis and I then estimated the conditional probability that such a crisis would occur, given that the initiating event had occurred. Combining the two quantities into a single estimate of the rate of occurrence of major crises seems more appropriate at this early stage in the risk analysis of nuclear war. With fewer parameters there is less chance for error or unconscious bias to set in.

Another change is to be as accurate as possible, as opposed to using conservative estimates to avoid appearing alarmist. The use of probability distributions instead of intervals helps in that endeavor. For example, in my 2008 paper, I used the interval from 0.01 to 0.5 as my estimate for the conditional probability that a major crisis leads to the use of a nuclear weapon. Just saying that that probability is somewhere in the interval between 0 and 1 conveys no information, while using a probability distribution that extends from 0 to 1 and that was derived from expert elicitation does provide useful information.

Another possible change would be to focus on estimating and reducing just the rate of occurrences of major crises, as opposed to estimating and reducing the annualized probability of a major nuclear war. That approach would eliminate any objections that the analysis is being applied to events that have not yet occurred. The Cuban missile crisis of 1962 provides one data point for estimating the rate of occurrences of major crises and it provides significant data for reducing their frequency.

Concluding Remarks

This chapter has outlined ways that PRA can be used to bring greater objectivity to the debate over nuclear deterrence, as well ways that PRA can reduce the risk of nuclear war.

It presented evidence that the risk of a major nuclear war is on the order of 1 percent per year, so that former secretary of defense James Schlesinger appears to have been dangerously wrong when he said that we will need to depend on nuclear deterrence "more or less in perpetuity." Instead, Robert McNamara appears correct in stating that doing so "will destroy nations."

It should be noted that this chapter is a beginning, not an end point. MIT professor and former Nuclear Regulatory Commissioner George Apostolakis noted that in every application of PRA that he has observed, there is a process.[47] At first, there is skepticism that PRA is of any use. But, as that application of PRA improves over time, skepticism gives way to increased acceptance.

Currently, we are at the beginning of that process for PRA to be applied to nuclear deterrence, and I hope that this chapter will help society realize that the danger it faces is even greater than that from pandemics, where warnings also were largely ignored. Once society recognizes that reality, resources hopefully will become available for more in-depth analyses that can sand off the many rough edges on what was presented here.

I also hope that society will then see the immense opportunity that rethinking national security presents.[48] In 1946, soon after Hiroshima and Nagasaki, Albert Einstein warned that "the unleashed power of the atom has changed everything save our modes of thinking and we thus drift toward unparalleled catastrophe."[49]

Not only can we avoid that unparalleled catastrophe, but we can also build a world that we can be proud to pass on to future generations if we will change our mode of thinking to make it consistent with the realities of the age in which we live. Nuclear weapons, along with other technological advances, have given a new, global meaning to the biblical injunction, "I have set before you life and death, blessing and curse; therefore choose life that you and your descendants may live" (Deuteronomy 30:19).

Acknowledgments: I thank Dr. James Scouras and Dr. Richard Duda for many helpful discussions that contributed to this chapter.

Appendix A. Some Events That Heightened the Risk of the Cuban Missile Crisis

The events described in this appendix are helpful in estimating the level of risk that our nation faced during the Cuban missile crisis, and that it would face if a similar crisis should reoccur.

This is particularly important since participants in the crisis have expressed highly divergent estimates of the level of risk. ExComm[50] member C. Douglas Dillon stated, "we didn't think there was any real risk of a nuclear exchange"[51] and Kennedy's national security advisor McGeorge Bundy estimated that risk at "one in 100."[52] At the other extreme, Kennedy speechwriter Theodore Sorensen quotes the president as saying the odds of war were "somewhere between one out of three and even,"[53] and Secretary of Defense McNamara remembers thinking he might not live out the week.[54]

Estimates made at the time of the crisis also need to be reevaluated in light of information that only became known afterward, such as the first two items below.

American destroyers attacked Soviet submarines that, unbeknownst to them, were armed with nuclear torpedoes. On October 27, at the height of the crisis, American destroyers intercepted a Soviet submarine near the quarantine line and forced it to surface by dropping "practice depth charges." Forty years later, we learned that this and two other Soviet submarines that also were forced to surface carried nuclear torpedoes.[55]

The presence of these nuclear weapons was unknown to the submarine's attackers or to any other Americans at that time.

According to a member of the submarine crew, its captain was under severe physical and psychological pressure; mistook the practice depth charges for regular depth charges; believed that World War III might already have started; and gave orders for the nuclear torpedo to be armed.[56] Fortunately, according to this same crew member, the captain was talked down and admitted a humiliating defeat by surfacing.

American decision-makers who advocated invading Cuba did not know that the Soviets had deployed battlefield nuclear weapons to repel such an attack. While President Kennedy eventually decided on a naval blockade, he and almost all the other American decision-makers initially favored air strikes against the missiles, to be followed by an invasion.[57] None of these decision-makers knew that the Soviets had deployed nuclear-capable battlefield weapons and mating warheads on Cuba to deter and, if need be, to repel such an invasion.[58]

An October 28, 1962, a Top Secret memorandum for the secretary of defense from the Joint Chiefs of Staff concluded "that the only direct action which will surely eliminate the offensive weapons threat is air attack followed by invasion and is, in the long run, the best course of action."[59]

At the height of the crisis, an American U-2 strayed into Soviet airspace, creating a risk that nuclear air-to-air missiles would be used. On October 27, which became known as Black Saturday, a U-2 piloted by US Air Force Captain Chuck Maultsby[60] became lost on an intelligence-gathering mission over the Arctic and accidentally flew into Soviet airspace. MiG fighters tried to intercept Maultsby, while F-102s from Alaska were sent to protect him and escort him home. Because of the crisis, the F-102s' conventional air-to-air missiles had been replaced with nuclear-armed missiles. As noted by Stanford professor Scott Sagan, "the only nuclear weapons control mechanism remaining was the discipline of the individual pilots in the single seat interceptors. The critical decision about whether to use a nuclear weapon was now effectively in the hands of a pilot flying over Alaska."[61] Fortunately, the MiGs never reached Maultsby's U-2 or the nuclear-armed F102s.

An American U-2 was shot down over Cuba. Approximately one hour after Maultsby became lost and penetrated Soviet airspace, US Air Force Major Rudolf Anderson was shot down and killed by a Soviet surface-to-air (SAM) missile while on a U-2 reconnaissance mission over Cuba. Four days earlier, JFK and his advisors had agreed that, if a SAM downed a U-2, the offending SAM site would be attacked.[62] But, when Major Anderson's U-2 was shot down, Kennedy had second thoughts, possibly because our killing Soviet personnel would put Khrushchev in the same escalatory bind in which Kennedy now found himself. Kennedy's reversal infuriated the military.[63]

The United States gave numerous indications that it intended to invade Cuba, causing Castro to tell Khrushchev to launch his missiles preemptively. The goal of a two-week American military exercise involving tens of thousands of military personnel, which started the day before the crisis erupted, was to execute an amphibious assault on a Puerto Rican island whose fictitious dictator was named Ortsac—Castro spelled backward.[64] In the months before the missiles were discovered, representatives, senators and the American media excoriated Kennedy for allowing the Soviet military buildup in Cuba, many demanding an invasion. The September 21 cover story in *Time* magazine argued, "The only possibility that promises a quick end to Castro . . . is a direct U.S. invasion of Cuba."[65] Castro became convinced that an invasion was imminent and, knowing of the Soviet battlefield nuclear weapons, he believed that a nuclear war would follow. He therefore suggested that Khrushchev "should launch a preemptive [nuclear] strike against United States."[66]

Seven months before the crisis, the Joint Chiefs of Staff (JCS) suggested blowing up an American ship in Guantanamo Bay and blaming Cuba to create support for an invasion. In March 1962, the chairman of the Joint Chiefs, Army General Louis Lemnitzer, sent Defense Secretary Robert McNamara a list of proposals known as Operation Northwoods, outlining ways to generate American public support for an invasion of Cuba. One suggestion was to "blow up a US ship in Guantanamo Bay and blame Cuba." Another read: "We could foster attempts on lives of Cuban refugees in the United States even to the extent of wounding [them]."[67]

On the first day of the crisis, at a meeting of President Kennedy and his key advisors, Attorney General Robert F. Kennedy similarly suggested: "We should also think of whether there is some other way we can get involved in this through Guantanamo Bay . . . you know, sink the *Maine* again or something."[68] RFK had made similar proposals at least twice before, on April 19, 1961, and August 21, 1962.[69]

The Joint Chiefs advocated similar proposals during the crisis. In an October 28, 1962, Top Secret memorandum[70] for the secretary of defense, they suggested "a series of provocative actions," including having US destroyers "inadvertently" violate Cuba's three-mile limit; "harass Cuban shipping;" and "incite riots on Cuban side of Guantanamo fence . . . [to] justify our providing military assistance to laborers." The memorandum stated that "the purpose of these actions is to induce the Cubans to fire on US elements, or make some mistake which would make politically acceptable and justify subsequent US air strikes or invasion."

While the above incidents might be hard to comprehend as serious proposals from today's perspective, they fit the pattern of that time, including covert sabotage operations against Cuban targets and assassination attempts on Castro's life. These incidents help explain why Castro and Khrushchev were so fearful of an American invasion.

President Kennedy took actions that extended the crisis for months after the public thought it had ended. After Khrushchev agreed to remove his missiles from Cuba, Kennedy seized on a wording ambiguity[71] to expand his list of demands beyond removal of just the missiles. This kept the crisis simmering out of public view.[72]

When a minor part of the deal fell apart, Kennedy also questioned whether our pledge not to invade Cuba was still effective, even though that commitment was comparable in importance to the Soviets' promise to remove their missiles.[73] American invasion plans peaked on November 15, three weeks after the public thought the crisis had ended,[74] and plans for assassination attempts on Castro's life continued until at least 1963.[75]

In the month before the crisis erupted, Kennedy and Khrushchev each drew lines in the sand that later boxed them in. Under pressure from Congress and the press over the Soviet buildup, on September 4, President Kennedy warned the Soviets that "the gravest issues would arise" if they introduced "offensive ground-to-ground missiles" into Cuba.[76] When the Cuban missiles were discovered in mid-October and nuclear war seemed imminent, Kennedy noted that "it doesn't make any difference if you get blown up by an ICBM flying from the Soviet Union or one from 90 miles away," and regretted his earlier ultimatum by stating, "Last month I should have said we don't care."[77]

On September 11, Moscow drew its own line in the sand when it warned that "one cannot now attack Cuba and expect the aggressor will be free from punishment. If this attack is made, this will be the beginning of the unleashing of war."[78]

Predictions of disaster were ignored. In the spring of 1962, nuclear-armed American missiles became operational in Turkey, adding to Khrushchev's motivation to base similar Soviet weapons in Cuba.[79] A risk of this nature had been foreseen several years earlier by President Eisenhower, when the Turkish deployment was first being considered. Minutes of a 1959 meeting quote Eisenhower as seeing a parallel to a possible Soviet deployment in Cuba:

> If Mexico or Cuba had been penetrated by the Communists, and then began getting arms and missiles from [the Soviets], we would be bound to look on such developments with the gravest concern and in fact . . . it would be imperative for us [even] to take . . . offensive military action.[80]

Despite recognizing this danger, Eisenhower set in motion events that resulted in our missiles being deployed to Turkey.

Appendix B. Some Other Cold War Nuclear Risks

April 17–19, 1961, the Bay of Pigs invasion. Planning to overthrow Castro's regime started under the Eisenhower administration, was inherited by Kennedy, and came to a head in this failed invasion attempt. It and subsequent US covert actions aimed at regime change in Cuba played a role in Khrushchev's offering, and Castro's accepting, Soviet nuclear weapons to prevent a second invasion attempt. America's feeling of humiliation contributed to public support for a second invasion, but this time with a large American force.

October 22–28, 1961, Berlin crisis. West Berlin was a symbol of freedom to the United States and a thorn in the side of Moscow. A 2009 US Army history notes that, in October, "tensions . . . nearly escalated to the point of war,"[81] with Soviet and American tanks facing off at Checkpoint Charlie. In addition to other risks associated with this standoff, each of the tank commanders—both Soviet and American—had the ability, though not the authority, to start a firefight that would have increased the risk of war.

November 22, 1963, JFK's assassination. According to a National Security Archive publication, "fears that Moscow might have masterminded the president's killing rose sharply when the CIA was unable to locate

Soviet Premier Nikita Khrushchev for 24–48 hours afterwards."[82] That same publication quotes CIA officials as fearing that Khrushchev might be "either hunkering down for an American reprisal, or possibly preparing to strike the United States."

June 5–10, 1967, Six-Day War. This Mideast war engendered many risks, including an allegation by former secretary of defense Robert McNamara that the United States and the Soviet Union "damn near had war" as a result of the Soviets misinterpreting actions by a US aircraft carrier.[83]

October 1969, Nixon's "madman nuclear alert." As related by Professor Scott Sagan and Professor Jeremi Suri, President Nixon ordered a military alert for the ostensible purpose of responding "to possible confrontation by the Soviet Union."[84] But, it was a ruse designed to try and end the Vietnam War on favorable terms. Nixon's chief of staff H. R. Haldeman recounts Nixon telling him:

> I call it the Madman Theory, Bob. I want the North Vietnamese to believe that I've reached the point that I might do *anything* to stop the war. We'll just slip the word to them that "for God's sake, you know Nixon is obsessed about Communism. We can't restrain him when he is angry—and he has his hand on the nuclear button"—and Ho Chi Minh himself will be in Paris in two days begging for peace.[85]

Despite efforts by Nixon and Kissinger to minimize the chances of an accidental escalation, Sagan and Suri detail a number of dangerous military activities that occurred.

October 6–25, 1973, Yom Kippur War. As with the 1967 Six-Day War, there were a number of nuclear risks in 1973. As one example, on October 24, the Israeli army was poised to capture the 22,000-man Egyptian Third Army and its large cache of Soviet military equipment. Soviet general secretary Leonid Brezhnev sent a letter[86] to President Nixon suggesting that a joint US–Soviet force be sent to enforce UN Security Council Resolution 338[87] that called for a cease-fire, and that had been supported by both the United States and the USSR.

On receipt of Brezhnev's letter, a National Security Council meeting was immediately called. Probably seeing a joint Soviet–American military effort as infeasible, the meeting focused on Brezhnev's warning "that if you find it impossible to act jointly with us in this matter, we should be faced with the necessity urgently to consider the question of taking appropriate steps unilaterally." In response, the council ordered US forces to DEFCON 3, an action that the Soviets saw as "irresponsible."[88]

The crisis ended the next day when Kissinger successfully applied strong pressure on Israel not to capture or destroy the Egyptian Third Army.[89]

November 9, 1979, false alarm due to training tape. According to former secretary of defense Robert Gates:

> [President Carter's National Security Advisor Zbigniew] Brzezinski was awakened at three in the morning by [General William] Odom, who told him that some 220 Soviet missiles had been launched against the United States. . . . Brzezinski was convinced we had to hit back and told Odom to confirm that the Strategic Air Command was launching its planes. When Odom called back, he reported that he had further confirmation, but that 2,200 missiles had been launched—it was an all-out attack. One minute before Brzezinski intended to telephone the President, Odom called a third time to say that other warning systems were not reporting Soviet launches. Sitting alone in the middle of the night, Brzezinski had not awakened his wife, reckoning that everyone would be dead in half an hour. It had been a false alarm. Someone had mistakenly put military exercise tapes into the computer system.[90]

December 25, 1979, Soviet invasion of Afghanistan. This invasion was seen ominously in the United States, with *Time* columnist Strobe Talbott referring to it as "the Soviet army's blitz against Afghanistan"[91] and warning that "the Soviet jackboot was now firmly planted on a stepping stone to possible control over much of the world's oil supplies."[92]

The day after the invasion, President Carter's national security advisor, Zbigniew Brzezinski, stated in a memo to the president, "the Soviet intervention in Afghanistan poses for us an extremely grave challenge."[93]

The British ambassador to Moscow from 1988 to 1992, Sir Roderic Braithwaite, saw the invasion very differently:

> The Russians did not invade Afghanistan in order to incorporate it into the Soviet Union, or to use it as a base to threaten the West's oil supplies in the Gulf, or to build a warm water port on the Indian Ocean. They went in to sort out a small, fractured and murderous clique of Afghan

> Communists who had overthrown the previous government in a bloody coup and provoked chaos and widespread armed resistance on the Soviet Union's vulnerable Southern border.[94]

Whoever is right, and there may well be some truth in both perspectives, the Soviet invasion produced a crisis. President Carter embargoed US shipments of grain to the Soviet Union and boycotted the 1980 Moscow Summer Olympics. Some of the rebels whom we aided added risk by crossing from Afghanistan *into the Soviet Union* to carry out acts of sabotage and propagandize the local Muslim population.[95]

President Reagan even referred to them as freedom fighters: "To watch the courageous Afghan freedom fighters battle modern arsenals with simple hand-held weapons is an inspiration to those who love freedom."[96] The reality was very different, and our aiding those rebels helped lay the foundation for 9/11 since many of the Afghan rebels, including Osama bin Ladin, later turned against the West. Thus, the nuclear risk attributable to 9/11 and subsequent events is traceable in part to these much earlier events.

Pakistan's nuclear arsenal is another risk that can be traced in part to the Soviet invasion of Afghanistan. Brzezinski's memo cited above went on to say, "we must both reassure Pakistan and encourage it to help the rebels. This will require a review of our policy toward Pakistan, more guarantees to it, more arms aid, and, alas, *a decision that our security policy toward Pakistan cannot be dictated by our nonproliferation policy*" (emphasis added; see page 3, item B, of the memo).[97]

June 20, 1983, Proud Prophet war game escalated uncontrollably. The outcome of war games is usually classified, so it was unusual—and helpful in assessing risk—when Professor Paul Bracken was able to detail the results of this 1983 war game in which he was involved:

> This wasn't any ordinary war game. . . . Proud Prophet [used] actual decision makers, the secretary of defense and the chairman of the Joint Chiefs of Staff. To make it as realistic as possible, actual top-secret U.S. war plans were incorporated into the game. . . .
>
> American limited nuclear strikes were used in the game. The idea behind these was that once the Soviet leaders saw that the West would go nuclear they would come to their senses and accept a cease-fire. … But that's not what happened. The

> Soviet Union . . . responded with an enormous nuclear salvo at the United States. The United States retaliated in kind. . . .
>
> A half billion human beings were killed in the initial exchanges and at least that many more would have died from radiation and starvation. . . . This game went nuclear big time, not because Secretary Weinberger and the chairman of the Joint Chiefs were crazy but because they faithfully implemented the prevailing U.S. strategy, a strategy that few had seriously thought about outside of the confines of a tight little circle of specialists. I have played other games that erupted, and they shared this common feature, too. A small, insulated group of people, convinced that they are right, plows ahead into a crisis they haven't anticipated or thought about, one that they are completely unprepared to handle. The result is disaster.[98]

We know that some later war games ended similarly as detailed in appendix C's entries "2004, war games escalated uncontrollably" and "2018, war games escalated out of control."

September 1, 1983, South Korean airliner shot down by the Soviets. Korean Air Lines (KAL) flight 007 was shot down by a Soviet SU-15 interceptor over Sakhalin Island, killing all 269 aboard, including Georgia congressman Lawrence McDonald. The airliner went off course and strayed into Soviet airspace over the Kamchatka Peninsula, where a Soviet missile test was scheduled for that day. The plane left Soviet airspace, but reentered a second time over Sakhalin Island, where it was shot down. President Reagan characterized this tragedy as a "crime against humanity [that] must never be forgotten. . . . He went on to say, "It was an act of barbarism, born of a society which wantonly disregards individual rights and the value of human life and seeks constantly to expand and dominate other nations."[99]

This tragedy occurred during a time of heightened tensions between the United States and the USSR, and it created additional risk.

Five years later, on July 3, 1988, the USS *Vincennes* shot down Iran Air 655, killing all 290 people on board. The next day, when President Reagan was asked about a possible comparison between that tragedy and KAL 007, he replied that "there was a great difference. . . . There's no comparison."[100] Later evidence shows that the president was relying on incorrect information.[101] Analysis, therefore, might uncover additional risks that were present in the KAL 007 tragedy owing to misperceptions.

November 1983, Able Archer exercise. I include this incident even though there is disagreement surrounding the level of risk that it entailed. In fact, I felt it important to include because of those disagreements, so that any readers who are familiar with only one perspective will become aware of the other as well.

On the one hand, former secretary of defense Robert Gates has characterized Able Archer as "one of the potentially most dangerous episodes of the Cold War."[102] On the other hand, Harvard professor Mark Kramer dismisses such assertions as "a mere myth."[103]

Whichever side is right, and again there may well be elements of truth in both perspectives, relations between the superpowers were very poor during the early 1980s, heightening the risk of war. Able Archer occurred just two months after KAL 007 had been shot down and less than eight months after President Ronald Reagan's "Star Wars" speech that greatly alarmed the Soviets.

Gates wrote that Soviet leader Yuri Andropov developed a "seeming fixation on the possibility that the United States was planning a nuclear strike against the Soviet Union" and "that such a strike could occur at any time, for example, under cover of an apparently routine military exercise."[104] Able Archer was just such an exercise, simulating the coordinated release of all of NATO's nuclear weapons.

Appendix C. Some Post–Cold War Nuclear Risks

By enumerating a number of post–Cold War nuclear risks, this appendix questions the belief that the nuclear threat ended with the fall of the Berlin Wall. It is worth noting that many of these events occurred during the 1990s, a decade that is usually thought of as having little nuclear risk.

1991 Soviet coup attempt. In August 1991 a coup attempt was mounted against Soviet president Mikhail Gorbachev. While the coup failed, the chaos and uncertainty surrounding control of the Soviet nuclear arsenal[105] increased nuclear risk.

1993 Russian constitutional crisis. This was a small civil war between parties loyal to Yeltsin and others loyal to the Russian parliament. The Russian parliament building was shelled, and there were over 600 casualties, including 187 dead. The first twenty seconds of a Radio Free Europe/Radio Liberty video[106] graphically depicts the chaos.

1995–1996, Third Taiwan Straits crisis. Taiwan's declaring its independence would be so intolerable to the People's Republic of China (PRC) that it could precipitate a war that could drag in the United States. In 1995, over the strenuous objections of the PRC, Taiwan's pro-independence president, Lee Teng-hui, was granted a visa to visit the United States. The PRC was incensed and conducted missile tests to express its anger. A *New York Times* book review starts off, "The possibility of a shooting war between the United States and the People's Republic of China was suddenly made real to Bill Clinton in early March 1996."[107]

This crisis has repercussions to the present day. China's current aggressive stance is partly a response to the humiliation[108] that it felt when Clinton, in a show of military force, sent two aircraft carrier battle groups to the area in March 1996.

The Taiwanese independence movement is still active,[109] and in a 2018 statement Lieutenant General Ben Hodges (US Army, Retired) noted that he thinks that "in 15 years—it's not inevitable, but it is a very strong likelihood—that we will be at war with China."[110]

1999–present, NATO expansion. Before the breakup of the Soviet Union, Russia had a large buffer between it and NATO—a buffer that it felt it needed in light of Hitler's devastating 1941 invasion. That buffer shrank considerably in 1999 when Poland, Hungary, and the Czech Republic were admitted to NATO, and disappeared in 2004 when Estonia, Lithuania, and Latvia became members.

Russia feels not only threatened but also cheated because, in a February 9, 1990, meeting, Soviet president Mikhail Gorbachev was assured by US secretary of state James Baker that, if Gorbachev allowed the reunification of Germany within NATO, "NATO's jurisdiction would not shift one inch eastward."[111] Even though this was not a legally binding guarantee and Gorbachev later took actions[112] that raised questions about whether Baker's assurance still applied, Russia feels cheated, thereby creating nuclear risk.

A 2019 RadioFreeEurope/RadioLiberty dispatch quoted NATO secretary-general Jens Stoltenberg as saying that it was "clearly stated that Georgia will become a member of NATO," even though that article describes "the Kremlin's fierce opposition" to such a move.[113]

1999 Pristina Airport crisis. In June 1999, as NATO peacekeeping troops moved into Kosovo, American general Wesley Clark ordered British lieutenant general Sir Mike Jackson to take actions that Jackson feared could lead to combat between NATO and Russian troops at the Pristina Airport. Clark's and Jackson's accounts agree that a heated argument ended with Jackson telling Clark, "Sir, I'm not starting World War III for you."[114]

Clark states that he gave that order to Jackson because, "I didn't want to face the issue of shooting down Russian transport aircraft if they forced their way through NATO airspace. . . . [and] I expected that when NATO met the Russians with determination and a show of strength, the Russians would back down."[115] Clark was probably right about the Russians backing down, but to assess the risk we would have to quantify *probably*, and then analyze what might happen if the Russians' response differed from the one Clark expected.

2002–present, North Korean nuclear crisis. North Korea and the United States came close[116] to fighting a second Korean War in June 1994, over the North's nuclear program. Intervention by former president Jimmy Carter resulted in the 1994 Agreed Framework[117] that averted war and was in place until 2002. North Korea did its first nuclear test four years later in 2006, in 2018 was estimated to have a nuclear arsenal of ten to twenty warheads,[118] and in 2021 was estimated to have enough fissile material for forty to fifty warheads.[119]

Relations have been extremely tense in recent years, including White House pressure early in 2018 to develop plans for attacking a North Korean missile on its launchpad.[120] Should the United States and North Korea go to war, there is some risk of losing one or more American cities, either by a missile attack or a smuggled weapon. If China became involved in the war, our risk would increase markedly.

Fortunately, President Trump's June 2018 Singapore summit with Kim Jong-un resulted in a halt to North Korea's nuclear and long-range missile tests, something that is still true as of October 2021. However, a lack of sanctions relief and other American policies may contribute to a resumption of North Korean tests.

2004, war games escalated uncontrollably. Echoing appendix B's entry about the 1983 Proud Prophet war game escalating uncontrollably, a 2008 RAND Project Air Force report noted:

> In 2004, Director of Air Force Strategic Planning Major General Ronald J. Bath sponsored a war game in which uncontrolled escalation occurred, surprising players and controllers alike. . . . this experience was just one in a series of escalatory events occurring in major war games over the past several years.[121]

See also this appendix's entry "2018, war games escalated out of control."

2008 Cuban bomber mini-crisis. In July 2008, elements within the Russian military threatened to deploy nuclear-capable bombers to Cuba.[122] This threat was in response to the United States planning an eastern European missile defense system that Russia felt threatened its nuclear deterrent.[123]

In his confirmation hearings as US Air Force chief of staff, General Norton Schwartz testified that this would cross "a red line."[124] Fortunately, other elements in Russia prevailed and the threat did not materialize. If the Russians had based nuclear-capable bombers on Cuba, a crisis comparable to 1962's might have resulted.

2008 Georgian War. In August 2008, Russia invaded Georgia after the latter tried to reclaim its breakaway region of South Ossetia, resulting in attacks on a Russian peacekeeping force.[125] The danger was compounded because most Americans were unaware that an EU investigation concluded that Georgia fired the first shots, "which was followed by a disproportionate response of Russia."[126] Reflecting the mood of many Americans at the time, vice presidential candidate Sarah Palin said that the United States should be ready to go to war with Russia if the conflict flared up again.[127]

2012–present, Senkaku-Diaoyu Islands. An ongoing dispute between Japan and China over the Senkaku-Diaoyu Islands heated up in 2012[128] when the governor of Tokyo took actions that riled China. According to a 2015 *New York Times* article, "At least once every day, Japanese F-15 fighter jets roar down the runway, scrambling to intercept foreign aircraft, mostly from China,"[129] and the risk is ongoing.[130]

This dispute puts the ability to start a firefight in the hands of individual pilots and ship captains who often engage in aerial and naval games of chicken. Should war break out between China and Japan, the 1960 US–Japan Security Treaty commits us to come to Japan's aid.

2014–present, Ukrainian crisis. The Ukrainian crisis coupled with Russia's conventional inferiority has led Vladimir Putin to make nuclear threats.[131] The risk of further escalation is increased because the United States and Russia each see the other party as solely to blame.

2015, Turks shot down a Russian jet. The Syrian civil war could have produced a major crisis in November 2015, when Turkish F-16's shot down[132] a Russian SU-24 near Turkey's border with Syria, and Turkmen Syrian rebels killed the pilot. If Russia had retaliated against Turkey, which fortunately it did not, Turkey could have cited our NATO commitment to treat an attack on Turkey the same as if we had been attacked.

This event would be even more dangerous if allegations prove true that the Turks ambushed the Russian jet. Pierre Sprey,[133] a longtime defense analyst and a member of the team that developed the F-16, is among those making such accusations.[134]

2018, war games escalated out of control. At a July 2018 conference, US Air Force general John Hyten, then USSTRATCOM's commander, described a war game that ended "bad." He clarified that, "bad meaning it ends with global nuclear war."[135] This bears a dangerous resemblance to earlier war games escalating out of control as detailed in appendix B's entry "June 20, 1983, Proud Prophet war game escalated uncontrollably" and this appendix's "2004, war games escalated uncontrollably."

January 8, 2021, chair of the JCS took action to prevent a possible rogue nuclear attack by Trump. Woodward and Costa's book, *Peril*, states that two days after the January 6, 2021, attempt by supporters of President Trump to prevent congressional certification of the election, the chairman of the Joint Chiefs, General Mark Milley, spent an hour and a half trying to reassure his Chinese counterpart, General Li Zuocheng, that Chinese fears of a US attack were unfounded.[136] Woodward and Costa also state:

> Milley had misled General Li when he claimed that the United States was "100 percent steady" and the January 6 riot was just an example of a "sloppy" democracy. To the contrary, Milley believed January 6 was a planned, coordinated, synchronized attack on the very heart of American democracy, designed to overthrow the government to prevent the constitutional certification of a legitimate election won by Joe Biden. It was indeed a coup attempt and nothing less than "treason," he said, and Trump might still be looking for what Milley called a "Reichstag moment."[137]

They go on to state that:

> [Milley] immediately summoned senior officers from the National Military Command Center (NMCC) . . . [to go over] the procedures and process for launching nuclear weapons. Only the president could give the order, he said.
>
> But then he made clear that he, the chairman of the JCS, must be directly involved. . . . [He told them that if there was] Any doubt, any irregularity, first, call me directly and immediately. Do not act until you do.[138]

A September 16, 2021, *Washington Post* article states that, "Col. Dave Butler, a spokesman for Milley, issued a statement Wednesday largely confirming what's disclosed in the book."[139]

Notes

1. George Apostolakis, "How Useful Is Quantitative Risk Assessment?," *Risk Analysis* 24, no. 3 (2004): 515–520, https://doi.org/10.1111/j.0272-4332.2004.00455.x.
2. David James Caswell, "Analysis of National Strategies for Combating the Proliferation of Nuclear Weapons" (PhD. diss., Stanford University, 2010), https://www.proquest.com/dissertations-theses/analysis-national-strategies-combating/docview/2449822805/se-2?accountid=11752.
3. Matthew Bunn, "Reducing the Greatest Risks of Nuclear Theft & Terrorism," *Daedalus* 138, no. 4 (2009): 112–123, https://www.amacad.org/publication/reducing-greatest-risks-nuclear-theft-terrorism.
4. Martin E. Hellman, "Risk Analysis of Nuclear Deterrence," *The Bent of Tau Beta Pi* 99, no. 2 (2008): 14–22, https://ee.stanford.edu/~hellman/publications/74.pdf; and Seth D. Baum, Robert de Neufville, and Anthony M. Barrett, "A Model for the Probability of Nuclear War" (working paper 18-1, Global Catastrophic Risk Institute, 2018), http://gcrinstitute.org/papers/042_nuclear-probability.pdf.
5. Transcript of *The Fog of War: Eleven Lessons from the Life of Robert S. McNamara*, directed by Errol Morris (Sony Pictures Classics, 2003), http://www.errolmorris.com/film/fow_transcript.html.
6. Melanie Kirkpatrick, "Why We Don't Want a Nuclear-Free World," *Wall Street Journal*, July 13, 2009, https://www.wsj.com/articles/SB124726489588925407.
7. Federation of American Scientists, "Status of World Nuclear Forces," lasted updates October 7, 2021, https://fas.org/issues/nuclear-weapons/status-world-nuclear-forces/.
8. Theodore C. Sorensen, *Kennedy* (New York: Harper & Row, 1965), 705.

9. Don Phillips," With One Crash, Concorde Ranks Last in Safety," *Washington Post*, July 30, 2000, https://www.washingtonpost.com/archive/politics/2000/07/30/with-one-crash-concorde-ranks-last-in-safety/39f473a9-0609-4520-adc7-6bab42cc0299/. After the fatal Concorde crash, its hull loss per million flights was more than ten times that of the 737 fleet. The cited article notes that, "because there are so few Concordes and because each flies fewer than 1,000 hours a year, the Tuesday crash boosted the hull loss per million flights figure to 11.64." It goes on to say that "the Boeing 737, by contrast, has had 77 crashes but still has an excellent safety record, ranging from 1.25 per million to .43 to zero hull losses for different versions of the plane, because it is the world's most common airliner. The huge 737 fleet flies more hours in one week than the Concordes have flown in their entire existence."
10. BEA (Bureau Enquêtes-Accidents), "Accident on 25 July 2000 at La Patte d'Oie in Gonesse (95) to the Concorde registered F-BTSC operated by Air France," January 2002, https://www.bea.aero/uploads/tx_elydbrapports/f-sc000725a.pdf. This report is the official accident report. Page 93 states, "there are fifty-seven cases of tyre bursts/deflations . . . of which six led to penetration of the tanks," which is more than 10 percent. Page 146 states: "As of 25 July 2000, it appears that the rate of tyre deflation/destruction on Concorde was on average one occurrence per 1,500 cycles (or 4,000 flying hours). This rate fell over time and the proportion was no more than one occurrence per 3,000 cycles (or 8,000 flying hours) between 1995 and 2000. By way of comparison, on long-haul aircraft, such as the Airbus A340, this rate is of the order of one occurrence per 100,000 cycles." Those two numbers produce tire failure rates that are sixty-seven and thirty-three times greater than that of the A340.
11. Joseph Harriss, "The Concorde Redemption," *Air & Space Magazine*, September 2001, https://www.airspacemag.com/flight-today/the-concorde-redemption-2394800/.
12. If each officer had an independent 50 percent probability of deciding to use the nuclear torpedo, the probability that two of them would agree to use it would be 25 percent. Some accounts maintain that three officers were involved in the decision and two of the three wanted to use the weapon, which, if true, might result in a probability estimate of $0.67^3 = 30\%$ for use of the weapon. These numbers assume that the weapon would be used only if all the officers involved agreed to its use, and that assumption needs to be carefully examined.
13. The Soviets had deployed nuclear-capable battlefield weapons on Cuba. Evidence indicates that the nuclear warheads were not mated to the weapons, but were readily accessible.
14. Mark Kramer, "Tactical Nuclear Weapons, Soviet Command Authority, and the Cuban Missile Crisis: A Note," *International History Review* 15, no. 4 (1993): 740–751, https://doi.org/10.1080/07075332.1993.9640662.

15. Arms Control Association staff, "The Cuban Missile Crisis," *Arms Control Today* 32, no. 9 (2002): https://www.armscontrol.org/act/2002-11/features/cuban-missile-crisis.
16. Joint Chiefs of Staff, "Memorandum from the Joint Chiefs of Staff to President Kennedy: Status of Readiness for the Cuban Operation (C)," JCSM-910-62, November 16, 1962, Avalon Project, Yale Law School, https://avalon.law.yale.edu/20th_century/msc_cuba186.asp.
17. Joint Chiefs of Staff, "Memorandum for the President thru the Secretary of Defense: Recommendations for Execution of CINCLANT OPLANS 312 and 316," JCSM-844-62, October 27, 1962, document 17 in William Burr, ed., *National Security Archive Electronic Briefing Book No. 397* (Washington, DC: National Security Archive, GWU, October 16, 2012), https://nsarchive2.gwu.edu/NSAEBB/NSAEBB397/.
18. John F. Kennedy, "Cuban missile crisis address to the nation," October 22, 1962, American Rhetoric, transcript and MP3 audio, https://www.americanrhetoric.com/speeches/jfkcubanmissilecrisis.html.
19. See Martin Hellman, "JFK's airstrike speech," *Defusing the Nuclear Threat* (blog), November 16, 2012, https://nuclearrisk.wordpress.com/2012/11/16/jfks-airstrike-speech/.
20. Dave Melancon, "Tensions Ran High at Checkpoint Charlie in 1961 as Easterners Fled to West, Berlin Wall Went Up," US Army website, November 2, 2009, http://www.army.mil/-news/2009/11/02/29658-tensions-ran-high-at-checkpoint-charlie-in-1961-as-easterners-fled-to-west-berlin-wall-went-up/.
21. General Wesley K. Clark, *Waging Modern War* (New York: Public Affairs, 2001), 394; and General Sir Mike Jackson, *Soldier: The Autobiography* (London: Bantam Press, 2007), 272.
22. Hans M. Kristensen, "World Nuclear Arsenals, Modernization Programs,and Employment Doctrines and Policies," briefing to the New York State Bar Association conference: Nuclear Weapons and International Law, November 12, 2020, https://gsinstitute.org/wp-content/uploads/2020/12/PPT-World-Nukes-Hans-Kristensen.pdf.
23. Alan Robock and Owen Brian Toon, "South Asian Threat? Local Nuclear War = Global Suffering," *Scientific American*, January 1, 2010, http://www.scientificamerican.com/article.cfm?id=local-nuclear-war.
24. The White House, Office of the Press Secretary, "Press Conference with President Obama and Prime Minister Rutte of the Netherlands," March 25, 2014, https://obamawhitehouse.archives.gov/the-press-office/2014/03/25/press-conference-president-obama-and-prime-minister-rutte-netherlands.
25. General John Hyten, Speech at the Mitchell Institute Triad Conference, July 17, 2018, US Strategic Command, transcript, https://www.stratcom.mil/Media/Speeches/Article/1577239/the-mitchell-institute-triad-conference/.

26. European Union, *Independent International Fact-Finding Mission on the Conflict in Georgia* (Belgium: EU, September 2009), https://www.echr.coe.int/Documents/HUDOC_38263_08_Annexes_ENG.pdf. Volume I states on p. 22: "There is the question of whether the use of force by Georgia in South Ossetia, beginning with the shelling of Tskhinvali during the night of 7/8 August 2008, was justifiable under international law. It was not."
27. 166 Cong. Rec. S457 (January 22, 2020) (statement of Timothy Morrison, former senior director for Europe and Russia at the National Security Council), https://www.congress.gov/116/crec/2020/01/22/modified/CREC-2020-01-22-pt1-PgS457.htm.
28. Ulrich Weisser, "No Digs at Moscow: The West Has to Stick to Its Promises," *Atlantic Times*, 2007.
29. Timothy Naftali, Ernest May, and Philip Zelikow, eds., *The Presidential Recordings: John F. Kennedy: The Great Crises*, vol. 2 (New York: Norton, 2001), 464.
30. Naftali, May, and Zelikow, *Presidential Recordings*, vol. 2, 441–443.
31. Naftali, May, and Zelikow, *Presidential Recordings*, vol. 2, 451.
32. Policy Subcommittee of the Strategic Advisory Group (SAG), *Essentials of Post-Cold War Deterrence* (Washington, DC: USSTRATCOM, 1995), http://www.nukestrat.com/us/stratcom/SAGessentials.PDF.
33. Robert Dallek, *An Unfinished Life: John F. Kennedy, 1917–1963* (New York: Little Brown & Co., 2003), 398–399, 581–582. These pages indicate that Kennedy may even have been on amphetamines *during* the Cuban crisis.
34. William Bryk, "Dr. Feelgood," *New York Sun*, September 20, 2005, http://www.nysun.com/out-and-about/dr-feelgood/20251/.
35. "TELECON, Scowcroft/Kissinger, October 11, 1973, 7:55 p.m.," copy reproduced at the National Archives and Records Administration, https://nsarchive2.gwu.edu/NSAEBB/NSAEBB123/Box22-File10.pdf.
36. Tony Blair, *A Journey: My Political Life* (New York: Knopf, 2010), 613.
37. Paul Thompson, "Drunk Boris Yeltsin Was Found Outside White House in Underpants Trying to Hail Cab 'Because He Wanted Some Pizza,' " Daily Mail, September 22, 2009, http://www.dailymail.co.uk/news/article-1215101/Drunk-Boris-Yeltsin-outside-White-House-underpants-trying-hail-cab-wanted-pizza.html.
38. William J. Perry and Tom Z. Collina, *The Button: The New Nuclear Arms Race and Presidential Power from Truman to Trump* (Dallas: BenBella Books, 2020), 5–6.
39. Scott D. Sagan, *The Limits of Safety: Organizations, Accidents, and Nuclear Weapons* (Princeton, NJ: Princeton University Press, 1993), 136–137.
40. Martin E. Hellman and Vinton G. Cerf, "An Existential Discussion: What *Is* the Probability of Nuclear War?," *Bulletin of the Atomic Scientists*, March 18,

2021, https://thebulletin.org/2021/03/an-existential-discussion-what-is-the-probability-of-nuclear-war.

41. Former secretary of defense William Perry, who holds a doctorate in mathematics, agrees with that estimate and has given me permission to state that publicly.

42. A former high-ranking defense official who served in the Trump administration told me that he would not rule out 10 percent per year. While he may have been thinking only in terms of the risk he perceived during the Trump administration, 10 percent per year cannot be ruled out based solely on the fact that sixty-six years of nuclear deterrence has not resulted in a nuclear war. There would be roughly one chance in a thousand of our being that lucky, which would be a rare, but not a miraculous, event. And, at 3 percent per year, which would be the lower end of his 10 percent per year order-of-magnitude estimate, there would be a 13 percent chance of no nuclear wars occurring in the last sixty-six years.

43. Although the risk will change significantly over such a long time period, I am only trying to estimate the annualized risk over at most the next few decades.

44. Some might count other crises as comparable, or near comparable—for example the 1961 Berlin crisis.

45. Transcript of *The Fog of War.*

46. Hellman, "Risk Analysis of Nuclear Deterrence."

47. Apostolakis, "How Useful Is Quantitative Risk Assessment?"

48. Martin Hellman, *Rethinking National Security* (Washington, DC: Federation of American Scientists, April 2019), https://ee.stanford.edu/~hellman/publications/78.pdf.

49. Albert Einstein, telegram to prominent Americans, May 24, 1946; published in the *New York Times* on May 25, 1946, with the headline "Scientist in Plea for $200,000 to Promote New Type of Essential Thinking."

50. Early in the crisis, President Kennedy formed a high-level executive committee to advise him. It is frequently abbreviated as ExComm.

51. James G. Blight and David A. Welch, *On the Brink: Americans and Soviets Reexamine the Cuban Missile Crisis* (New York: Hill and Wang, 1989), 72.

52. Thomas Blanton, "Annals of Blinksmanship," reproduced from *Wilson Quarterly*, summer 1997, in Laurence Chang and Peter Kornbluh, eds., *The Cuban Missile Crisis, 1962* (Washington, DC: National Security Archive, GWU, 2002), https://nsarchive2.gwu.edu/nsa/cuba_mis_cri/annals.htm.

53. Sorensen, *Kennedy*, 705.

54. Robert S. McNamara, *Blundering Into Disaster* (New York: Pantheon Books, 1986), 11.

55. For an English translation of the crew member's recollection of the captain's wanting to use the nuclear torpedo, see William Burr and Thomas S. Blanton,

eds., "The Submarines of October: U.S. and Soviet Naval Encounters During the Cuban Missile Crisis," in *National Security Archive Electronic Briefing Book No.* 75 (Washington, DC: National Security Archive, GWU, October 31, 2012), https://nsarchive2.gwu.edu/NSAEBB/NSAEBB75/.

56. Burr and Blanton, "Submarines of October."

57. Sheldon M. Stern, *The Week the World Stood Still: Inside the Secret Cuban Missile Crisis* (Stanford: Stanford University Press, 2005), 40–41, 67–69, 87–90. Stern was the historian at the John F. Kennedy Presidential Library from 1977 to 1999 and is often regarded as the world's leading expert on deciphering the low-quality audio tapes JFK secretly made of many meetings during his presidency. Stern's book is derived from those tapes and can therefore be considered primary source material.

58. Aleksandr Fursenko and Timothy Naftali, *One Hell of a Gamble* (New York: W. W. Norton & Company, 1997), 212.

59. Secretaries to the Joint Chiefs of Staff, "Alternative Actions if Build-up in Cuba Continues Despite Russian Acceptance of the Quarantine (U)," in *The Nuclear Vault* (Washington DC: National Security Archive's Nuclear Documentation Project), http://www2.gwu.edu/~nsarchiv/nukevault/ebb457/doc%201A%20 10-28-62%20from%20Air%20Force%20files.pdf. The suspicions of the joint chiefs were not unwarranted since the Soviets earlier had lied about the presence of the missiles. However, unknown to the chiefs, the Soviet battlefield nuclear weapons increased the risk that their proposed solution would lead to nuclear war.

60. Some accounts refer to Maultsby as a major in the Air Force, while others call him a captain. I have used the latter since it comes from the usually reliable National Security Archive website. [See Michael Dobbs, "One Minute To Midnight: Kennedy, Khrushchev and Castro on the Brink of Nuclear War" (Washington DC: National Security Archive, GWU, June 11, 2008), https://nsarchive2.gwu.edu/nsa/cuba_mis_cri/dobbs/maultsby.htm.] I suspect that the references to him as a major were written after he had attained that rank.

61. Sagan, *The Limits of Safety*, 136–137.

62. Sheldon Stern, on p. 30 of *The Cuban Missile Crisis in American Memory: Myths versus Reality* (Stanford: Stanford University Press, 2012), notes: "[JFK] rejected ExComm demands to implement his earlier decision to destroy the SAM site that had fired the fatal missile." As noted earlier, Stern is one of the top scholars on these matters. A slightly "noisy" transcript of the tapes appears in Naftali, May, and Zelikow, *Presidential Recordings,* vol. 3, 115. On p. 124 Kennedy refers to "this plan we just agreed on this morning" and the editors add in brackets "for retaliation if a U-2 were shot down."

63. See "Chronology 1, October 26, 1962 to November 15, 1962" in Chang and Kornbluh, *Cuban Missile Crisis*, p. 377, column 1, first paragraph of 4:00 P.M. entry, https://nsarchive2.gwu.edu/nsa/cuba_mis_cri/621026_621115%20 Chronology%201.pdf.

64. Chang and Kornbluh, *Cuban Missile Crisis*, 370-371. Note that the page numbers are for the 1998 edition, not an earlier one.

65. "The Presidency: The Durable Doctrine," *Time* 80, no. 12 (September 21, 1962): 17–20; Dallek, *An Unfinished Life*, 539–540; and Richard Ned Lebow and Janice Gross Stein, *We All Lost the Cold War* (Princeton, NJ: Princeton University Press, 1994), 20–21.

66. Jerold L. Schecter (trans. and ed.), with Vyacheslav V. Luchkov, *Khrushchev Remembers: The Glasnost Tapes* (Boston: Little Brown & Co., 1990), 176–177: "Castro suggested that in order to prevent our nuclear missiles from being destroyed, we should launch a preemptive strike against United States. He concluded that an [American] attack was unavoidable and that this attack had to be preempted. In other words, we needed to immediately deliver a nuclear missile strike against the United States." After being removed from office, Khrushchev put these memoirs on tape and smuggled them out of the Soviet Union. This is a translation of those tapes. Their authenticity was initially questioned, but after censorship was lifted, Khrushchev's son Sergei vouched for their authenticity.

67. "Memorandum for the Secretary of Defense: Justification for US Military Intervention in Cuba (TS)," March 13, 1962, posted on the National Security Archive website, https://nsarchive2.gwu.edu/news/20010430/northwoods.pdf. This is a copy of the originally Top Secret document, signed by General L. L. Lemnitzer, chairman of the Joint Chiefs of Staff, clearly showing the authenticity of these otherwise hard-to-believe facts. The quotes used in this chapter are in "Annex to Appendix to Enclosure A: Pretexts to Justify US Military Intervention in Cuba." They are easier to find in a searchable version of the document on Cryptome's website, http://cryptome.org/jcs-corrupt.htm.

68. Naftali, May, and Zelikow, *Presidential Recordings*, vol. 2, 452; and Stern, *The Week the World Stood Still*, 50.

69. Stephen G. Rabe, *The Most Dangerous Area in the World: John F. Kennedy Confronts Communist Revolution in Latin America* (Chapel Hill: University of North Carolina Press, 1999), 207n19.

70. Secretaries to the Joint Chiefs of Staff, "Alternative Actions if Build-up in Cuba Continues."

71. Instead of promising to remove the missiles, Khrushchev said he would remove "the arms which you described as offensive" [Edward C. Keefer, Charles S. Sampson, Louis J. Smith, and David S. Patterson, eds., *Foreign Relations of the United States, 1961–1963, Volume XI, Cuban Missile Crisis and Aftermath* (Washington, DC: US Department of State, 1996), https://history.state.gov/historicaldocuments/frus1961-63v11.] Khrushchev probably used these words to drive home the point that he regarded the missiles as defensive, intended not to attack the United States but to prevent a second American invasion of Cuba. But Kennedy seized on this wording ambiguity to demand the removal of a number of additional weapons systems that he thought might be regarded as offensive.

72. Chang and Kornbluh, *Cuban Missile Crisis*, 394, 396–398. On November 5, 1962, Khrushchev warned Kennedy that his "additional demands . . . [risk bringing] our relations back again into a heated state in which they were but several days ago."
73. Lebow and Stein, *We All Lost the Cold War*, 345.
74. David G. Coleman, "The Missiles of November, December, January, February . . . : The Problem of Acceptable Risk in the Cuban Missile Crisis Settlement," *Journal of Cold War Studies* 9, no. 3 (2007): 5–48, https://doi.org/10.1162/jcws.2007.9.3.5.
75. US Senate Report No. 94-465, *Alleged Assassination Plots Involving Foreign Leaders: An Interim Report of the Select Committee to Study Governmental Operations with respect to Intelligence Activities* (Washington, DC: US Government Printing Office, November 20, 1975), 85.
76. Chang and Kornbluh, *Cuban Missile Crisis*, 367.
77. Naftali, May, and Zelikow, *Presidential Recordings*, 441, 433.
78. Richard K. Betts, *Nuclear Blackmail and Nuclear Balance* (Washington, DC: Brookings Institution, 1987), 112.
79. Fedor Burlatsky, *Khrushchev and the First Russian Spring* (New York: Charles Scribners Sons, 1991), 171.
80. Barton J. Bernstein, "Reconsidering the Missile Crisis: Dealing with the Problem of the American Jupiters in Turkey," 55–129, in James A. Nathan, ed., *The Cuban Missile Crisis Revisited* (New York: St. Martin's Press, 1992). The Eisenhower quote is on p. 58.
81. Melancon, "Tensions Ran High at Checkpoint Charlie."
82. Jeffrey T. Richelson, ed., *National Security Archive Electronic Briefing Book No. 493* (Washington, DC: National Security Archive, GWU, November 20, 2014; originally posted June 4, 2013), https://nsarchive2.gwu.edu/NSAEBB/NSAEBB493/.
83. "McNamara Says U.S. Russia Close to War in 1967," *Spokane Chronicle*, September 15, 1983, http://news.google.com/newspapers?nid=1345&dat=19830915&id=61dOAAAAIBAJ&sjid=oPkDAAAAIBAJ&pg=3052,2764299.
84. Scott D. Sagan and Jeremi Suri, "The Madman Nuclear Alert Secrecy, Signaling, and Safety in October 1969," *International Security* 27, no. 4 (2003): 150–183, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/sagan_is_spr03.pdf.
85. H. R. Haldeman with Joseph DiMona, *The Ends of Power* (New York: Times Books, 1978), 83. Emphasis is in the original.
86. Douglas E. Selvage, Melissa Jane Taylor, and Edward C. Keefer, eds., "Letter from Soviet General Secretary Brezhnev to President Nixon," Document 146 in *Foreign Relations of the United States, 1969–1976, Volume XV, Soviet Union, June 1972–August 1974* (Washington, DC: Office of the Historian, 2011), https://history.state.gov/historicaldocuments/frus1969-76v15/d146.

87. UN Security Council, Resolution 338, Cease-Fire in the Middle East, October 22, 1973, https://peacemaker.un.org/sites/peacemaker.un.org/files/SCR338(1973).pdf.
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Chapter 5
Nuclear Deterrence as a Complex System

Edward T. Toton and James Scouras

Even if the US Cold War nuclear deterrence system could be regarded as a triumphant success because no nuclear war occurred between the United States and the Soviet Union, the strategic nuclear deterrence system of today must contend with a geopolitical landscape far more complicated than that of the Cold War. Seven acknowledged nuclear powers exist, and others, including transnational organizations, are attempting to join their ranks. Multiple nuclear states, nuclear capabilities that vary widely in technological sophistication, and different levels of stockpiles and security implementations all suggest that the nuclear deterrence landscape is far more uncertain in its risk of failure than at any other time in history. These components also suggest that the nuclear deterrence system has features that are consistent with the formal definition of complex systems; therefore, complex systems theory is most appropriate for addressing fundamental questions of risk. We explore these features and discuss failures from the points of view of accidents and human error or missteps, drawing on treatments of complex systems in general and the Cuban missile crisis in particular. We suggest how fundamental research in complex systems theory can contribute to assessing the risk of failure of nuclear deterrence. Whether formal modeling of nuclear deterrence systems can provide practical utility in a multipolar nuclear world has yet to be determined. We suggest construction of simplified mathematical models as a first step in grappling with the complexities of systems of nuclear deterrence. We propose that assessment of the risk of failure of nuclear deterrence associated with the close calls in the Cuban missile crisis would be a practical test of preliminary understanding of this complex problem.

"We came so close . . . The world came within a hair breadth of nuclear war."[1] These were the words of Robert McNamara, secretary of defense during the

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Kennedy administration and the Cuban missile crisis, upon learning in the 1990s that the Soviet Union had succeeded in placing nuclear warheads in Cuba, including tactical warheads to repel any invasion. During the crisis itself, the United States did not know whether the Soviets had any nuclear warheads in Cuba.[2] According to Secretary McNamara, "We had photographs of missile launchers but thought the warheads were yet to come."[3] The possibility of tactical warheads that could be used to defeat an invasion had not been considered. Relying on this incomplete intelligence, the Joint Chiefs of Staff recommended an invasion of Cuba, and at one point during the crisis, McNamara considered an invasion "almost inevitable."[4] Fortunately, as it almost certainly would have triggered nuclear war, the recommended invasion ultimately was not executed.

The body of unclassified and declassified documents and eyewitness testimony from participants on both sides of the Cuban missile crisis has revealed numerous instances in which there was potential escalation to nuclear war. Like the unexecuted plan for invasion, some of these instances resulted from incomplete information, others resulted from inappropriate subordinate action, and still others from actual missteps. It can be argued that these instances represent "close calls" that provide an evidentiary basis for inferring the risk of failure of nuclear deterrence. On the other hand, according to the declassified Defense Department assessment of military operations during the crisis, "The military establishment responded to a threat to our national security promptly, with imagination, vigor, and an exemplary degree of professional competence and skill."[5] The US Air Force's official study agreed that "the Air Force response to the Cuban crisis was outstanding."[6] These two statements are consistent with the optimistic view that the US deterrence system in place during the crisis had such a degree of reliability that close calls either could be managed or were of such low risk that they would not jeopardize the system's overall performance.

The question of the reliability of the US deterrence system at the time of the Cuban missile crisis notwithstanding, the Soviet Union's placement of ballistic missiles in Cuba created great instability in that system. Cuban-based ballistic missiles would have greatly increased the number and reduced the times of flight of nuclear weapons to major portions of the United States. In an era when the mutuality of assured destruction had not yet been accepted, the United States viewed this as an intolerable threat, particularly because it emanated from the Western Hemisphere, long a sphere of dominant US influence.

One of the lessons of the Cuban missile crisis was to avoid direct confrontation between the superpowers; heeding this lesson contributed to nuclear stability throughout the remainder of the Cold War. But is the geopolitical environment in the post–Cold War world prone to instabilities that could trigger nuclear war? According to the *Nuclear Posture Review* of 2010,[7] "The fundamental role of US nuclear weapons, which will continue as long as nuclear weapons exist, is to deter nuclear attack on the United States, our allies, and partners." Today's nuclear deterrence system is considerably improved over the system that existed in 1962. The nuclear triad has been completed, and new technologies, capabilities, and procedures have been incorporated throughout its evolution. However, the bipolar world of the United States and the Soviet Union has dissolved. There are now seven acknowledged nuclear powers, one reportedly undeclared nuclear power, one recent withdrawal from the Nuclear Nonproliferation Treaty with evidence of at least partially successful nuclear testing, one Middle Eastern state well advanced toward a nuclear capability, and at least one transnational terrorist group with expressed interest in acquiring and using nuclear weapons. It is a new multipolar nuclear world.[8]

How might an assessment of the risk of nuclear deterrence failure in this emerging multipolar world be useful? One example can be found in deliberations concerning the New Strategic Arms Reduction Treaty (START) Treaty, which reduces US and Russian nuclear arsenals. Adjustments of arsenals, changes in the political prominences of nuclear states, and evolution in the nuclear capabilities of participants have the potential not only to decrease but also to *increase* the risk of failure of nuclear deterrence. For the United States to make informed decisions about restructuring its nuclear posture and about the consequences of agreements such as the New START Treaty, it is prudent to consider the changes in this risk, arguing for a formal examination of the risk of failure of nuclear deterrence.

The search for ways to characterize the risk of failure of nuclear deterrence must be conducted in a data environment for which there has never been a nuclear exchange. The challenge of estimating the risk of failure of nuclear deterrence is formidable: fundamental questions on how to characterize the sociological behavior of human actors in the nuclear deterrence system, how to establish the existence of paths that could lead to failure, and how to quantify these elements remain unanswered.

The law of unintended consequences is sometimes referenced when unanticipated consequences occur as the result of some decision or action in a societal system. In fact, the failure to anticipate potential unintended consequences results from what amounts to a piecemeal understanding of the system to be acted on. Complicated systems, such as a Swiss watch or a personal computer, have many often intricately interconnected components or parts, yet they follow a rigorous blueprint for behavior. As long as legitimate operations are exercised, complicated systems do not produce unanticipated consequences.

On the other hand, complex systems are complicated systems (including a variety of component types, a multiplicity of components, or both) with an added feature: the interactions of their components are not simple. As we will see in the subsequent discussion, systems that are complex in this technical sense have the property of nonlinearity (i.e., the response of a system to some selected input can be disproportionate to that input). More generally, disproportionate behavior may be observed as an unanticipated system response. As an example, we will see in the next section that a small navigational error made during a course correction over Alaska led a US strategic bomber carrying megaton-class nuclear weapons on a 1,300-mile flight that ultimately would have penetrated Soviet airspace; only a last-minute discovery of the error by a ground intercept radar in Alaska avoided this outcome. This small navigational error could have resulted in nuclear escalation—a consequence far greater in magnitude than the navigational error would suggest alone and an example of disproportionate or nonlinear response.

Identifying unintended consequences requires understanding the complex system of interest. In the case of a system of nuclear deterrence, unintended consequences could be catastrophic. The question then is whether the US nuclear deterrence system exhibits the behavior of a complex system in its technical sense. We posit that it does.

There is a consequence of identifying the nuclear deterrence system as a complex system. Complex systems exhibit the property of emergence: the appearance of behavior at the system level that cannot be predicted by the nature of the system components. We infer that the concept of nuclear deterrence itself is an emergent property of the system of nuclear deterrence; a corollary is that the risk of failure must be an emergent property as well.

The consequence of this identification is significant: it is not possible a priori to rule out the existence of failure modes that lie entirely at the systems level without concomitant component-level failures. (It is tantalizing to identify potential system-level failures with black swan events—a term coined by Nicholas Taleb in his popular book, *The Black Swan*.[9]) Therefore, the analysis of risk of failure of nuclear deterrence is incomplete unless it is based on complex systems theory.

The discussion is organized as follows. The first section presents incidents in the Cuban missile crisis that potentially could have led to unintended nuclear war. These incidents serve as lessons for how complex systems can have components whose interactions could lead to unintended consequences. The deterrence system extant during the Cuban missile crisis behaved as a complex system; we infer that the current deterrence system is also complex.

The second section introduces concepts of complex systems theory, a research discipline that seeks to understand and predict systems' behavior through an understanding of how new properties and behaviors of a system emerge from component subsystems—the characterizations of which do not presage emergent system behavior. Complex systems theory provides insights for behaviors of many physical systems, living organisms, and colonies where classical physics and engineering principles fail. The present and future nuclear deterrence system is discussed within this understanding of complex systems.

Finally, the "Conclusions and Recommendations" section discusses what we have learned and what research may be necessary in the search for a complex systems theory of nuclear deterrence and its failure.

The Cuban Missile Crisis

It is often claimed that the nuclear deterrence system that existed between the United States and the Soviet Union was successful: after all, no nuclear weapons were launched, and no nuclear war broke out between these two nuclear superpowers. However, examination of declassified documents and eyewitness testimony revealed a number of incidents that can be categorized as near misses[10]—that is, it is conceivable that escalation to nuclear weapon exchanges could have occurred. The claim that nuclear deterrence worked might need to be replaced with the claim that we were lucky.

The successful orbiting of Sputnik on October 4, 1957, was a technological shock to the United States that demonstrated that the Soviets had the capability to deliver payloads over intercontinental distances with launch-to-impact times of approximately thirty minutes, making US nuclear bombers vulnerable to a surprise attack. In response, through an intense technology development program, the United States developed an intercontinental ballistic missile nuclear capability as well as a fleet of eight nuclear ballistic missile submarines—all in place by the time of the Cuban missile crisis in 1962. This nuclear defense system ensured a second-strike capability (the ability to launch a successful, devastating nuclear attack on the Soviet Union in response to a nuclear first strike on the United States), which is the basis of nuclear deterrence. As expressed by then secretary of defense Robert McNamara in the 1960s, such an assured second-strike capability possessed by both sides became enshrined in the doctrine of mutual assured destruction—a property that *emerged* from the Cold War race for nuclear armament supremacy.

There was a general sense in the United States that the country was very close to nuclear war during the Cuban missile crisis. The risk of nuclear war was perceived to hinge on the actions of the respective command centers of the two powers. In the United States, the command center created by President Kennedy was the ExComm—the Executive Committee of the United States National Security Council. The nuclear deterrence system below the ExComm was composed of the vast infrastructure for weapons' preparation, management, intelligence gathering, alert functions, and response to command updates. It was considered to function as designed—that is, flawlessly. If not, then errors could be managed promptly and without compromising the defense mission.

Published in 1993, Scott Sagan's book *The Limits of Safety*[11] (on which this section is largely based) explores Cuban missile crisis events that bring into question the belief that a nuclear arsenal can provide a flawless nuclear deterrent. Uncovered from unclassified materials in the public domain, materials obtained through the Freedom of Information Act, and eyewitness accounts, these events were within the strategic defense infrastructure on which the command center relied, were close calls in that there were plausible alternatives that could have led to war, and were unanticipated. These features have important implications for how to characterize such complicated systems.

We next discuss two examples selected from the large number of cases Sagan examined. While these examples can be regarded as close calls, there has been no assessment of the likelihoods that they might have led to nuclear escalation. The examples demonstrate the difficulty in anticipating such events and the importance of understanding human action in a complex system.

The Lost Bomber Incident

As described by Sagan, at the moment of President Kennedy's television address on October 22, the US Strategic Air Command increased its B-52 airborne alert system (code-named Chrome Dome) to sixty-six sorties a day from the peacetime level of twelve sorties a day.[12] During the crisis, these sorties were distributed over three basic routes: the southern route crossed the Atlantic Ocean and established orbital loitering over the Mediterranean Sea; a second route extended over Ontario to the Hudson Bay and established orbital loitering near Thule, Greenland; and the third route essentially circumnavigated North America—to and across Greenland, over the Arctic Ocean north of Canada, across Alaska, and down the Pacific coast of the United States to return to their bases. Each of the B-52s carried three or four thermonuclear (i.e., megaton-class) weapons.

The airborne alert routes used by the US Strategic Air Command Chrome Dome bombers were supposed to be safe, and direct orders from the secretary of defense specified that no aircraft would approach the territories of the Soviet Union or China.[13] However, on August 23, 1962, the crew of one of these flights made a navigational error during a course correction over Alaska and assumed a course that would lead the bomber eventually to penetrate Soviet territory if not corrected. The crew was unaware of this navigational error, flew a distance of approximately 1,300 miles, and came within 300 miles of Soviet airspace when a ground control intercept from Alaska detected the location error and radioed an immediate course change.

It was known that the Soviet Union had invested heavily in the development of air defense interceptors in the 1950s and 1960s. By 1962, the Soviet Union had hundreds of MIG-19s, with a combat range of four hundred miles, and MIG-21s, with a combat range of two hundred miles. Although the basing of these was not known, the projection of the lost bomber route strongly suggests that at the time that the bomber was alerted, it was already well within interceptor combat range.

It is not known whether the Soviet Union was aware of this potential intrusion into its airspace by the lost bomber. However, the potential intrusion by a B-52 armed with at least three thermonuclear weapons must be regarded as an event that could have resulted in a serious confrontation between the Soviet Union and the United States. We see from this that a relatively small failure in the system—as easily attributable to equipment error as human error—could have had catastrophic consequences.

The Vandenberg Missile Launch

The second incident of concern to us involved Vandenberg Air Force Base in Southern California.[14] Vandenberg housed both the US Strategic Air Command operational test and evaluation facilities and intercontinental ballistic missile test facilities. Test missiles were flown into the Pacific Kwajalein test range. On October 22, 1962, when alert status was raised to DEFCON 3, test silos and missiles were in various states of repair or test preparation. Air Force Systems Command began preparations to ready the sites for combat capability. By October 30, nine missiles at Vandenberg had been outfitted with nuclear warheads and were prepared for launch.

One Atlas intercontinental ballistic missile had been standing ready for a test flight in the week after October 22 when DEFCON 3 was announced. While other missiles surrounding this intercontinental ballistic missile were being reconfigured for nuclear combat capability, this missile was held in reserve as a test missile. On the night of October 26, at 4:00 a.m., this missile was launched toward the Kwajalein test range. This launch was executed without the knowledge of Washington, which focused its attention on actions, and possible launches, in Cuba.

It is difficult to estimate the risk involved in this launch. It is not known, for example, whether the Soviets were aware of the launch. There was no satellite coverage at this time, but it would be unreasonable to assume that the Soviet Union would have had no observers in the vicinity of Vandenberg during the missile crisis. Certainly there would have been opportunity to observe the heightened activity at the launch sites between October 22 and 26, and there would have been opportunity for visual detection of an early morning launch from a presumptive nuclear-configured launch facility.

What we have here is an event that resulted from decision-making (to proceed with the scheduled test) at the local command level without the knowledge of the highest command level in Washington and failure of the highest command level to rescind local decision-making authority in this crisis. For a time, this local command functioned autonomously without realizing the potential impact of its action. It is difficult to argue that there was no great risk in this action: if the Soviet command had received intelligence of a nighttime launch from a presumed nuclear-capable facility, for which the time from launch to impact would be considerably less than that of an intruding bomber, it would have undoubtedly fostered a high-risk decision-making environment for that command. This event must be regarded as a high-risk close-call event.

Observations

It is evident from these two examples that human behavior is an important factor in the reliability of systems for nuclear deterrence. This is well known to the designers of the current US nuclear deterrence system: a culture of safety is established through functional design and extensive training. Functional design uses cooperative decision-making to mitigate individual errors; extensive training of operational personnel emphasizes the importance of safety and training in appropriate responses to anticipated problems and ingrains safe operational procedures during heightened threat levels and potential crises. In other words, the risk of failure resulting from human error is thought to be made acceptably low through rigorous training and redundancy of responsibility. On the other hand, this thought must be tempered by the reality of cultural complacency, as was exhibited in the cross-US flight of a B-52 bomber loaded with six nuclear cruise missiles in September 2007.[15]

The Vandenberg missile launch occurred as a result of component-level decision-making independent of national command; the lost bomber incident occurred because of navigation error. The latter could be attributed to a mechanical or physical error in which the navigator believed the instrument readouts, or there could have been actual human error in the interpretation of indicators. In any case, this form of error (now extremely unlikely with modern navigation tools) is quite analogous to a simple hardware component error. Human management of navigational systems remains paramount, however, and the sustained flight of the lost bomber shows that its crew did not discover this error for an extended period of time. It is therefore appropriate to attribute this failure to human error as well.

These failures are just two examples of human component-level system errors that could have led to an escalated confrontation during the Cuban missile crisis and nuclear war. The command-level belief that there were no Soviet nuclear warheads on Cuban soil during the crisis, as discussed in the introduction to this chapter, reveals the risk of failure of nuclear deterrence attributable to command-level assumptions in decision-making. We conclude from this that human decisions in a nuclear deterrence system have the potential for catastrophic consequence when the decisions themselves may not at the time be perceived as having this import. That is, the deterrence system can have responses that are disproportionately greater than the human actions may first suggest. We will see later that this nonlinear behavior is consistent with behavior of a complex system.

Nuclear Deterrence as a Complex System

Sagan points out that both the hawkish and the dovish positions on the Cuban missile crisis reflected the belief that nuclear weapons had an intense inhibiting effect on the likelihood that John Kennedy or Nikita Khrushchev would make a premeditated decision to authorize a nuclear strike.[16] On the other hand, neither position acknowledged the possibility of an accidental escalation to nuclear war.

We have seen that the Defense Department and Air Force assessments of performance during the Cuban missile crisis reflected an optimistic view of the reliability of the system of nuclear deterrence even in the face of what we have called close calls. The nature of the events discussed in the previous section suggests that it is appropriate to label these as close calls (i.e., events that had some nonnegligible probability of leading to nuclear escalation).

The question arises as to whether there is a meaningful, objective expression for the risk of failure of nuclear deterrence, an expression that reduces the large gap between those who believe that the risk is slight and those who believe that the risk is significant. We will shortly see how the system architecture of a nuclear deterrence system raises issues that must be addressed, if such an expression is sought. We will see that the few examples of close calls already discussed clearly establish the fact that the nuclear deterrence system in place during the Cuban missile crisis was, in fact, a complex system in the technical sense of this term. It is therefore necessary that we address properties of complex systems in general.

The Nature of Complex Systems

Weaver, in his paper "Science and Complexity,"[17] was perhaps the first scientist to set down a categorization of the types of problems that science has resolved or needs to resolve. The first of these he called problems of simplicity. Problems of simplicity are characterized by variables. A manageable set of variables could be used to predict future behavior from current observation, and this approach was successful in physics and engineering in the seventeenth through nineteenth centuries. A simple example is the modeling of the solar system, for which variables of location, rotation, and velocity could reliably be predicted from careful initial observation.

The second category he named problems of disorganized complexity. These were problems that implied fantastically large numbers of variables for which it would be impossible to predict future behavior from present observation, even granting that a comprehensive observation could be accomplished. Here, the discipline of statistical mechanics was dramatically successful in characterizing a system with a very large number of identical components (such as molecules in a gas) even if the details of the interactions of individual molecules were unknown; it was only necessary to assume that there was randomness of behavior from one component to another.

Weaver's third and final category is one that he called problems of organized complexity. Here problems are characterized by the presence of qualitatively different components (in contrast to molecules in a gas, for example), and the number of variables implied for description may be large but not as large as in problems of disorganized complexity. In addition, the interactions of the components may be much more complicated than would be assumed for problems of disorganized complexity. Weaver offered examples such as employee unions, political organizations, and even nations. He expressed the point of view that problems of organized complexity were the next great challenge, and the next great opportunity, for science in the second half of the twentieth century.

Even in problems of disorganized complexity, we see behaviors that are not evident or anticipated in the components composing these complex systems. For example, the thermodynamics of a bulk collection of gas molecules is developed with powerful statistical mechanics theorems. The resulting thermodynamic laws—the second law of thermodynamics, in particular—are clearly behaviors not possibly implied in the simple collision mechanisms of individual molecules. Behavior that appears in a system as a whole but is not implied in the components and their individual interactions is called emergent behavior.

Vertebrates provide a more compelling example. There is a great deal of structure in any vertebrate: there is differentiation of cells among those that support specific function or organ composition, and there is considerable functional differentiation to provide subsystem support to the system (individual organism). We also see purposeful action on the part of the individual to forage for food and to reproduce, for example. On the human level, we see highly intellectual activity as well. These system-level functions are not presaged in the makeup of the constituent cells of the body. These are dramatic manifestations of emergence.

Emergent properties may be indiscernible, rudimentary, or sophisticated, depending on the sophistication of the system components and the degree of complexity of the interactions among components. For example, on first look, harvester ant colonies appear to be fairly disorganized collectives. However, on closer inspection, these colonies exhibit structural differences in their components (the breeding queen, foragers, and soldier ants, for example). There is purposeful behavior to pressures of famine or attack by another colony. And, most interesting, there is a life span of a colony—from adolescence to adulthood to senescence and eventual death over a period of approximately fifteen years. This collective life span is far greater than the life span of any one ant. We conclude that the colony's behavior cannot be presaged in the behaviors of individual ants.

It is useful to discuss another example of colony behavior, which was ultimately understood through mathematical representation of the interactions of single organisms. Slime molds are commonly found in forests in areas that are rich in nutrients. They are composed of single-cell organisms that typically have dimensions measured in micrometers and are therefore seen individually only through microscopes. However, when the number of these organisms is in the millions or greater, the characteristic mold carpet is clearly identifiable by the naked eye.

Because the slime mold is so simple in structure, it exhibits behavior that has long been mysterious. Whenever a colony becomes environmentally distressed (e.g., because of nutrient depletion in its neighborhood), it begins to exhibit collective behavior; the colony functions as a single organism with macroscopically visual structural movement.[18] In the case of nutrient depletion, this coordinated movement leads the macroscopic organism to crawl in search for a more nutritionally rich location; once the organism finds such a location, it reverts to individual single-cell behavior.

Microbiologists have long known that each slime mold cell could produce a common substance called acrasin (also known as cyclic adenosine monophosphate, or cAMP). They also knew that the individual organisms would respond to concentrations of cAMP and migrate according to the gradient of the concentration of this substance. The microbiology community generally believed that there were special cells (pacemaker cells) that directed the motion of the colony through a process of chemical communication with cAMP. However, continued research failed to find any cells that were morphologically and functionally different from the majority of the colony.

Keller and Segel took a different approach to describing this collective behavior. They postulated a mathematical representation of a slime mold colony for which only two parameters were needed—the number density of individual cells and the local concentration of a chemical substrate.[19] It is useful to use a more simplified version of the Keller–Segel model, as described by Blanchet et al., in which there are just two coupled equations representing the number density (n) of the single-cell organisms and the concentration of cAMP (c):[20]

$$(1) \qquad \frac{\partial n}{\partial t} = \nabla^2 n - \chi \nabla \cdot (n \nabla c)$$

$$(2) \qquad \nabla^2 c = -n \quad .$$

The quantity χ is a number that represents the sensitivity of the individual organisms to the concentration of cAMP; its value is derived from experimental observation.

It is easy to see that there is an inherent nonlinearity in these equations. The second equation is itself linear in the sense that a doubling of the number density is consistent with a doubling of the concentration. But in the first equation, a doubling of these quantities does not work: the second term grows by a factor of four under this operation, whereas the other terms in the equation are only doubled. This means that the behavior of concentration and number density must depend critically on the actual values of these parameters.

In the life of a slime mold colony, there are times when the second, nonlinear term is small enough to be ignored and there are times when it is not; when the nonlinear term is negligible, there is no collective behavior. The behavior of the general solution of these equations reveals the periods for which the colony will function as a collective entity. This collective behavior arises from the overall structure of the two-component system (cells and chemical). Throughout this process, each individual cell responds only to its local environment, propelling itself according to the local gradient of chemical concentration (∇c) (chemotaxis).

We see that the collective behavior of a slime mold colony is an emergent property of the system; this property is not presaged in the behavior of individual cells. More importantly, however, is the fact that the understanding of the origin of collective behavior is achieved through a mathematical representation of the slime mold colony as an example of Weaver's systems of organized complexity. Furthermore, this mathematical representation allows us to determine quantitative behaviors through integration of these equations (whether exactly or through numerical analysis)—a level of insight that is not achievable through discourse alone.

These examples show how insights into the behavior of systems in nature can be achieved using the principles of complex systems theory when the conventional principles of physics and engineering have proven inadequate. Furthermore, it is easy to understand how the assumption of linear, proportionate interactions for a system must fundamentally overlook the richness of behavior of these systems and potential emergent behavior, and how behavior expected under such an assumption can be prone to error.

Complex systems theory can be applied to artificial systems as well as living organisms, the principles being essentially the same. Many systems of the technological age imply nonlinear interactions, such as nuclear reactor power plants and airline transport aircraft. It is even possible to consider the human brain in the context of complex systems theory when behavioral features are considered. In fact, human thought is likely an emergent property of the brain, because behavioral responses (such as emotional behaviors) can be nonlinear and thought is not presaged in the behaviors of individual neurons.

Researchers in complex systems theory since the time of Weaver have identified properties of complex systems that are useful for identifying new problems as complex systems problems. For example, Yates[21] has identified these identifying properties for complex systems:

- **High number of components/interactions.** Large numbers of components and interactions make it difficult for anyone to apprehend the system and understand the significance of interactions.
- **Significant interactions.** Significant interactions can be those perceived and those hidden interactions that essentially determine the relationships of outputs to inputs.
- **Nonlinearity.** Nonlinearity describes the disproportionate scale of an output in comparison to an input to a complex system—small changes in interactions can produce dramatically different systems behavior and sometimes counterintuitive responses.
- **Asymmetry.** Components of complex systems are disparate in nature and complexity, increasing the difficulty of understanding.
- **Nonholonomic constraints.** Subsystems can be isolated from the system command structure; independent subsystems responses are possible.

Generally, several of these features will be discernible in complex systems, and it is not necessary that all be present for a system to be identified as a complex system.

As we will shortly see, these characteristics can be used to determine to what degree the nuclear deterrence system during the Cuban missile crisis can be considered a complex system and, by inference, to what degree the current nuclear deterrence system can be considered a complex system.

The Nuclear Deterrence System Is a Complex System

We discussed the Cuban missile crisis and introduced two examples of close calls—events that conceivably could have led to escalation to a nuclear war. We remarked that the United States had developed an intercontinental ballistic missile nuclear capability as well as a fleet of eight nuclear ballistic missile submarines, thereby providing an assured second-strike capability—the ability to launch a successful, devastating nuclear retaliatory attack on the Soviet Union in response to its nuclear first-strike attack on the United States.

The deterrence system at the time of the Cuban missile crisis was highly complicated, and its components varied greatly in their composition (e.g., land, air, and sea equipment). Not only was a multiplicity of disparate hardware essential to the system, but there was also a hierarchy of human components with the knowledge and training necessary to fulfill the deterrence mission as well as retaliatory strikes, if necessary. This great assembly of hardware and communications needed to support the missions confirms the presence of many components and interactions—one of the hallmarks of complex systems. The disparate nature of the components of the system, including hardware and human components, satisfies the attribute of asymmetry of a complex system.

The lost bomber incident was likely the result of human error, although a technical malfunction might have been a causative agent. Whatever the cause, the crew did not discover the navigational error during a flight of more than 1,300 miles. If the Soviet Union had decided to attack this nuclear-armed bomber, escalation to nuclear war could not be ruled out. Here, a relatively small error could have resulted in a catastrophic outcome. This conforms to the attribute of nonlinearity.

The Vandenberg launch incident was the launch of a test missile in the direction of the Sino-Soviet bloc territory. This launch was executed during the height of the Cuban missile crisis without the knowledge of national command authority. This is an example of nonholonomic constraints, another attribute of complex systems.

If we acknowledge that any system of nuclear deterrence must essentially incorporate significant interactions, then we see that the consideration of just two close-call events is sufficient to satisfy the attribution of all five of Yates's attributes of complex systems. We can conclude with confidence that the US nuclear deterrence system in existence at the time of the Cuban missile crisis can be fully characterized as a complex system.

The US nuclear deterrence system of today has considerably improved since the time of the Cuban missile crisis. For example, there are now sophisticated satellite-based sensors that provide more timely and accurate intelligence. Equipment and training improvements have been implemented over the years to reduce the risk of failures such as those that occurred during the Cuban missile crisis. Nonetheless, most of the attributes of complex systems remain attributes of the modern nuclear deterrence system. We can conclude that the current US nuclear deterrence system should be discussed in the context of complex systems and their behaviors.

Nuclear Deterrence Is an Emergent Property

The doctrine of mutual assured destruction did not exist at the dawn of the atomic age. As the Soviet Union developed a nuclear capability, the United States responded with further development of its own arsenal and delivery capability. Eventually the United States developed a reliable second-strike capability. The recognition that the assurance of an effective second-strike capability meant that no first strike by an opponent could avoid certain nuclear annihilation led ultimately to the perception of nuclear stability between the two superpowers. In the 1960s, then secretary of defense Robert McNamara finally recognized and expressed the concept of assured destruction as a property that emerged from the Cold War race for nuclear armament supremacy. The Soviet Union's development of a second-strike capability meant that a concept of mutual assured destruction was in place and that a more stable status had been achieved between the two superpowers.

As a product of the buildup of a nuclear deterrence system that included a second-strike capability, we see on the one hand that the concept of nuclear deterrence itself is a system-level attribute and, on the other hand, no component itself presages this attribute. One might argue that the human components will be aware of this attribute, but this knowledge does not determine the task performance of the human components. If anything, knowledge of this attribute in times of escalated tensions might interfere with the proper functioning of human components because of compelling cultural or familial concerns. We can conclude that nuclear deterrence is an emergent property of the system.

The Risk of Failure of Nuclear Deterrence Is an Emergent Property

It is at least possible to conceptualize the process of evaluating performance of nuclear deterrence over the full spectrum of conflict scenarios, hardware and human component failures, and all command-level choices. Some fraction of these factors would terminate in the use of a nuclear weapon, whereas others would not. In each and every possibility, the outcome is entirely dependent on the evaluation of the system performance. The set of failures and the entire set of possibilities are each system-level entities that depend fundamentally on the emergent property of deterrence. It is incontrovertible: the probability of failure is itself an emergent property of the deterrence system, leading us to infer that the risk of failure as well is an emergent property of the deterrence system.

This conclusion has profound consequences. We have already shown that there are fundamental nonlinearities inherent in the system, some of which originate from human behavior—either as human components within the system or at the command level. Of course, we expect that the deterrence system might be susceptible to physical accidents (even an accidental nuclear detonation) or component-level human error, as displayed in the lost bomber incident during the Cuban missile crisis. These are what we might call single-point or single-cause failures. However, when nonlinear interactions exist in the system, it is possible that the simple reduction of response of a component rather than an outright failure could lead to unexpected responses elsewhere in the system that could ultimately lead to failure. And finally, nonlinearities in the system that can cause failure of nuclear deterrence must also, in principle, allow for a system failure when no individual component in the system has failed. We need only refer to the history of airline transport accidents to see that many catastrophic failures were attributable to "pilot error" when human error in decision-making after some relatively minor mechanical problem led to loss of the aircraft. The system-level failure is analogous to a series of pilot decisions that appear rational in and of themselves but lead to the loss of the aircraft nonetheless. These are the kinds of system failures that cannot be ruled out a priori; only careful analytical representation and analysis can establish the absence or existence of such potential failures in any particular complex system.

Implications

There are two schools of thought about the reliability of complex systems that could be advanced for systems such as nuclear power plants, oceanic tankers, airline transport aircraft, and, in our case, the system of nuclear deterrence.[22] The first is the high-reliability point of view that attempts to reduce the risk of failure by training, inculcation of a culture of safety, and redundancy. This point of view primarily addresses the human component's contribution to the reliability of complex systems. It is an optimistic point of view because it holds that, if sufficient emphasis is placed on these human components, any catastrophic error could essentially be rendered impossible. The second school of thought is the normal accidents point of view and is based on Perrow's research presented in his book *Normal Accidents*.[23] Perrow argues that complex systems will always exhibit catastrophic failures that remain essentially unpredictable. He also argues that failure-specific remedies or fixes to existing complex systems likely introduce unforeseen interactions so that other failures may then be possible. This point of view is the more pessimistic view of complex systems in that it expects catastrophic failures to be inherent in these complex systems.

It could be argued that the human component has the potential to enhance system reliability as well as to be the source of system failures. Of course, this is implied in the high-reliability point of view that emphasizes training under failure simulations to cope with surprise failure events. Where human intervention is eschewed is in unplanned improvisation; the risk of unintended consequences is so great for the failure in nuclear deterrence that improvisation cannot be relied on as a safe mitigation of developing unplanned failure events.

On the other hand, command-level decision-making is essentially improvisational. Although studies of historical conflicts may be conducted and judgment of human character may be available, there is no formal declaration of the conditions under which one decision-might be preferred over another when conflict arises among nuclear powers. This underscores the essential difference between human involvement at the command level and the component level in a nuclear deterrence system for which training, safety, and redundancy are intended to ensure a high-reliability system for the command level.

The existence of failures arising through the complexity of the deterrence system would give substance to the belief in black swan events that would be tied essentially to system-level interactions. The potential existence of system-level failures would cast doubt on the belief in the high-reliability point of view and validate the normal accidents point of view. The question before us is whether any rational means can be developed to establish the extent of potential catastrophic failures in the nuclear deterrence system and whether any measure of the probabilities of their occurrence can be estimated.

Nuclear Deterrence Modeling Requirements

We have presented a series of arguments that establishes the following three things: (1) the US system for nuclear deterrence is a complex system in the formal sense; (2) nuclear deterrence must be regarded as a system-level function; and (3) as consequence of this recognition, the failure of nuclear deterrence can arise through hardware failures, human component failures, and command-level missteps, and there is even the possibility of system-level failures not obviously connected to any component failures. To understand the potential risk of failure of the US nuclear deterrence system as it exists now and as it might exist in the larger context of multiple national actors and progressive disarmament, it is necessary to understand the potential interactions of components and command authority. For the analyst, this means constructing models that attempt to capture the nonlinearities of interaction, the existence of which we are now aware.

Morton Kaplan, in his book *System and Process in International Politics*,[24] sought to develop a systems methodology to analyze international political systems. He posited six systems that he considered representative (but not necessarily exhaustive) of potential international systems. Of these (balance of power, loose bipolar, tight bipolar, universal, hierarchical, and unit veto), two are of interest to our problem:

- **Loose bipolar.** Here, two supranational actors decomposed into national actors—the Communist bloc and NATO participants. In addition, the United Nations exists as a supranational system.
- **Unit veto.** The unit veto system is something of an anomaly in the listing of potential political systems. It arises through the possession by its members of a weapon that is assured of destroying an opponent member even if the owner of the weapon cannot guarantee its own survival. As such, there can be no political system, and the status of the system is frozen once all members possess this weapon.

Kaplan's international political systems are theoretical constructs, with the exception of balance of power (composed of the pre–World War I states) and loose bipolar (composed of the United States and the Soviet Union, together with their allies). The bipolar system during the Cold War dissolved with the Soviet Union, and only the US–NATO supranational actor remains. On the other hand, the emergence of nuclear nations has elements of the unit veto system, and the consequences of this system must be taken into account when considering the evolution of the multiactor nuclear power system.

Kaplan's approach to international political systems allows him to assess characteristics such as stability or evolutionary development alternatives for these systems. Our discussion of the US system of nuclear deterrence up to this point has taken the viewpoint of this system bounded by an external environment of other actors and the nuclear systems they have. Alternatively, Kaplan's approach leads us to consider the point of view that the US system of nuclear deterrence should be treated as a subsystem in the larger context of a multiactor nuclear power system. We conclude that the modeling requirements must include specification of the domain of the nuclear deterrence system: on the one hand, we can treat the deterrence system as confined to US interests and assets; on the other hand, we can consider these as a subsystem within the larger context of a multiplayer nuclear power system.

We have now identified most of the factors that need to be considered for modeling. However, it is also necessary to consider information flow within the complex system.

The assembly of all the equipment and human component assets in the US nuclear deterrence system is not random but is instead a well-coordinated network of these components. There is a well-defined structure of information exchange and flow that is clearly designed to obtain the maximum useful information that flows across the system boundary from its external environment (when the focus is on the US deterrence system viewed as a system in an environment of external nuclear power actors) and efficient and reliable information flowdown through the network to convey command instructions.

Shannon and Weaver[25] described the general problem of communications in terms of three levels:

- **Level A.** "How accurately can the symbols of communication be transmitted?"
- **Level B.** "How precisely do the transmitted symbols convey the desired meaning?"
- **Level C.** "How effectively does the received meaning affect conduct in the desired way?"

For the US system of nuclear deterrence, we can be confident that there is continuing improvement in the technical capability addressed in level A. However, level B precisely addresses the semantics problem. During heightened alert, as was the case during the Cuban missile crisis, it is evident that there was uncertainty in intentions and meaning of content in communications from the Soviet Union command level, and it can be presumed that the Soviet Union's perception of the United States' intentions suffered similarly. In the current multiactor nuclear power system, factors such as cultural differences, religious affiliation, sensitivity to perceived slights by neighbors, and interpretations of foreign influences represent semantic challenges that constitute a contextual problem for meaningful interpretation. We see that context is an important factor through its influence on how information is to be used to determine whether a nuclear alert is warranted, whether a negotiation strategy is in need of changing, or which strategies are likely to be successful in designing an arms reduction procedure, for example.

Because human motivation and intent are so vital to the description and prediction of the nuclear deterrence system, sociological behavior must be sufficiently understood so that it can be represented in a form useful to system modeling. Sociological behavior includes those factors that qualify intent and meaning in communication and therefore assist in providing context.

Conclusions and Recommendations

As was said earlier, whether one argued from a high level of confidence in prevailing through the Cuban missile crisis or from a state of great concern that unintended, catastrophic consequences could result, nuclear weapons had an intense effect inhibiting both Kennedy and Khrushchev from making a premeditated decision to authorize a nuclear strike. That is, both positions held that a deliberate breakout of nuclear war in the Cuban missile crisis was unlikely. The multipolarity of today's world suggests, however, that the risk of nuclear war could be much greater now than during the Cuban missile crisis. Is this really the case? Is there a way to arrive at an objective, or at least less subjective, assessment of the risk of failure of nuclear deterrence by considering the question from the perspective of complex systems theory?

The identification of the US system of nuclear deterrence as a complex system forces us to recognize that ignoring features such as nonlinear interactions amounts to piecemeal thinking: judgments about the risk of events are likely to be in error, but, at minimum, there can be no confidence in such judgments without an appreciation of the impact of complex systems' behavior in nuclear deterrence.

Having come this far in the analysis, we are nonetheless confronted with considerable uncertainty. If, for example, we succeed in constructing a mathematical model for a system of nuclear deterrence, how do we determine the objective validity of its predictions? Any constructed models are bound to entail approximations; we may restrict choices for command levels or discretize what would normally be a range of potential options in order to make the analysis manageable. On what basis could we decide that improvements in detail would lead to a convergence of predictions to some true value? Is it not possible that high detail could lead to large changes in predictions? These are some of the questions that arise and that only future research can address.

Nuclear Deterrence as a Complex System

The insights developed from the conclusion that a nuclear deterrence system is a complex system include the realization that the risk of failure of nuclear deterrence is an emergent property of the system and that the existence of failures that are wholly dependent on system properties for which there is no component failure cannot be ruled out a priori (i.e., without formal assessment).

Norbert Wiener described cybernetics as the control and communication in the animal and machine and developed mathematical analyses of complex systems such as the cell in the human body.[26] The flow of information from the environment in which the system finds itself as well as information about the status of the system itself are similarly described for the human cell and for a system of nuclear deterrence. In the case of deterrence, the flow of information to and from the command level is of paramount importance, and corruption by noise or ambiguity of meaning is an important factor for the successful operation of this complex system. That is, information conveyed by transmission over a network must be calibrated against the context of origination (such as cultural beliefs and biases of the originator) and by other factors such as the state of alert of the system.

The human cell may be a complex system, but it is almost always surrounded by other human cells in the body. In other words, the human body is a complex system composed of complex subsystems. The import of this is that the interaction of a human cell with its environment is not that of interaction of a passive environment but instead the interaction that can respond to the behavior of the given cell. So far in this discussion, we have regarded the US nuclear deterrence system as the complex system in interaction with an environment, much like the single individual human cell. In the case of nuclear deterrence of the last century, we have discussed nuclear deterrence as if the Soviet system were an essentially independent system. However, if we regard the US–Soviet standoff as a complex system in and of itself, we see that there can be interactions among the two subsystems that may support emergent behavior not realizable by studying the US deterrence subsystem as an independent system. It is therefore important that we remain aware of this level of complexity in the current political state of the world.

Nuclear Deterrence in the Multipolar World

In the 1960s, Kaplan sought definitions of system variables and formal rules that govern the political relationships among actors—the national and international groups that can decide and order implementations of these decisions. His intent was to build a predictive methodology that could project future changes in international politics. Kaplan studied six categories of political systems; by extension, we can discuss the multipolar nuclear power world.

The new multiactor nuclear world is composed of not only nuclear states but also transnational terrorist groups that are interested in acquiring and using nuclear weapons. Each of these can be regarded as a complex subsystem in the complex multiactor nuclear world. Kaplan stressed the need for identifying the conditions for political stability and the consequences of changes in stability, such as the change of a democratic government into a dictatorship, to name one example. For us, the definition of stability in nuclear deterrence has great importance; nuclear stability in a future of arms reduction has even greater importance.

Kaplan said,

> The crux of the matter is whether regularities can be discovered which permit the organisation of the materials of international politics within a simple framework of reasonable explanatory or predictive power. If such an endeavour is to succeed, analytical tools are required in order to abstract systematically the materials of international behaviour from their biographical or historical setting and to organise them into a coherent body of timeless propositions.[27]

This remains true for the system of nuclear deterrence.

Recommendations

It is clear that any attempt to model a system of nuclear deterrence with the intent to quantify the risk of failure of nuclear deterrence must overcome a number of obstacles. Perhaps the most formidable obstacle is the construction of algorithms that can represent human response to a multitude of requirements as well as political, cultural, and religious beliefs. Studies in the domain of social sciences need to be coordinated with mathematical modelers who can express the needs of formal representation in systematic complex systems models.

The architecture of a nuclear deterrence system is the structure on which a complex systems model can be built. This structure forms the basis of a network interpretation of the command and control function as described by Wiener; this provides the framework on which the essentially nonlinear functional responses operate.

Attempts to quantify the probability of catastrophic events in complex systems when no such events have yet occurred are analogous to the dropping of a blind man on a plateau. How does he decide whether the rise under his feet is from a local hillock or the base of foothills of a mountain ridge? The JASON report takes the following position:

> It is simply not possible to validate (evaluate) predictive models of rare events that have not occurred, and un-validated models cannot be relied upon. An additional difficulty is that rare event assessment is largely a question of human behavior, in the domain of the social sciences, and predictive social sciences models pose even greater challenges than predictive models in the physical sciences. Reliable models for ameliorating rare events will need to address smaller, well-defined, testable pieces of the larger problem.[28]

We concur and recommend the construction of complex systems models that are simple in design yet capture selected features of a nuclear deterrence system. From these, we can develop strategies that could facilitate descriptions of stability, how to return to stability when disturbances occur, and how it might be possible to characterize the risk of classes of improbable events, if not specific events themselves.

The elements we have identified that are relevant to the modeling of nuclear deterrence apply to the US system in an external environment or as a subsystem in a larger multiactor nuclear power system and are summarized here:

- **Composition.** This identifies the components within the system ("hardware"). Components may be actual hardware and human operators below the command level.
- **Command.** This is composed of those individuals and organizations with hierarchical authority over the deterrence system and who actively participate in the decision-making with respect to nuclear deterrence in peacetime and in periods of alert.
- **Network architecture.** This is the blueprint by which the components are integrated with one another and with the command level. In the case of the multiactor system, there is no system command level; the integration is predominantly within each subsystem, and interaction channels are established among the subsystems command levels.
- **Sociological representation.** This is the body of information that characterizes command-level actors in their respective subsystems: the breadth of choices in decision-making, the factors that may introduce cultural biases, and other factors.

- **Context.** This encompasses the cultural factors that influence inference of meaning in the semantics biases due to cultural and other factors. This also includes factors such as geographical advantages or difficulties for the movement and positioning of forces, economic ramifications, and non-nuclear-state neighbors.
- **Algorithmic representation.** This refers to the actual construction of mathematical rules for behavior, functioning, and communications among the nodes of the nuclear deterrence network.

These elements provide the basis for embarking on the search for a formal model of nuclear deterrence from which the quantified risk of failure of nuclear deterrence could be assessed.

Formal model development is the next step toward a goal of characterizing the risk of failure of nuclear deterrence. This must be considered as an exploratory process that could yield much insight into the problems of sociological response modeling and methods for establishing the existence of potential failure modes in a complex system. Because the feasibility of useful prediction of the risk of failure of nuclear deterrence is not yet established, it should prove useful first to investigate relatively simple system models. After the development of confidence in modeling capability, the resulting tools should return to the US nuclear deterrence system extant during the Cuban missile crisis and ask the question, what was the risk of failure of nuclear deterrence from the known close calls? The credibility of the answer will reflect on the credibility of the analysis.

Finally, we reiterate the importance of the relationship between the granularity or resolution of a model and the stability of predictions. It is not been established, nor is it obvious, that adding technical detail inevitably leads to a more accurate (i.e., less uncertain) result. If, in fact, predictions become more uncertain with increased fidelity, then the quantification of the risk of failure of nuclear deterrence will prove elusive, even with the insights developed here.

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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]

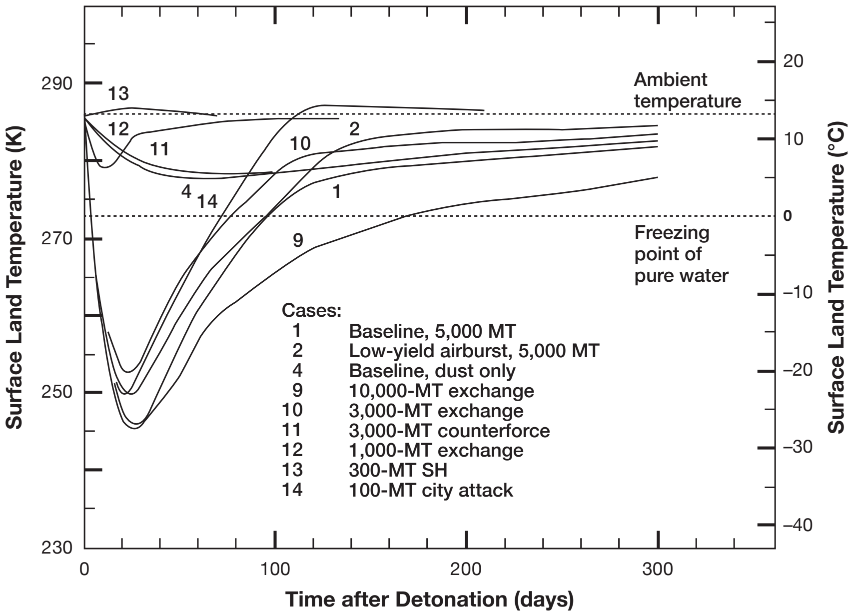

Figure 6.3. TTAPS Nuclear Winter Predictions. These calculations show the drop in surface land temperature levels over time for various nuclear exchange scenarios. Note the prediction of temperature drops for most of the exchange scenarios considered below the freezing point of water for months. The 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).

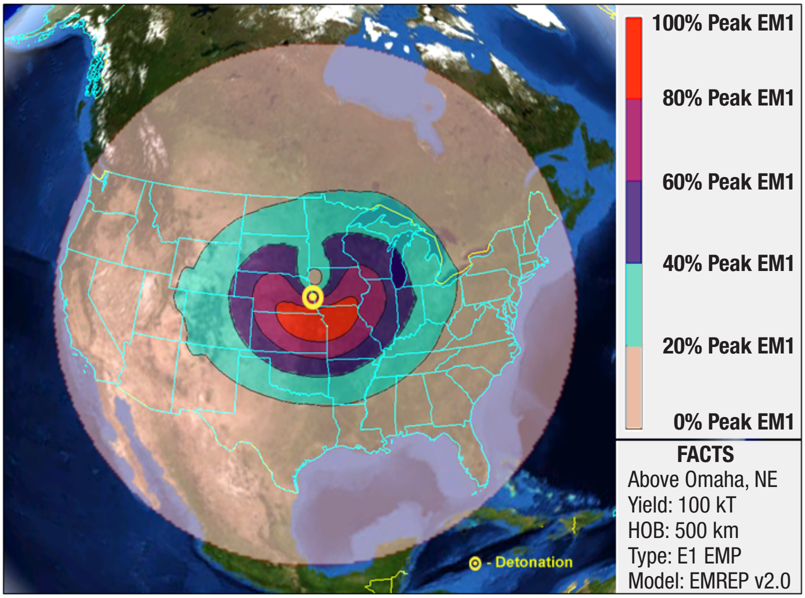

Figure 6.6. EMP Coverage Contours. EMP coverage area on the ground increases as the height of the burst increases. A nuclear detonation at an altitude of five hundred kilometers over Omaha, Nebraska, will generate an EMP that covers the contiguous land mass of the United States. The electric field strength 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.

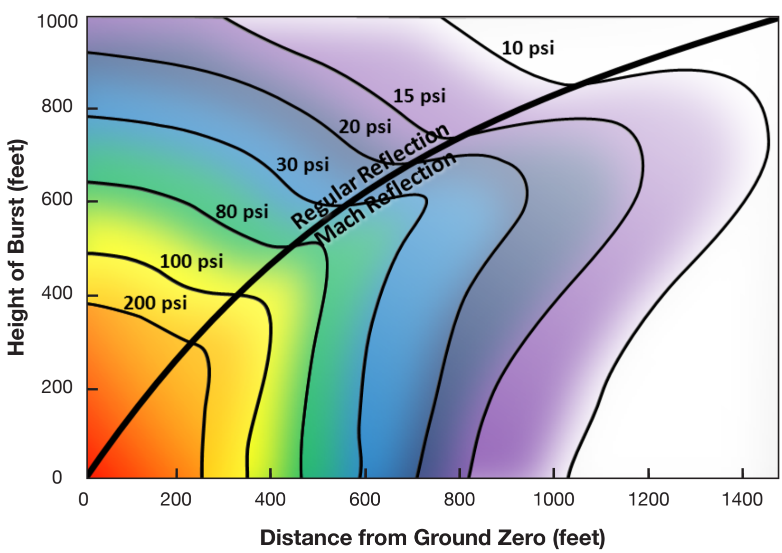

Figure 6.7. One Kiloton Iso-Pressure Contours. In the Mach reflection region, the incident and reflected shock waves have merged to form a single shock front called the Mach stem. Extended knees in the Mach reflection region, more prominent at overpressure levels below one hundred pounds per square inch, 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.

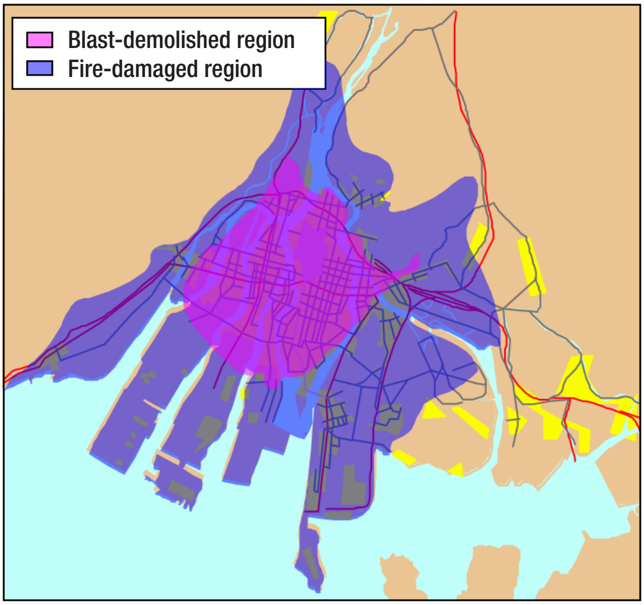

Figure 6.10. Hiroshima Fire Damage. The fire damage region from the Hiroshima bombing extended well beyond the region of damaging blast. A firestorm raged for several hours, destroying 4.5 square miles of the city and two-thirds of its buildings, adding considerably to the total casualty reckoning. The 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.

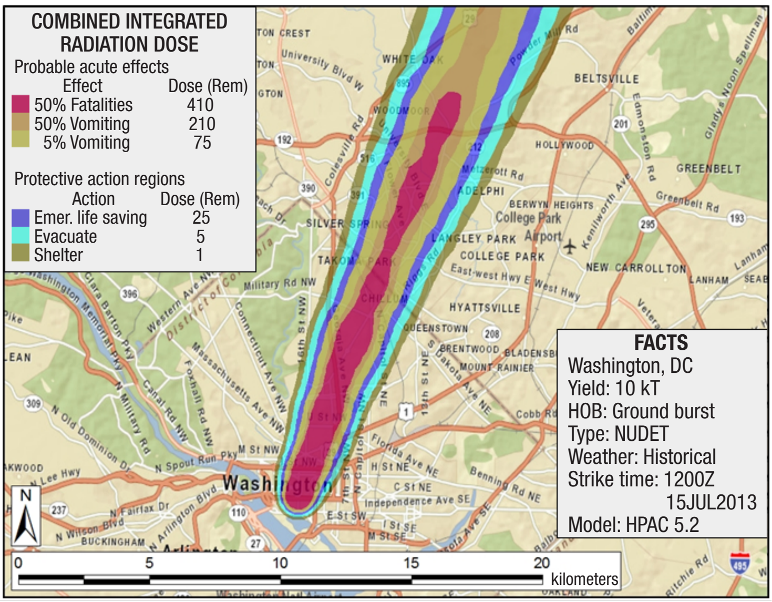

Figure 6.11. Hazard Prediction Assessment Code Fallout Prediction. Depicted are the bands of varying fallout contamination as predicted by the Hazard Prediction Assessment Code (HPAC). Each color contour represents the cumulative dose that would be seen by a sensor situated at that location from the 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.

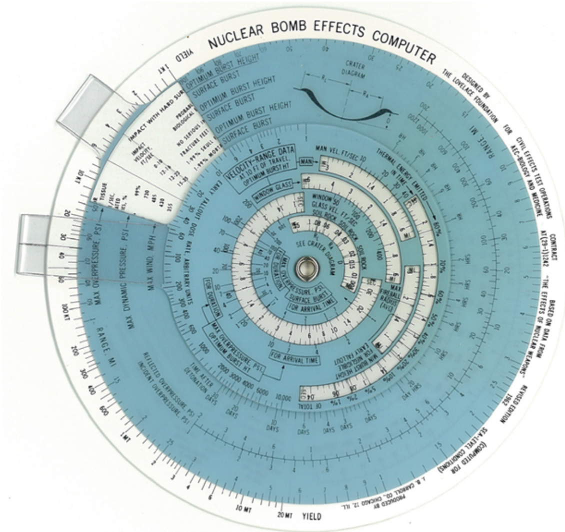

Figure 6.12. Nuclear Bomb Effects Computer. Previously provided as a supplement to Glasstone and Dolan's classic *Effects of Nuclear Weapons*, this shirt pocket slide rule calculator was widely used in the 1950s–1970s but has now been replaced by digital computational resources that use fast-running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

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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.
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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.

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Chapter 7
The Intangible Consequences of Nuclear Weapons Use

Dallas Boyd

Analyses of the effects of nuclear weapons have traditionally focused on the physical destruction they produce, especially their human toll, devastation of cities, and damage to the environment. To the extent that nonphysical effects are taken into account, strategists have emphasized the influence of nuclear weapons on national decision-making, particularly whether a limited strike would escalate to an all-out nuclear exchange. Yet, the range of nonphysical weapon effects is much broader, encompassing social, psychological, political, and economic impacts that would reverberate long after a nuclear attack. In a limited-use scenario, these ramifications—designated as "intangible" effects in this analysis—may greatly surpass the physical damage incurred, just as the cost and scope of the response to September 11 dwarfed the direct effects of the attacks. Moreover, unlike physical phenomena, many of these intangible effects are the result of human decisions and are thus theoretically controllable. Given that the limited use of nuclear weapons is probably more likely than a massive nuclear war, there is a pressing need to understand these intangible effects and identify practical steps to minimize them.

From the first use of the bomb in 1945, the imagery associated with nuclear weapons and the grim descriptions of their effects have left an indelible mark on the human consciousness. The ubiquity of these media—photographs of mushroom clouds, postapocalyptic films, and the vast literature on nuclear war—has produced a nearly universal conception of what a nuclear exchange would entail. Yet, precisely because images of widespread death and devastation are so easily recalled, the *physical* effects of nuclear weapons have always overshadowed in our imagination the many other consequences of their use. This emphasis on physical phenomena was understandable during the Cold War, when the destruction from a nuclear war was understood to be nothing short of apocalyptic. To the extent that nonphysical effects were considered at all during this period, they were generally deemed superfluous to the physical damage from a nuclear exchange. As Arthur Katz and Sima Osdoby noted then, the images of mass destruction that these weapons evoke are "so overwhelming that they normally represent the end, not the beginning, of a dialogue."[1]

Today, however, a global nuclear war is probably less likely than limited-use scenarios involving a handful of nuclear weapons. Notwithstanding the persistent hostility between the United States and Russia, no great ideological struggle exists between the major powers; US and Russian nuclear stockpiles have sharply receded; and the few states reckless enough to start a nuclear war can do so only on a modest scale. Likewise, terrorists would be exceedingly lucky to achieve even a single nuclear detonation. Any deliberate use of nuclear weapons may therefore be limited in scope, and the destruction would not be so great that humankind would be indifferent to the state of the world after the attack. For this reason, greater attention should be paid to the broad category of nuclear weapon effects besides purely physical ones. These include the social, psychological, political, and economic repercussions of an attack, which result largely from reactions—conscious and unconscious, rational and irrational—of people and institutions that are physically unaffected. This shift in focus is necessary because the relative salience of an attack's nonphysical effects rises as the magnitude of its physical consequences declines. Just as the cost and scope of the response to September 11 dwarfed the direct effects of the attacks, the social and political ramifications of a limited nuclear attack may greatly surpass its physical damage. Recognition of this likelihood has two chief implications: in the calculus over whether to initiate a nuclear strike on another state and in the response to a nuclear attack on one's own country, either by a foreign government or by terrorists.

In the first circumstance, a nuclear attack should never be undertaken without a firm understanding of its probable effects, broadly defined. As scholar George Perkovich cautions, "Part of the calculation of whether a state would be willing to use nuclear weapons is that the consequences of doing so should be less harmful to that state than the alternative of not using these weapons."[2] Making this calculation requires an appreciation of the full range of consequences, including the many intangible effects that may be more significant and durable than physical ones. These intangible phenomena are so named because their dependence on individual and collective reactions makes them inherently more nebulous and unpredictable than physical effects. Yet, their amorphous nature should not be seen as subtracting from their gravity, as numerous historical events attest.

In the second scenario, when one's country is the victim of a nuclear attack, national leaders and the public at large should recognize that, in contrast to physical destruction, many intangible effects are theoretically controllable. This feature allows certain adverse consequences to be limited by the quality of individual and government decisions. To enable wise decision-making, there is value in developing as complete a picture as possible of the intangible effects of a nuclear attack, an exercise that might shed light on the most consequential of these, as well as those that are most amenable to intervention.

Before cataloging these intangible consequences, however, a brief taxonomy of nuclear weapons effects is useful. The first category—direct physical effects—is the most obvious: human casualties, destruction of infrastructure, environmental degradation, and other tangible results of blast, radiation, fire, electromagnetic pulse, and fallout. Within this class are both prompt effects, such as the immediate fatalities from a nuclear blast, and delayed effects, such as long-term cancer-related deaths from radiation. Although direct physical effects are geographically limited and finite in duration, their diversity is nonetheless considerable. They include, for example, injuries from falling glass far from the blast site, fires spreading through collapsed buildings, and traffic accidents caused when drivers are blinded by the flash of a detonation.[3]

The next category consists of *indirect* physical effects, such as the phenomenon known as nuclear winter. This term refers to the hypothesis that soot from a nuclear exchange would enter Earth's stratosphere and blot out the sun, in an extreme case preventing photosynthesis and removing the necessary conditions for life on the planet.[4] Other indirect effects involve cascading disruptions from the loss of key assets, such as the destruction of factories that manufacture products (e.g., ball bearings) that many other industries need to function. (This phenomenon can also apply to human assets. For example, the deaths of almost three hundred physicians in the Hiroshima bombing and another sixty in Nagasaki greatly hindered the provision of medical aid to survivors.[5]) While the disruption of systems that support life—food production, water distribution, electrical power, communications, and so on—would have profound human impacts, this damage is, strictly speaking, physical and thus is not addressed extensively in this chapter.[6] As time goes by, however, the failure to restore these services may have less to do with physical damage sustained than with the competence of political or commercial entities, complicating the designation of their nonoperation as an "effect" of the attack.[7]

The role of human agency in amplifying the consequences of a nuclear attack, or producing altogether new ones, calls for a qualitatively distinct category of effects. These intangible consequences are understood to occur alongside physical phenomena but are inherently more difficult to predict and quantify. Moreover, because the former often manifest at the individual level, they may be as diverse and numerous as the population they affect. A brief but illustrative list of these potential effects would include irrational behavior resulting from the public's fear of radiation; the social effects of large-scale migration from an affected region; the disruption to domestic and overseas equity markets; the shift in global attitudes toward nuclear weapons and perhaps even commercial nuclear energy; the military response of the targeted nation; and a host of other effects too numerous to count.

Although the focus on physical effects dominated nuclear scholarship throughout the Cold War, a smattering of research on intangible consequences occurred during this period. Government-funded studies covered such arcane topics as the mental effects on soldiers after the battlefield use of nuclear weapons and the social discord that would attend life in fallout shelters.[8] One such effort was a Department of Defense study in the early 1960s on the social and psychological effects of a nuclear war. This research addressed a wide range of intangible effects, including the family unit in a postattack world, cooperative versus competitive behavior, the debilitating effects of fear, and difficulties in motivating survivors. The authors acknowledged that "it is unquestionably more difficult to predict survivors' behavior than the state of physical resources after any specific hypothetical attack." However, they argued that understanding both was important to prepare for life after a nuclear exchange.[9]

While much of this scholarship concerned massive nuclear attacks, many of its insights are applicable to limited-use scenarios as well. For example, a major research focus was the effect of psychological trauma on society, particularly its potential to produce counterproductive behaviors. This phenomenon is no less germane to limited nuclear attacks than to widespread ones. Accordingly, the following section reviews noteworthy themes from research on intangible consequences from the beginning of the nuclear age through the Cold War.

Scholarship on Intangible Effects

While the world was preoccupied with the physical destruction of Hiroshima and Nagasaki, a small number of strategists recognized a decidedly nonphysical effect of the new atomic bomb. In his 1946 book *The Absolute Weapon*, Bernard Brodie predicted that the chief value of nuclear arms would be their effect on human decision-making rather than their destructive power. He posited that leaders would be dissuaded from destroying an enemy's cities with these weapons because their own would be destroyed in turn and no advantage would accrue from striking first.[10] Thus, the central purpose of military power, which had historically been to win wars, would henceforth be to avert them. This insight would form the foundation of nuclear deterrence, the reigning military paradigm of the Cold War. Although "counterforce" targeting of enemy strategic weapons would soon undermine Brodie's logic, it remained the case thereafter that the principal utility of nuclear weapons would be their influence on human behavior.

Nonetheless, strategists could not ignore the terrible ramifications if nuclear weapons were actually used, and analyses of these consequences soon began to proliferate. Unsurprisingly, these studies focused heavily on physical phenomena. Yet, a minority of scholars chose to focus on the potential social and political effects of nuclear weapons, many of which they extrapolated from the nearest empirical analogue to nuclear war that was then available: the strategic bombing of cities during World War II. Because early nuclear doctrine assumed that these weapons would be used against civilian population centers, the "terror bombing" of British, German, and Japanese cities during the war provided useful points of comparison.

Fred Iklé, who would later serve as under secretary of defense for policy, was among the first to examine what he termed the "social versus the physical effects from nuclear bombing." In a 1954 analysis, he painted a disturbing picture of these social effects, describing the life of survivors of a nuclear war who would "dwell in congested housing, commute in crowded vehicles, queue for food, eat in emergency cafeterias and perhaps live without water except for a communal emergency supply." For those relocated to other parts of the country, he predicted tension with populations in "reception towns" due to ethnic, religious, and class differences. "Evacuees will have to trek on in search of shelter and food, gradually spreading over the countryside and colliding with the flow of refugees from other devastated cities," he wrote. "Friction and competition for the diminishing sources of existence are bound to occur." Iklé speculated that in the case of a massive attack, the number of evacuees would be so overwhelming that residents of unaffected communities would be forced to "share their homes, their kitchens, and their household goods." Consequently, they would be "engulfed in the deprivations and distress of the evacuees" and "fare little better than the survivors from devastated cities."[11]

Scholar Johan Galtung identified several additional factors that might erode social cohesion after a nuclear war. For example, citizens may feel anger toward government leaders for having enjoyed better physical shelters during and after the attack, manifesting itself in disobedience of their orders. Survivors may feel the need to "come to cognitive and emotional grips with the disaster," possibly leading them to conclude that their own government was culpable and thus an illegitimate source of authority. An "everybody for himself" mentality may prevail in which the population fragments into small, self-interested groups and large-scale cooperation becomes impossible. Galtung also speculated that the synergies between short-term physical effects and longer-term consequences would induce "a feeling that the worst may be still to come, a factor that may make a nuclear war very different from other disasters in human history that usually have a well-defined worst, initial period." Most ominously, he suggested that the distress from such a war might "remain unprocessed as a collective psychological time bomb that can be released, e.g., through skillful use by particular types of politicians."[12]

In 1979, the Office of Technology Assessment released *The Effects of Nuclear War*, a widely cited study that described a Soviet nuclear attack on Detroit and a corresponding US strike on Leningrad.[13] While the study focused overwhelmingly on physical phenomena, it also addressed effects stemming from psychological injury, noting the possibility of "major changes in human behavior as a result of the unprecedented trauma." These changes included the prospect that survivors might "place the blame on 'science' or on 'scientists,' and through a combination of lynchings and book-burning eliminate scientific knowledge altogether."[14] Given the unprecedented nature of nuclear war, such outlandish predictions were inevitable. Scholars were free to conjure virtually any postwar reality they wished as long as their vision assumed significant and long-lasting aftershocks on society.

While many of these Cold War era analyses have retained their relevance, the emphasis on massive nuclear exchanges is too narrow for contemporary studies of intangible effects. Because the range of nuclear-use scenarios is arguably more diverse today, a reexamination of nonphysical consequences is in order. The following sections examine the potential effects of two conceivable uses of nuclear weapons in the present day—a limited state-launched attack and an act of nuclear terrorism. Although the ratio of physical effects to intangible ones is uncertain in these scenarios, the social, political, and economic effects of either event would be extraordinary, especially in comparison to their relative proportion in a massive nuclear exchange.

Limited State-Based Nuclear Attack

Unlike the physical effects of a nuclear detonation, which, with the exception of variables such as height of burst, are basically fixed, intangible consequences would depend on the target struck and the context in which the attack occurred. A single warhead that decapitated a country's leadership, for example, would obviously produce greater political repercussions than an identical weapon used against a remote oil refinery. Likewise, an attack on a state's overseas military outpost, where the casualties would largely be uniformed personnel, would presumably be more permissible under international law than a comparable attack on civilians. The range of responses to such an attack would therefore be governed by a sense of proportionality that would likely be absent in the latter case.

The geopolitical circumstances of a nuclear attack would also influence its intangible effects. For instance, a completely unprovoked strike by a foreign government would elicit outraged calls for revenge, which would likely be heeded. Yet, if the attack were itself in retaliation for an earlier military action against that state, some of the blame might be apportioned to the leaders who initiated the original aggression. Or consider an attack that is perceived as having saved more lives than it extinguished, such as the destruction of a nuclear facility of a state with potentially malevolent designs. While many of the consequences of breaking the nuclear taboo would still obtain in this scenario, the intangible effects of such an attack would bear no resemblance to those that followed an indiscriminate attack on civilians. (Scholar George Quester goes so far as to suggest that the relatively modest damage from a tactical weapon might produce a highly counterintuitive outcome: a "nuclear war that is surprising for how *little* damage it inflicts."[15] If this perception reduces the long-standing terror of these weapons to some extent, it might increase the probability of their further use at some later date.)

In light of the diversity of conceivable attack scenarios, a closely bounded test case is necessary for a manageable analysis. The following discussion therefore considers a single-warhead attack on a civilian population center in the context of an international crisis. Although this choice is somewhat arbitrary, it satisfies two crucial criteria. First, the scenario is fundamentally plausible; second, it features many of the familiar physical effects to which intangible consequences can be compared: high casualties and physical damage to a major urban area. A 2013 case study by the antinuclear organization Article 36 assesses such an attack, describing the effects of a one-hundred-kiloton detonation above the British city of Manchester, population 2.7 million.[16] The size of this yield provides a useful contrast to a terrorist nuclear attack, which the conventional wisdom suggests would be at most in the ten-kiloton range.[17]

Despite the study's nominal focus on the "humanitarian" consequences of a nuclear attack, it heavily emphasizes physical effects: 81,000 dead, 212,000 injured, devastation to residential and commercial buildings, destruction of vital infrastructure, and so on. While the loss of the services and facilities that the article highlights (e.g., hospital beds, first responders, and communications networks) would indeed make life difficult for survivors, the deeper effects of the attack are largely unexamined. Indeed, the study's brief mention of intangible consequences consists of passing reference to an "unprecedented social and cultural loss" and a massive "long-term impact on the psychological, social and economic fabric of UK society." The following analysis therefore adds texture to these themes, identifying specific intangible effects and exploring their impact on human behavior. These consequences are divided into domestic and international phenomena, with the former focusing on impacts to the targeted country and the latter speculating on the global ramifications of the first use of nuclear weapons in seventy years. However, before enumerating these effects, it is worth revisiting the atomic bombings of Japan, whose aftermath may foreshadow many of the potential effects of interest to this chapter.

The Past as Prologue: The Intangible Effects of the Atomic Bombings of Japan

Of the historical events that can be used to infer the intangible effects of a nuclear attack in the present day, the most obvious are the atomic bombings of Hiroshima and Nagasaki. Beyond the well-documented physical destruction of these cities, scholars have recorded a wide range of social, psychological, and political effects of the bombings, many of which persist to this day.[18] Firsthand accounts attest to the profound effects on the mental state of survivors, which in turn drove a range of noteworthy behaviors. Father John Siemes, a Jesuit priest who witnessed the Hiroshima attack, authored a harrowing account of its carnage, conveying the breakdown in social order that occurred. "Among the passersby, there are many who are uninjured," he wrote. "In a purposeless, insensate manner, distraught by the magnitude of the disaster, most of them rush by and none conceives the thought of organizing help on his own initiative. They are concerned only with the welfare of their own families."[19]

Robert J. Lifton, a psychiatrist who studied the psychological effects of the bombings, described Hiroshima survivors as experiencing "a sudden and absolute shift from normal existence to an overwhelming encounter with death."[20] In the years that followed, many of them recounted an obsessive attention to their health, living with the fear that delayed symptoms would one day materialize.[21] They also reported concern that their future children would be afflicted with radiation-related illness, a prospect that was the basis for their stigmatization by others. As Mikihachiro Tatara recounts, "knowledge that an individual comes from a Hibakusha [atomic bombing survivor] family raises the specter that there may be 'bad blood.' . . . As a result, the Hibakusha Nisei [second generation] may be socially rejected out of fear that their genes will taint marriages and families."[22]

As poignant and far-reaching as these social and psychological effects were, the political impacts of the bombings proved to be their most significant consequences. The first of these was of course Japan's decision to surrender, which is widely (although not universally) attributed to the bombings.[23] Other intangible effects would take more time to materialize, although the significance of the new weapon in human affairs was immediately apparent. In particular, one effect of unveiling the atomic bomb in such a dramatic fashion was the instant recognition by the other world powers that the United States possessed a military weapon without peer. This revelation especially influenced the dynamic between the United States and the Soviet Union, then just beginning to embark on the Cold War. Indeed, any subsequent effect of the bomb on Soviet decision-making must be counted among the attacks' intangible consequences.[24]

Over the long term, one of the more enduring effects of the atomic bombings was their influence on international perceptions of Japan. So great was the shock to human sensibility that this event has improbably allowed Japan—the perpetrator of wholesale atrocities during the war—to don the garb of a *victim*. To the chagrin of the many countries Japan has subjugated, the Japanese have largely escaped the generational guilt that has attached to the German people since the war's end. To Japan's credit, however, the effect of the bombings on its national psyche appears to be sincere; the Japanese allergy to nuclear weapons is so profound that the faintest hint of developing an indigenous nuclear deterrent elicits national hand-wringing to this day.

Although the atomic bombings of Japan provide a wealth of scholarship on intangible effects, they represent a very limited data set. Further, the attacks did not occur in a vacuum; Hiroshima and Nagasaki were merely the final two Japanese cities destroyed in a bombing campaign that had already devastated dozens of others, and the Japanese were by then thoroughly inured to violence against civilians. A nuclear attack on a country at peace, even one embroiled in an international crisis, would be vastly more jarring to that state's psyche. Because the intangible consequences would be correspondingly greater in this circumstance, a reassessment of this category of effects must be made, albeit with the benefit of various nuclear disasters that have occurred in recent decades.

Domestic Effects of a Nuclear Attack

For understandable reasons, the first metric used to gauge the severity of any disaster is typically its human toll. While the deaths and injuries from a nuclear attack represent a strictly physical effect, many manifestations of these casualties fit squarely in the intangible category. For example, the knowledge that mass death had occurred in one's country would be psychologically devastating to millions of people who are physically unaffected by the event. To put the notional Manchester attack in perspective, the eighty-one thousand dead would be four times the number of British fatalities on the first day on the Somme in World War I, a national tragedy that continues to haunt the United Kingdom a century later.

Although the psychological trauma from a nuclear attack would be felt nationwide, it would be most acute for survivors in close proximity to the detonation. Fred Iklé notes that nuclear weapons would aggravate the "emotional disturbances" that normally attend warfare because they produce "injuries that distort the appearance of victims and have a powerful effect upon those who see them."[25] Disposal of the dead, as well as caring for the sick and injured, would inevitably scar those who undertook these tasks. Even among those not directly affected by the detonation, the fear of its migrating effects, particularly radiation, would be profound. Indeed, as psychologically jarring as the Hiroshima and Nagasaki attacks were, public awareness of radiation was extremely low at the time. Today the fear of this form of energy is universal, and events involving radiation have an extraordinary potential to produce mass terror.[26]

A predictable result of this fear would be the flight of survivors from the surrounding region, many of them permanently. During the Three Mile Island crisis, which involved a partial meltdown of a nuclear reactor in Pennsylvania, approximately 40 percent of the local population self-evacuated, including 140,000 pregnant women and preschool-age children.[27] Likewise, after the 1986 Chernobyl disaster, more than 336,000 people were forcibly evacuated from contaminated areas, with many more leaving voluntarily.[28] A crucial difference between these events and a nuclear attack is that the latter may not be a one-off event. Residents of other major cities, fearing that theirs may be targeted next, may also choose to self-evacuate, creating a nationwide exodus from urban areas.

Although these evacuations evoke images of terrified mobs fleeing for their lives, there is reason to believe they may be more orderly than is commonly assumed. Studies have found that genuine panic tends to occur only when survivors find themselves in an enclosed space from which escape routes are closed or believed to be closing.[29] Whether this condition would be present after a nuclear attack is difficult to predict. Emergency response guidance from the National Security Council strikes an optimistic chord, suggesting that the "dominant behavioral response" after a nuclear attack would "likely be for people to engage in the kinds of pro-social, altruistic behaviors that occur in most disaster situations, unless fear of radiation and contamination or lack of needed information complicates response and recovery efforts."[30] However, the absence of panic does not mean that mass evacuations would be free of antisocial behavior. Depending on the size of the affected population and the length of the displacement, considerable discord might occur. During World War II, for example, relationships between British evacuees from the cities and their hosts in the countryside often deteriorated because of the stress of the upheaval on both groups, as well as class differences, the urban–rural divide, and the inadequacy of government services.[31]

Once outside of the immediate danger zone, the number of evacuees seeking medical treatment would likely far exceed the actual group exposed to radiation, straining an already taxed medical infrastructure. This phenomenon, known as the "worried well," occurred in the 1987 radiological incident in Goiânia, Brazil, when junkyard workers broke apart an abandoned cancer therapy device containing cesium-137 and distributed its glowing blue pieces to unsuspecting friends and family.[32] Although only 249 people were directly exposed, more than 112,000—roughly 10 percent of the city's population—sought medical exams once the recipients began to suffer radiation sickness and die.[33] After a nuclear attack, servicing the worried well would compete with the medical needs of the legitimately stricken, which would likely be a sizable group.

Over the long term, the psychological trauma sustained by survivors would lead to significant health effects. This phenomenon was borne out in the aftermath of the Chernobyl accident, arguably the closest historical analogue to the actual use of a nuclear weapon since World War II. Chernobyl produced a range of mental health problems for those living near the reactor, including depression, anxiety disorders, substance abuse, and posttraumatic stress disorder. Indeed, a 2005 report by the Chernobyl Forum observed that psychological consequences continue to be "the largest public health problem unleashed by the accident to date." Those living in the surrounding communities developed "an exaggerated sense of the dangers to health of exposure to radiation" in which they "exhibit a widespread belief that [they] are in some way condemned to a shorter life expectancy."[34] Sadly, inner torment is not the only long-term effect with which survivors would have to contend. If history is any guide, some degree of social stigma would also attach to individuals from areas associated with radiation, as it did in the wake of Hiroshima and Nagasaki, Chernobyl, Goiânia, and the 1999 nuclear criticality accident in Tokaimura, Japan.[35] The stigmatization that followed the Goiânia incident was particularly severe: visitation to the area plummeted, local products went unsold, and residents were often treated like lepers when they traveled to other parts of Brazil.[36]

While those nearest to a nuclear detonation would feel these short- and long-term effects most acutely, the consequences of the attack would not be confined to a fixed area. The realization of an event dreaded for generations would leave the broader public reeling in shock and disbelief. In addition to grieving for the dead, a desperate uncertainty would hang over the country about what the future held. In particular, a widespread fear might take hold that humankind had just entered an ominous new age in which behavioral norms between states would no longer be observed. It is difficult to predict what effects these emotions would have on individual and group decisions, but some reasonable guesses can be made.

One assured consequence would be a grave injury to the national economy, the first manifestation of which would be a precipitous drop in the stock market. Although computer limits would quickly halt trading on the day of the attack, the collective loss of investor confidence would result in steep losses when the market eventually reopened. Indeed, between the close of trading on September 10, 2001, and the end of the first week of trading after the September 11 attacks, the NASDAQ lost 16 percent of its value and the New York Stock Exchange lost more than 11 percent, a total market capitalization loss of more than $1.7 trillion.[37] Given that a nuclear detonation would vastly exceed the destruction of those attacks, the effect on the market would be far greater.

Other economic effects would depend on the dispensability of the targeted city to the national economy, with damage to struggling cities like Cleveland or Detroit being less harmful than comparable damage to Chicago or New York. Additionally, targets that perform specialized functions (e.g., port cities) or account for a substantial fraction of a crucial industry (e.g., Silicon Valley) would produce a disproportionate level of economic damage. For example, Charles Meade and Roger C. Molander studied the effects of a nuclear attack on the port of Long Beach, the second-busiest container port in the United States, and calculated the direct costs would be in excess of $1 trillion. While staggering in and of itself, this figure does not account for cascading economic effects such as disruptions to transoceanic commerce and the unavailability of goods after the attack.[38]

Meade and Molander also identified a range of longer-term economic effects, including widespread defaults on loans and mortgages in the affected area, the bankruptcy of national insurance companies, and the failure of investors in large financial markets to meet contractual obligations for futures and derivatives.[39] Additional costs would include outlays for survivors' medical care, workers' compensation, and, if the precedent of the September 11th Victim Compensation Fund is any guide, billions in federal payouts to victims' families.[40] Other economic consequences would not be tied to the site of the attack, such as the nationwide rate of work absenteeism in jittery urban areas. Although the large-scale shift to telework during the COVID-19 pandemic might mitigate the impact of this phenomenon in some sectors, the separation of workers from their workplaces in key industries would lead to lost productivity. And whether working remotely or on-site, the lingering trauma might distract workers across the economy from peak productivity for some time. Consequently, extraordinary intervention by the government might be necessary to buttress the economy, reassure investors, and ensure liquidity after the attack.

The government's ability to function effectively in this circumstance would be one of the great uncertainties, and various disasters have featured starkly different public attitudes toward institutions of power. After the September 11 attacks, the American people rallied around President George W. Bush, giving him approval ratings above 90 percent less than a year after a bitterly contested presidential recount.[41] During the Three Mile

Island incident, by contrast, distrust of the government rose dramatically in the affected communities. Residents believed that neither the nuclear industry nor the state and federal governments were in control or being fully candid about the danger, and one of the most pronounced legacies of the crisis was a general loss of trust in these institutions.[42] As a testament to how deeply the event shook the public, the Nuclear Regulatory Commission did not issue a license to build a new nuclear reactor in the United States for more than thirty years.[43]

If a loss of confidence in the government were to occur after a nuclear attack, it would come just as a major expansion of government power was necessary to cope with the scale of the disaster. This response would entail a mobilization of government resources—and perhaps coercive authority—unseen since World War II. Early in this process, the notion that state and local governments would bear primary responsibility for response operations would likely be dispensed with quickly. In all likelihood, the federal government would assume responsibility for many dimensions of the response with or without the consent of governors and mayors.[44] Emergency equipment, vehicles, and perhaps personnel from nearby states could be pressed into service, effectively nationalizing these assets for an indefinite period. Beyond this upheaval to federalism, recourse to even more extreme measures, such as price freezes on consumer goods and the imposition of martial law, is entirely conceivable.

Over the long term, the government would face the wrenching decision of what to do with the devastated city. If it were sufficiently large and commercially vital, such as New York, permanently abandoning the city would probably not be palatable. For a more moderately sized city, however, the cost of rehabilitation would have to be weighed against the loss of its commercial and symbolic value. If the former outweighed the latter, the decision would be extremely difficult. After Hurricane Katrina, for example, policy-makers seriously debated whether it was advisable to rebuild New Orleans or simply relocate its displaced residents and accept a permanently diminished city in its place.[45] Given the presence of radiation after a nuclear attack, which is costly to decontaminate and invokes a unique dread, the decision to abandon a city might be easier than in the case of a comparable natural disaster. Yet, this decision would produce an intangible consequence of its own: the long-term effect on the nation's morale of seeing a permanent reminder of the tragedy in the rusted, crumbling husk of a once-great city.

In truth, the degree to which a nuclear attack would transform society is difficult to overstate. No catalog of intangible consequences can make any remote claim of comprehensiveness, nor perhaps is there even value in speculating on these effects beyond the broad level discussed here. A more useful exercise might be to look past the attack's domestic effects and consider its ramifications for the rest of humanity. Although these global consequences are no less difficult to enumerate, even the most superficial treatment of them underscores the extraordinary impact that a nuclear attack would have on the international system.

Global Effects of a Nuclear Attack

Although certain effects of a nuclear event would be largely confined to the country that had been struck, others such as political turmoil and economic disruption would not stop at its borders. Still others would be unique to foreign states, such as the decline in exports to the targeted country due to increased security restrictions and diminished consumer demand. However, this analysis does not attempt to distinguish between the domestic and global intangible effects of a one-off nuclear attack. Nor does it attempt to enumerate the many possible military responses to the event, which would produce wide variance in its global consequences. The most significant of these possibilities is that the response would take the form of a nuclear counterstrike, in which case the social and political repercussions in the first country attacked would be replicated wherever additional nuclear detonations occur. Instead, the following discussion addresses the long-term impacts to international security that could result from a nuclear attack and especially the ways in which it might affect attitudes toward nuclear weapons over time.

Among the most significant international reactions would be the attempt to grapple with the violation of the nuclear taboo, an unwritten inhibition against the use of nuclear weapons that has been a tremendous source of global stability.[46] It is unclear whether a single nuclear attack would undermine the taboo irrevocably or whether it could eventually be restored. Worldwide revulsion over the strike might be enough to reinforce the tradition of nonuse, but a more radical expression of disapproval may also be necessary. One school of thought holds that the only statement strong enough to underscore the unacceptability of a nuclear attack is, paradoxically, the further use of nuclear weapons. While many other factors would supersede the integrity of the nuclear taboo in deciding whether to retaliate with nuclear weapons, the notion that such retaliation might be necessary to restore this tradition would be a significant intangible effect of the attack.

Whether or not the nuclear taboo could be reinstituted, crossing the nuclear threshold may also have implications for other international norms, such as the inhibition against chemical weapons use. Such was the abhorrence of these weapons after the First World War that this taboo has held, with relatively few exceptions—the most notable being their use by Saddam Hussein and Bashar al-Assad—for more than ninety years.[47] Yet, because any chemical attack would pale in comparison to a nuclear one, the occurrence of the latter might persuade the remaining holders of chemical weapons that their use would somehow be more permissible going forward.

Closely linked to the future of the nuclear taboo is how the attack would influence the attractiveness of nuclear weapons to other states. If this event were perceived as ushering in a new era in which these weapons would be used more promiscuously, several latent nuclear powers (e.g., Japan and South Korea) might feel compelled to develop nuclear weapons for their own security. This decision would hinge to a great extent on perceptions of the future credibility of nuclear deterrence. After all, if the targeted state had been a nuclear power and possession of these weapons did not prevent the strike, the very premise of nuclear deterrence—that threats of retaliation inoculate a state from nuclear attack—might be called into question. If so, two starkly different conclusions might be reached.

On one hand, nuclear-armed states might revise their operational doctrine to emphasize preemption rather than deterrence. If one or more nations were perceived as impervious to threats of retaliation, the nuclear powers might adopt declaratory policies reserving the right to forcibly disarm them at the slightest hint of an attack. Or they might simply strike these countries without provocation just to be safe. New capabilities might also accompany these doctrinal shifts, including improved missile accuracy and greater earth penetration for counterforce strikes. Coupled with a lowered political threshold for using nuclear weapons, these improved capabilities might usher in a period in which nuclear attacks become more common. That is, nuclear systems with appropriate yields and accuracy could become newly perceived as effective warfighting weapons rather than instruments of Armageddon. In this case, a new deterrent model based on credible use might supplant the traditional construct based on nonuse with apocalyptic overtones.[48]

On the other hand, the failure of deterrence might have the opposite effect, leading to a fundamental rejection of the political and military utility of nuclear weapons worldwide. In light of the ominous direction that world affairs could take after a nuclear attack, it is easy to overlook the possibility that there might be positive repercussions of the event. To wit, the destruction of Hiroshima and Nagasaki arguably made such an impression on world leaders that they behaved conservatively in subsequent nuclear crises, a crucial intangible effect of the bombings. Or consider the Chernobyl disaster, perhaps the most lasting consequence of which was its effect on Mikhail Gorbachev's attitude toward nuclear weapons. The Soviet leader was by all accounts deeply influenced by the catastrophe, and scholars have speculated that his subsequent openness to arms control, and his eagerness to improve relations with the West more generally, was a direct consequence of Chernobyl.[49]

Similarly, the horrific effects of a nuclear attack might induce an even stronger aversion to these weapons, perhaps reinvigorating the global campaign to abolish them. Indeed, the attack might galvanize world opinion to such a degree that even more sweeping changes to the international order are made possible. Just as the United States received an outpouring of solidarity after the September 11 attacks, the victim of a nuclear strike could enjoy an unprecedented opportunity to use the tragedy for constructive purposes. If this event set in motion a process to demilitarize international politics more broadly, the balance between the tragic and hopeful effects of the attack might ultimately tip toward the latter.

For good or for ill, the first nuclear attack in more than seventy-five years would be an event so monumental that few dimensions of world affairs would be untouched by it. Perhaps no other development holds the potential to effect such radical global change save one: an act of nuclear terrorism. Yet, despite their obvious similarities, there would be important differences between these events. In the interest of identifying the full spectrum of intangible effects, special consideration must be given to the unique consequences of terrorist violence.

Nuclear Terrorism

After the September 11 attacks, policy-makers and the public alike were tormented by the idea that an even greater catastrophe might occur at the hands of terrorists. This fear was stoked by speculation about the probability of a terrorist nuclear attack and ever more lurid descriptions of what such an event would entail. A widely cited Harvard study calculated that a ten-kiloton nuclear device detonated in New York City would kill upward of 500,000 people.[50] (Even if this estimate is off by an order of magnitude, the deaths from such an event could approach the number of US combat deaths in the entire Vietnam War.) Another study by the RAND Corporation concluded that a similar weapon detonated in the port of Long Beach would kill some 60,000 people, exposing 150,000 more to hazardous radiation and displacing several million residents.[51] Despite the emphasis on physical effects in these studies, the statements of many public leaders seem to recognize the potentially deeper impact of intangible consequences.

President Barack Obama, among others, has argued that a terrorist nuclear attack would devastate "our very way of life" and represent nothing less than "a catastrophe for the world"—an admonition that suggests far more grievous effects than mere physical destruction.[52] After all, it is not uncommon for human beings to die by the hundreds of thousands in natural disasters, disease outbreaks, and violent conflicts without significant international repercussions, much less genuine global upheavals. The 2004 Indian Ocean tsunami, for instance, killed more than 230,000 people with little long-term impact, while upward of 5.4 million people died in the Second Congo War, a conflict that few Westerners were even aware of.[53] And although the aftershocks of the COVID-19 pandemic have not yet taken shape, the deaths of more than four million people worldwide do not appear to have produced any tectonic shifts in the international order. Thus, the death toll alone from an act of nuclear terrorism would not constitute the global calamity that Obama imagined. Rather, his implication seemed to be that the true catastrophe would come in the form of cascading effects, which would convulse the international system long after the attack itself. Among these effects would be the inevitable policy responses of the wounded nation, which history has shown can compound an injury manyfold.[54]

Indeed, the range of unfortunate reactions to the September 11 attacks is a case study of the phenomenon, providing a rough baseline of intangible effects that may be reprised after an act of nuclear terrorism. Notwithstanding the differences between these events, a brief review of the United States' response to September 11 is valuable, if only to underscore that the intangible effects of a disaster can greatly exceed its physical devastation.

The Past as Prologue: The Intangible Effects of September 11

Without diminishing the appalling human toll of September 11, the range of nonphysical effects of the attacks is even more imposing. It includes the extraordinary expense of response and recovery operations, lost economic output, the disruption from border closings and restrictions on air travel, the costs of short- and long-term domestic security measures, and the hemorrhaging of blood and treasure in overseas military operations, to say nothing of the opportunity costs of each of these. Also noteworthy were the psychological and social effects of the attacks, both positive and negative. On the positive side were the upsurge in public displays of patriotism, the sincere (if short-lived) comity between the nation's political parties, and the public's willingness to finally confront the threat of Islamist terrorism. The adverse consequences were far more numerous and in many ways more difficult to capture, but it suffices to note that the first major attack on US soil in sixty years profoundly altered Americans' mental well-being.

For those in close proximity to the attacks, the gruesome scenes—disintegrating buildings, office workers leaping to their deaths—were profoundly traumatizing. An epidemiological survey conducted after September 11 found that the prevalence of posttraumatic stress disorder in the New York City area stood at more than 11 percent.[55] Moreover, these psychological effects were not restricted to the cities directly affected. A study published in the *Journal of the American Medical Association* found that 17 percent of the US population outside New York reported symptoms of posttraumatic stress two months after the tragedy, and almost 6 percent did so six months later.[56] This psychological trauma, coupled with the fear that other attacks would soon follow, gave rise to policies whose severity would have been inconceivable before this event. Some of these were reminiscent of a particularly shameful episode in American history, the wartime internment of Japanese Americans. Not long after September 11, a controversial policy was instituted requiring noncitizen male residents from a number of predominantly Muslim countries to register with the government, and more than 177,000 did so before the program was terminated.[57] More ominously, hundreds of aliens were held for months in connection with the investigation without being informed of the charges against them and with severe restrictions on communications with family and counsel. Many of these detainees were subjected to harsh treatment, such as the use of hostile dogs to intimidate them.[58]

In the years after the attacks, senior US officials sanctioned the use of even more inhumane methods at Guantánamo, Abu Ghraib, and secret CIA facilities.[59] As one nonpartisan review concluded, September 11 produced unprecedented discussions "directly involving a president and his top advisers on the wisdom, propriety and legality of inflicting pain and torment on some detainees in our custody."[60] In addition to the reputational costs these tactics imposed on the United States, they also proved harmful to US security, not least in bolstering resistance to American war aims in Iraq. According to the head of the unit tasked with locating al-Qaeda leader Abu Musab al-Zarqawi, "the No. 1 reason foreign fighters flocked [to Iraq] to fight were the abuses carried out at Abu Ghraib and Guantánamo. Our policy of torture was directly and swiftly recruiting fighters for al-Qaeda in Iraq."[61]

The invasion of Iraq itself was of course the most significant intangible effect of the September 11 attacks, a decision that led to the deaths of 4,500 Americans and the wounding of another 32,000, in addition to as many as 200,000 Iraqi civilian deaths.[62] Moreover, the economic cost of the war was estimated to exceed $2.4 trillion by 2017, a figure almost thirty times greater than the roughly $80 billion toll of the terrorist attacks.[63] Although the Iraq War was not solely due to the September 11 attacks, it is highly doubtful that public support for the invasion could have been mustered in the absence of this national trauma nineteen months earlier. Indeed, the Bush administration explicitly linked the Iraq action to the "war on terrorism" and succeeded to such an extent that at the time of the invasion, nearly seven in ten Americans believed that Saddam Hussein was personally involved in September 11.[64] Even less ambiguous is the link between the terrorist attacks and the war in Afghanistan, from which the United States took no less than twenty years to extract itself. Coupled with the Iraq War, the colossal toll of these discretionary reactions to September 11 becomes apparent.

Understanding the intangible consequences of terrorism—psychological trauma, military and police overreaction, and so on—is crucial because their achievement is often as desirable to terrorists as physical destruction, and perhaps even more so. Indeed, in a model of terrorist objectives and values created by the Center for Risk and Economic Analysis of Terrorism Events, the "benefits" of attacks from their perpetrators' perspective included "horror effect," economic impact, symbolic value, and impact on the American way of life.[65] All these consequences fall squarely in the intangible category. Because many of them are within the control of the targeted nation, recognizing terrorists' desire to achieve these outcomes is critical to forming judicious responses to an attack. Of course, the shock from an act of nuclear terrorism would be so great as to test the resolve of even the most resilient society, perhaps defying the best-laid plans to respond dispassionately. Nevertheless, the response to the September 11 attacks should serve as a cautionary tale in navigating the landscape after an even greater catastrophe.

Domestic Effects of Nuclear Terrorism

Many intangible effects of a terrorist nuclear attack would resemble those resulting from other large-scale disasters. Others would be unique to the event, especially effects stemming from the public's fear of radiation. Likewise, while an act of nuclear terrorism would feature many of the same characteristics as a state-orchestrated nuclear strike, certain factors that are peculiar to terrorism may compound the adverse reactions to the event.

In a study on how to enhance the public's resilience to mass-casualty terrorism, Joshua Pollack and Jason Wood identify a number of potential "indirect effects" of such an attack, which are merely intangible consequences by another name. These include posttraumatic stress disorder, depression, self-evacuation from urban areas, civil violence, and erosion of support for the sitting administration.[66] At the root of each of these phenomena is the psychological injury that would attend this event, which would be exacerbated by the unique nature of terrorist violence. Unlike the case of a state-launched strike, there may be no physical assets to retaliate against after a terrorist attack, denying the catharsis of avenging the insult. Similarly, whereas conflicts with states have a finite duration, and relations with enemies can theoretically be repaired, the threat from nuclear-capable terrorists can only end with their total annihilation. The difficulty of achieving this outcome may lead to despair over the potential for indefinite conflict, which would carry not only the possibility of further attacks but also the enormous cost of security countermeasures and military operations to prevent them. Additionally, the inevitable military mobilization may be understood as inaugurating a conflict not only with the terrorists themselves but also with their coreligionists worldwide. Each of these sources of distress would be present from the first moment of the attack, although more urgent concerns would likely preoccupy survivors in the attack's immediate aftermath.[67]

For those outside the blast zone, many of whom would be severely injured, two objectives would be paramount: seeking safer ground and gathering information. Both of these would be hindered by the disruption of internet and cell phone communications, heightening survivors' sense of helplessness. Elsewhere in the city, family members would try to reconnect with one another—in particular, parents would try to reach their children—even in inhospitable areas and in defiance of evacuation orders. (School policies enacted after September 11 that prevent children from being released to their parents may set the stage for hostile confrontations.[68]) Routes of egress from the devastated city would quickly become clogged, and large movements of people on foot would occur. The challenge of securing essential services—food, water, shelter, sanitation—for evacuees would tax their already strained capacity to cope with the catastrophe. Although a spirit of cooperation may take hold in this environment, the unprecedented nature of a nuclear attack may lead to antisocial behaviors on a significant scale. For example, competition for limited medical resources, and especially radiation decontamination, could produce breakdowns in civility.

People in other regions would also be preoccupied with their physical safety, which they may judge to be threatened even if they lived far from the site of the attack. These concerns would arise because the terrorists would almost certainly try to gain extra mileage from the attack by raising anxieties that another may be imminent. For instance, the perpetrators might make a dramatic public announcement that another city would be attacked unless certain political demands were met. This announcement would present the residents of other cities with a difficult choice: either remain in place and risk death or join the throngs of citizens evacuating the nation's urban centers.[69] Some of these refugees may choose to permanently relocate to more rural areas, a migration that could eventually include businesses and government agencies.[70] The social and political consequences of this phenomenon would be difficult to predict, but even a modest reversal of the worldwide trend toward urbanization, in which more than half of the world's population lives in cities, would be of enormous lasting import.[71]

Enticing survivors to return to the devastated city would require a mammoth decontamination effort that would likely exceed actual needs. After the Goiânia incident, for example, scores of contaminated buildings were demolished over an area of forty city blocks.[72] The economic toll of this incident included $20 million in remediation costs and hundreds of millions in losses from a downturn in tourism and damage to the commercial infrastructure—all from a small source of cesium. Little imagination is required to envision the economic impact of a genuine nuclear detonation. Nonetheless, analysts have made these very calculations, and the cost is as staggering as one would expect.

In 2005, researchers at Pacific Northwest National Laboratory studied the economic consequences of a terrorist nuclear attack, beginning with the cost of decontamination, decommissioning, and disposal of contaminated debris. They also included variables such as the expense of evacuating and relocating residents; the cost to repair or replace damaged property; compensation to owners for lost property use; the cost of lowered real estate values; and the financial toll of lost business to the local, regional, and national economies. Finally, the team included a macabre estimate of the lost future productivity of the dead. Their conclusion was that a thirteen-kiloton device detonated in New York City would produce economic costs comparable to the total US gross domestic product for all of 2005.[73]

In addition to these costs, security policies enacted after the attack would likely hamper commercial activity: borders and ports would be closed, rail shipments from ports suspended, and air traffic grounded for an indeterminate period. Further, restrictions on domestic travel and other personal freedoms might be imposed to assist the apprehension of terrorists still at large in the country. The speed with which these measures are relaxed would depend on whether the threat had been neutralized, but as long as they were in effect, shortages of fuel and basic goods would begin to occur, further demoralizing the population.[74] These effects would require a massive government intervention to ameliorate. The cost of this effort, coupled with the chilling effect of security measures on commerce and a general loss of investor confidence, could trigger a prolonged depression.

Over the mid to long term, other social and political ramifications would take shape whose character is difficult to surmise. Whether these would have a net negative or positive effect on society is uncertain, although some combination of constructive and harmful responses can be expected. A renewed sense of national unity like that seen after September 11 is certainly possible, although its duration and tangible impact may be just as ephemeral. Depending on the identity of the attackers, a climate of intolerance toward certain ethnic or religious groups could arise, possibly leading to organized violence. This development could undermine the assimilation of these groups into mainstream society, increasing the threat of religious and political militancy over the long term.[75] Within the broader population, anger over the attack could give rise to enthusiasm for radical responses to the terrorist threat, including the suspension of certain civil liberties. Finally, the thirst for retribution would almost certainly lead to military operations abroad. This response would play a significant role in determining the global effects of the attack, although many such developments would occur independently of the wounded nation's reaction.

Global Effects of Nuclear Terrorism

Various factors ranging from the flow of information on the internet to the globalization of markets would ensure that an act of nuclear terrorism anywhere would be a truly international event. Many global consequences would merely be external extensions of phenomena experienced in the targeted country (e.g., disrupted commerce), whereas others, such as the casualties from its military response, would have no domestic analogues. Cumulatively, the magnitude of these global effects might surpass that of the consequences in the country where the attack occurred.

Among the immediate overseas effects would be the psychological repercussions of the attack, which would be felt in every corner of the planet. Recent research suggests that September 11 had a pronounced psychological "spillover" effect, resulting in lower levels of "subjective well-being" among British residents interviewed after the event.[76] At the very least, a vivid confirmation that nuclear terrorism is possible would force the residents of every large city in the world to contemplate a similar attack where they live. Additionally, if the perpetrators of the attack were Islamist terrorists, innocent Muslims in countries that have traditionally been the setting of foreign military operations might be apprehensive that they will become collateral victims of the targeted nation's retaliation.[77]

The psychological effects of the disaster would manifest themselves in a variety of ways, but one probable response would be heightened opposition to all things nuclear. Indeed, Three Mile Island, Chernobyl, and Fukushima each contributed to a widespread anxiety about nuclear energy that shaped global nuclear policy for years. After the Fukushima disaster, for example, Germany quickly moved to shutter eight of its nuclear reactors permanently and undertook to close the remainder of its fleet by 2022.[78] Similarly, in an Italian referendum three months after Fukushima, 94 percent of voters rejected a plan to restart the country's nuclear program, which had been abandoned in the 1980s—after a similar referendum following the Chernobyl disaster.[79] The collective backlash after a malicious use of nuclear energy might be even more intense, demanding the disposition of nuclear fuels not only in military stockpiles but also in the civil energy sector.

A successful antinuclear movement would have grave implications for the economies of many nuclear-reliant states. However, the most staggering economic effects of a terrorist nuclear attack would result from more immediate phenomena. To begin with, equity markets around the world would inevitably plunge, as they did the day after the September 11 attacks.[80] Later, if the attack led to a recession in the targeted country, as it almost certainly would, the cancer could metastasize into a sharp global downturn. These economic effects would impose considerable suffering throughout the world. As former United Nations general secretary Kofi Annan has noted, an act of nuclear terrorism "would not only cause widespread death and destruction, but would stagger the world economy and thrust tens of millions of people into dire poverty." Given the relationship between poverty and infant mortality, he warns that "any nuclear terrorist attack would have a second death toll throughout the developing world."[81]

As in the case of a state-launched nuclear strike, the wounded nation's retaliation would likely be the most consequential reaction to a terrorist attack. After a manufactured disaster of this scale, national leaders would face enormous pressure to slake the public's desire for revenge. Advances in radiochemical forensic analysis would probably allow the source of the nuclear material used in the device to be identified, which could implicate a foreign government in assisting the plot. The penalty for having done so would be severe, possibly including efforts to hold individual political and military leaders personally responsible. Even if there is a tenuous or nonexistent connection between the state from which the material originated and the terrorist attack, the desire to hold *someone* accountable might override standard legal and moral thresholds governing the use of force.[82]

Military action against the terrorists themselves would of course be unrelenting. Recall that almost a decade passed between the September 11 attacks and Osama bin Laden's death, illustrating the durability of a state's grievance against the authors of mass murder. Virtually all the organizers of those attacks have been killed or captured, and the top tier of al-Qaeda has been systematically eliminated. Likewise, the group responsible for an act of nuclear terrorism would be ruthlessly dismembered. The extent to which this campaign affects innocent people, whose injury would be a significant intangible effect of the attack, would depend on the nature of the armed response. A war paradigm, complete with air strikes or outright invasion, would naturally cause more collateral deaths than a covert approach, such as Israel's assassination of Black September's leaders after the 1972 Munich massacre. Furthermore, the externalities of the former approach would be much greater. For example, those who lose family members and property in the action would be deeply hostile toward the responsible state, possibly resulting in further acts of terrorism over the long term.

In addition to these direct outcomes, military retaliation could force a restructuring of the international order, with formerly unaligned states pressed to cooperate with the wounded nation against the terrorists and any state sponsors. Resistance to such pressure, or disapproval of the military and political response writ large, could strain relations with erstwhile allies, as the Iraq War did with many of the United States' allies. Additionally, the long-term behavior of the victim state would surely be colored by the tragedy, possibly in ways that alienate friends and neutral states alike. If the attack led to persistent bellicosity on the world stage, the hostility that it generated would count as a lasting intangible consequence.

As in the case of a state-launched attack, the domestic and global ramifications of an act of nuclear terrorism are simply too diverse to enumerate in any comprehensive way. However, several key themes emerge from even a limited examination of these phenomena, and these themes can be used to identify policy implications concerning intangible effects. Chief among them is the fact that many such effects are discretionary. With proper foresight and discipline, the individual and collective responses to a nuclear attack can minimize self-inflicted damage to a considerable degree. Consequently, efforts to mitigate the adverse effects of an attack would be most efficiently directed at intangible consequences, the category that is most within our control. The remainder of this chapter is devoted to exploring the means by which this essential truth can be practically applied.

Policy Implications

Fostering awareness of the nonphysical consequences of nuclear weapons is an exercise in tension with the long history of fetishizing physical effects, which only increased after September 11. When the prospect of a terrorist nuclear attack suddenly became all too imaginable, websites soon sprang up allowing one to enter a ZIP code and observe the physical destruction of a nuclear device at various distances from ground zero.[83] Yet, the folly of this myopia was plain over sixty years ago when Fred Iklé observed that the public "knows more about the physical effects [of nuclear weapons] than it can cope with. It makes little difference whether a certain destruction radius is ten or fifteen miles if we cannot grasp the social implications of large-scale destruction at all."[84]

Despite the overwhelming focus on physical damage, there are sporadic acknowledgments in US government literature of the broader range of effects from a nuclear detonation. For example, an Air Force guidance document entitled *Nuclear Operations* notes that beyond the physical consequences of nuclear weapons use there are "significant psychological and political effects, which may lead to unintended consequences." A US nuclear attack may have "short- and long-term negative effects on relations with other countries," including allies who find the use of these weapons unacceptable. Thus, the president and US military planners are advised to consider military options "in the full context of their effects rather than in isolation."[85] However, the mechanisms through which this understanding is to be imparted are not specified, and the impression forms that they do not exist in any formal sense.

Similarly, some US officials have demonstrated awareness of intangible effects in the context of nuclear terrorism. Then CIA director John Brennan, for instance, remarked in 2012 that an attack with weapons of mass destruction would, in addition to killing large numbers of people, have "a mass effect on economic, social, political, and cultural systems far beyond the carnage generated at the point of attack."[86] However, such rhetoric seems to be employed for shock value, underscoring how horrific an attack would be rather than illuminating plans to manage these consequences. Although government literature occasionally acknowledges intangible effects, formal planning documents generally neglect these phenomena. To wit, a 2011 Lawrence Livermore National Laboratory report on "response planning factors" for the aftermath of nuclear terrorism addressed prompt physical effects, fallout, and so on but scarcely touched on human reactions to the event.[87] National Security Council guidance issued the previous year was slightly more attentive, at least noting that "social, psychological, and behavioral impacts of a nuclear detonation would be widespread and profound, affecting how the incident unfolds and the severity of its consequences." Yet, even in this document, physical effects reign supreme—the discussion of behavioral responses is not significantly longer than the recommendations for radiation decontamination of household pets.[88]

Several factors account for the nuclear policy community's allergy to intangible effects. First, technical personnel dominate this field, and their quantitative inclinations pull them toward metrics that can be readily measured, such as physical destruction.[89] Because intangible consequences are less amenable to quantification, technical experts tend to zero them out in their thinking. Second, analysis of these consequences is extremely difficult, and there has been little rigorous research on the subject beyond the speculative writings surveyed earlier. As a result, even if policy-makers could be persuaded to address intangible effects, ignorance of these phenomena would make it challenging to identify the most effective approaches for doing so. Given the diversity of intangible consequences, the obvious candidates for government intervention would be policies that address the root causes of multiple phenomena. Yet, even this approach is problematic because many of these root causes are highly resistant to intervention. For example, what practical means are available to assuage the psychological injury that results from the death of tens of thousands of one's countrymen?

Nonetheless, attempting to minimize intangible effects should not be seen as a hopeless task. These phenomena are largely the products of human behavior, and history suggests that individual and collective conduct can be conditioned, for good or for ill. In light of the salience of intangible effects in many historical events, serious efforts should be made to identify areas that are most ripe for policy prescriptions. Further study of these consequences should inform not only preparedness efforts for coping with a nuclear attack but also domestic and international policy responses in its aftermath. The final sections of this chapter explore potential policies that might help mitigate the harm of intangible effects at both the individual and government levels. Although state-launched nuclear attacks and acts of nuclear terrorism present different implications, there is sufficient overlap in the consequences of these events that certain government interventions may apply to both.

Influencing Individual Responses to a Nuclear Attack

Perhaps the most widely recognized but elusive means of mitigating counterproductive behavior after a disaster is to strengthen the public's "resilience."[90] While no universal definition of this quality exists, it generally refers to the capacity to cope with a difficult event, whether man-made or naturally occurring, and quickly return to a state of normality. Attempts to strengthen resilience date to the earliest years of the Cold War, when the government took efforts to educate citizens on steps they could take to protect themselves from a nuclear attack.[91] Most famously, American children were taught to "duck and cover" when they saw the flash of a nuclear detonation. According to scholar Michael T. Kindt, many of these policies were designed not so much to provide real protection against nuclear weapons but to "place preparedness in the hands of the population rather than establishing the federal government as the primary protector of Americans against attack."[92]

In the present day, allusions to resilience are littered throughout the disaster preparedness literature, and references to the concept have been enshrined in government doctrine.[93] The 2011 *National Strategy for Counterterrorism*, for example, states that the nation contributes to its "collective resilience" by demonstrating that the United States possesses "the individual, community, and economic strength to absorb, rebuild, and recover from any catastrophic event."[94] Yet, these documents are marked by a poverty of specific proposals for nurturing resilience, and there is little evidence that terrorism preparedness has taken hold in the public consciousness in the way that civil defense did during the Cold War.

President Bush launched Citizen Corps after the September 11 attacks to bring together government and communities for "all-hazards" emergency preparedness.[95] However, high rates of inactivity have been found among Citizen Corps councils, the community organizations established to foster preparedness.[96] Similarly, an early attempt to increase individual responsibility was decidedly unsuccessful. In 2003, the Department of Homeland Security recommended that various items be stored in family preparedness kits, including duct tape and plastic sheeting to seal rooms in the event of a chemical attack.[97] This advice was roundly ridiculed in the media and arguably made the public *less* inclined to take disaster planning seriously.[98] Nonetheless, through its Ready campaign, the Department of Homeland Security continued to conduct public messaging on preparedness, advocating the storage of a seventy-two-hour supply of food and water, a first-aid kit, and the development of emergency plans for families to rendezvous after a disaster. However, these steps are only as effective as they are followed, and there is little reason to believe that a critical mass of Americans has responded to the call for preparedness.[99]

A possible explanation for this failure is that campaigns to strengthen resilience simply cast the net too wide, addressing disparate disaster scenarios under a single rubric. Indeed, the Citizen Corps' stated mission is to make communities "better prepared to respond to the threats of terrorism, crime, public health issues, and disasters of all kinds."[100] By lumping terrorist attacks together with forest fires, the government may dilute its ability to influence behaviors that are specific to man-made catastrophes. Rather than attempting to increase resilience generally, focused interventions may yield better results. And given the uniquely destructive nature of a nuclear attack, it seems appropriate that this scenario should receive the lion's share of attention in preparing the public to cope with a catastrophic event.

One behavior whose modification would be hugely consequential after a nuclear attack is the flight of survivors from an area that has just been struck, an impulse driven largely by the fear of radiation. Planners have long advocated conditioning the public to shelter in place after a nuclear detonation rather than self-evacuate, which would minimize exposure to fallout when radiation dose rates are highest.[101] The Lawrence Livermore report cited earlier found that if survivors understood basic principles of radiation and behaved accordingly, 96 percent of potential casualties from fallout—potentially hundreds of thousands of people—could be avoided after an attack.[102] However, achieving this outcome would be difficult for several reasons.

Advising residents to remain in place after a nuclear detonation very much contradicts the human instinct to flee danger. Further, seeking shelter is superior to self-evacuation for *most* but not all survivors. As Ashton Carter, Michael May, and William Perry note, "For most people in the city struck, their best bet to avoid serious radiation exposure would be to find shelter below ground for approximately three days until radiation levels had subsided and only then to evacuate the area." But for a "comparatively few people just downwind of the detonation . . . sheltering would not in fact offer enough protection, and their only chance would be to leave as soon as possible."[103] Learning in real time which group one belonged to requires a means of communication that presently does not exist. Furthermore, even if such a system were created, responding to this information accordingly requires the public to be conditioned to trust government instructions in an emergency, which may be the most difficult requirement of all.

With regard to the first of these necessities, there are no plans for a system that can withstand the unique physical effects of a nuclear detonation and rapidly disseminate critical data (e.g., fallout plume direction) to the population of a major city. Although the government maintains an Emergency Alert System to issue warnings via television and radio, this tool lacks the ability to influence individual behavior among those most at risk of exposure.[104] This is so because the system broadcasts only audio messages (to those who happen to have the television or radio turned on) and does not distinguish between radiation risk groups. For several years the government has been implementing the Commercial Mobile Alert System, which would broadcast emergency messages to mobile devices. However, even when fully operational, this system would only issue blanket warnings to the public, and plans call for its use in a variety of scenarios, including weather warnings and AMBER alerts for missing children.[105] A more sophisticated tool could conceivably leverage the GPS feature of many cell phones and tablets, which might allow specific groups to be targeted with tailored instructions (e.g., shelter in place versus self-evacuate). Further, narrowing the use of this medium to catastrophic attacks might increase the seriousness with which the public takes emergency alerts.[106]

While the challenge of issuing life-saving information is potentially solvable with technology, conditioning people to follow government instructions is arguably more challenging. This effort would involve either educating an apathetic public before a nuclear attack or a terrified population after one. In the first instance, most people prefer not to mentally engage the prospect of a nuclear attack in their daily lives. Once a detonation has already occurred, it would be difficult to impart complex and often counterintuitive information to panicked survivors in real time. A substantial body of literature has explored the challenge of communicating risk to the public after a radiological or nuclear attack, but there is little evidence that this scholarship has produced many actionable conclusions, much less that these findings have made their way into US planning efforts.[107]

Despite these obstacles, there are reasons to believe that communicating technical information to the lay public can succeed. Notably, the United Kingdom's Health Protection Agency won plaudits for its communication strategy after the 2006 polonium poisoning of Alexander Litvinenko in London. The agency was diligent in assuring the public that the radiation risk was confined to a specific geographic area, which reassured those outside the affected zone. Although some approaches used in the Litvinenko case, such as offering free urine tests for those concerned about radiation exposure, may not be scalable for an act of nuclear terrorism, the response to this incident demonstrates that technical information can be successfully imparted to an unlearned population and that psychological consequences can be alleviated.[108] If similarly effective methods can be devised to transmit information after a nuclear detonation, not only would survivors' mental health be spared but so would many of their lives.

Minimizing casualties from fallout is not a panacea, but doing so may mitigate other consequences far from the site of the attack. For example, if the size of the death toll and images of mass evacuations are sources of mental anguish in other parts of the country, both would be reduced by optimal behavior on the part of survivors near the blast site. Likewise, managing a much smaller pool of casualties and a more orderly evacuation from a devastated city would relieve pressure on first responders, allowing them to target their resources more effectively. Above all, managing the scale of the disaster might help temper the impulse of national leaders to respond excessively to the attack.

While the government has an obvious interest in influencing individual behavior following a nuclear attack, one class of reactions is exclusive to government leaders—domestic response and recovery operations, law enforcement and homeland security measures, military operations, and diplomatic initiatives overseas. Given that such policy responses are often the most consequential effects of terrorism, it is crucial that leaders' decisions not compound the damage should an attack occur. The following discussion focuses on heightening awareness of intangible consequences among government leaders and identifying the various ways their decision-making may improve as a result. Although this knowledge would be most applicable in the aftermath of a nuclear attack, it is also germane to the decision to initiate the first use of nuclear weapons. In both cases, the full range of nuclear effects, and not just physical ones, should inform leaders' decisions.

Influencing Nuclear Doctrine and Government Responses to a Nuclear Attack

Of the two most momentous decisions that leaders can make with respect to nuclear weapons—whether to launch a nuclear strike and how best to respond to such an attack on their own country—it is difficult to predict which would be most influenced by an appreciation of intangible effects. In the first instance, every leader would have some intuitive grasp of these consequences even without a conscious campaign to highlight them. Any president contemplating a nuclear attack would surely feel the weight of history on their shoulders, and sensitivity to its judgment would probably lead to conservative decision-making. However, there are conceivable scenarios in which a vague notion of intangible consequences might not be enough to override the perceived military advantages of using a nuclear weapon. One such scenario is the detonation of a weapon in an uninhabited area as an expression of resolve, which might be seen as less provocative than the destructive use of a weapon and thus more likely to de-escalate a crisis.[109] However, the short-term effect of this act must be balanced against its broader global repercussions. If the full range of intangible effects were properly understood, their magnitude might outweigh the perceived advantages of conducting a nuclear demonstration.

Although the consequences of a state-launched nuclear attack have already been surveyed at some length, certain of these effects would redound to the particular detriment of the perpetrator. One would be a significant reputational cost regardless of the circumstances of the attack. Indeed, the United States still bears a stigma in some quarters for dropping the bomb on Japan despite that country's serial war crimes and unprovoked attack on Pearl Harbor. Any violator of the nuclear taboo would suffer a considerable political penalty for this decision, especially if subsequent attacks occur and are then attributed to the weakening of this international norm. While such opprobrium would be less troubling to states accustomed to international scorn (e.g., Russia and Israel), certain expressions of disapproval would be felt by even the most recalcitrant regimes. It is entirely conceivable, for instance, that long-standing allies would join in economic sanctions against the offending state, inflicting pain on its general population and diminishing the government's popular support. Finally, the agent of the attack might be seen as inviting similar aggression on itself over the long term. Just as a nation that tortures detainees has no reasonable expectation that its own captives will be treated humanely, the author of a nuclear strike would arguably forfeit its right not to be attacked similarly in the future.

Assuming the policy community accepts the salience of intangible effects, two principal steps must be taken before these consequences can be integrated into nuclear policy. First, further research is needed to identify the full range of intangible phenomena as well as means to mitigate especially harmful effects. Second, mechanisms must be developed to incorporate these findings into crisis decision-making, nuclear doctrine, arms control policy, and national security strategy writ large. The latter requirement is perhaps the more difficult of the two because it involves institutionalizing complex and often subjective concepts, to say nothing of overcoming the bias toward physical effects in the nuclear policy establishment.

One approach is to socialize intangible consequences as widely as possible, with particular emphasis on the externalities of poor decision-making. Even without prescribing specific means to avoid these consequences, simply being exposed to them would make decision-makers more mindful of their pernicious nature. A variety of media can be used toward this end, such as government strategy documents and academic literature, both of which should feature a greater symmetry between physical and nonphysical effects. Likewise, intangible consequences should be included in the curricula of security studies courses and professional military education programs. Members of the armed forces and civilians with responsibility for nuclear operations should be exposed to these concepts at every stage of their careers, which could be accomplished by incorporating the concepts into their frequent war games and tabletop exercises. Finally, nongovernmental organizations should encourage a public discourse on the cascading effects of nuclear weapons use. Rather than focusing chiefly on the physical destruction from a major nuclear exchange—typified by the Doomsday Clock of the *Bulletin of the Atomic Scientists*—these organizations might emphasize the spiraling consequences of more limited nuclear strikes.[110]

Each of these approaches would be equally germane to preparing leaders for the response to a nuclear attack—a scenario in which intangibles are more likely to influence their judgment. Unlike the decision to launch a first strike, where the question is whether or not to initiate a truly world-historical event, responding to a nuclear attack in some form is unavoidable, and decisions are simply a matter of choosing the most advantageous course of action from many competing alternatives. Because every reaction, large or small, would be an intangible effect of the attack, leaders' appreciation of intangible effects would color a much wider range of choices than the largely binary decision of a first strike.

Although the need to positively influence reactions to a nuclear attack is clear, the same conundrum that complicates this objective at the individual level also applies to governments: the enormous range of potential responses makes it difficult to craft targeted guidance. One possible way to address this dilemma is to reinforce select themes that touch on a wide variety of policies, much as managing the public's fear of radiation has broad applicability at the individual level. With respect to government decisions, if there is an analogue to strengthening public resilience, it is the need to underscore the potential for counterproductive responses to a nuclear attack. Because the pitfalls of poor decision-making after a state-sponsored strike have been explored for decades, the following discussion focuses on responses to an act of nuclear terrorism, although many of its observations would apply equally to both scenarios.

The tenor of the reaction to a terrorist nuclear attack, and especially its military dimension, offers perhaps the best opportunity to minimize harmful intangible effects. After such an incomprehensible national trauma, government leaders would seek to punish the guilty party as quickly and severely as possible, if only to assuage public anguish. Yet, acting on erroneous information or lashing out indiscriminately could have profoundly damaging effects. This is particularly true given the knowledge that precipitating an overreaction is often the explicit aim of violent extremists. Indeed, shortly after September 11, Princeton scholar Michael Scott Doran warned that a rash military response to the attacks would follow the script of Osama bin Laden's "piece of high political theater" whose audience was not the American people but the *umma*, or global Islamic community:

> The script was obvious: America, cast as the villain, was supposed to use its military might like a cartoon character trying to kill a fly with a shotgun. The media would see to it that any use of force against the civilian population of Afghanistan was broadcast around the world, and the *umma* would find it shocking how Americans nonchalantly caused Muslims to suffer and die.[111]

To their credit, US leaders initially resisted the impulse to lash out after September 11. Almost two months passed between the attacks and the first US military operations in Afghanistan, and that campaign was marked by scrupulous efforts to minimize civilian casualties. Only with the US misadventure in Iraq did the United States begin to follow bin Laden's playbook, killing huge numbers of Iraqi civilians, poisoning attitudes toward the United States in the Muslim world, and sinking hundreds of thousands of American troops in a multiyear quagmire. With luck, this historical lesson would counsel against a similar reaction to a terrorist nuclear attack. Yet, the demand for a commensurate response may prove to be irresistible. Of particular concern is the danger that leaders would retaliate with nuclear weapons, if only to answer the attack with an act of comparable significance. As Scott Sagan notes, such a response might play directly into the hands of Islamist terrorists. "U.S. threats to retaliate in kind might be welcomed," he warns, "since the U.S. use of nuclear weapons could hasten the downfall of allied regimes in the Muslim world through protests in the mosques and riots in the streets."[112]

Retaliating against a terrorist nuclear attack might also include states that had aided the plot, wittingly or unwittingly. Aside from straightforward sponsorship, a state may inadvertently facilitate an attack through lax security practices that allow terrorists to acquire fissile material. Various American officials have suggested that the United States might take military action against such states, as then senator Joseph Biden did in 2007 when he declared that "we will hold accountable any country that contributes to a terrorist nuclear attack, whether by directly aiding would-be nuclear terrorists or willfully neglecting its responsibility to secure the nuclear weapons or weapons-usable nuclear material."[113] Whether such rhetoric will actually deter states is open to question, but there are several reasons why the threat might be counterproductive. As Michael Levi cautions, threatening retaliation in this circumstance "undercuts efforts to work cooperatively with those states to improve their nuclear security; dissuades those states from informing others if they discover that their nuclear weapons or materials are ever stolen . . . and makes it difficult to work with those states in the aftermath of an attack to prevent further detonations."[114]

As a general rule, it is advisable to avoid pronouncements before an event that prescribe certain inflexible responses once it occurs. Although there may be some deterrent value in threatening a severe response to a nuclear attack, if deterrence then fails, the state may find itself in a "commitment trap."[115] At this point, it must either make good on the pledge, even if it is not in the country's interest to do so, or risk harm to its national reputation, especially the credibility of future threats. In short, by making such pronouncements, leaders squander the crucial quality that makes intangible effects more manageable than physical ones—their ability to be controlled through wise decision-making.

Appreciation of this quality applies no less to domestic policy responses than to overseas military operations. The former might take a variety of forms, ranging from wasteful or counterproductive security measures to more fundamental trespasses against the norms of governance. The first variety can be difficult to resist because the demand for "security theater" after a disaster is both a bottom-up and a top-down phenomenon. That is, the general public yearns, sometimes subconsciously, for reassurance that it is being protected, and policy-makers grasp for symbols that they are doing *something* to protect the public even if the measures are largely cosmetic. The result is often as ludicrous as it is wasteful, such as the lavish terrorism preparedness grants to rural communities with virtually no risk of being attacked. Other domestic responses may be far more corrosive, affecting the very way of life of the society struck by terrorists. These might include the imposition of curfews and price controls on consumer goods, increased monitoring of communications, extrajudicial detentions, and restrictions on the movement of people and commodities. Although such policies might have little bearing on the recovery from an attack or the prevention of new ones, they might reflect an ineffable sense that the event "changed everything," requiring almost axiomatically that radical changes to society occur.

In this climate, a key challenge for policy-makers would be to ensure that every policy enacted has a demonstrable link to security and justifies any fundamental change to society that results. However, this responsibility does not fall to the government alone. Individuals have an obligation to resist responses that exchange timeless elements of the national character for short-term increases in security, real or perceived. At the very least, they should avoid in their personal conduct behaviors that signal acquiescence to such policies. If an element of human agency is the defining feature of intangible consequences, every individual has an obligation to behave in ways that do not exacerbate the damage from an attack.

Conclusion

For various structural reasons, the difficulty of factoring intangible effects into preparations for a nuclear event is unlikely to diminish. During the Cold War, when a massive nuclear exchange was considered plausible, intangible consequences simply could not compete with the awesome physical damage of such a war in the human imagination. Following that era, when the likelihood of a nuclear exchange was thought to have plummeted, contemplation of *all* nuclear weapons effects, physical and nonphysical, virtually evaporated. Thus, a convenient reason to overlook intangible effects has always been close at hand. Any attempt to focus attention on these consequences today would run counter to the steady retreat of nuclear weapons from the public consciousness over the last three decades.

Even if the mounting disinterest in these weapons could somehow be reversed and the dominance of physical effects could be overcome, there are further reasons to doubt that a greater appreciation for intangible effects will have the impact on global nuclear policy that it should. After all, no stampede to eliminate nuclear weapons followed the discovery of nuclear winter, and more than a quarter century later thousands of these weapons still exist. Yet, it is also possible that this is too cynical an interpretation of the influence of studies and writings on nuclear decision-making over the decades. Perhaps the seventy-five years in which these weapons have not been used is due in part to efforts to underscore just how horrific a nuclear war would be. In this respect, efforts to increase awareness of intangible consequences are clearly called for, regardless of their probability of success. To ignore this call would be to render ourselves defenseless against the large proportion of nuclear weapons effects that are entirely within our control.

Notes

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2. George Perkovich, "The Diminishing Utility and Justice of Nuclear Deterrence," in *Thinking About Strategy: A Tribute to Sir Michael Quinlan*, ed. Bruno Tertrais (Paris: L'Harmattan, 2011), 99–112.
3. Charles Meade and Roger C. Molander, *Considering the Effects of a Catastrophic Terrorist Attack* (Santa Monica, CA: RAND Corporation, 2006), 15, https://www.rand.org/pubs/technical_reports/TR391.html.
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5. Kenjiro Yokoro and Nanao Kamada, "The Public Health Effects of the Use of Nuclear Weapons," in *War and Public Health*, ed. Barry S. Levy and Victor W. Sidel (Oxford: Oxford University Press, 1997), 79.
6. See John S. Foster, Earl Gjelde, William R. Graham, Robert J. Hermann, Henry (Hank) M. Kluepfel, Richard L. Lawson, Gordon K. Soper, Lowell L. Wood Jr., and Joan B. Woodard, *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical National Infrastructures* (McLean, VA: Commission to Assess the Threat to the United States from Electromagnetic Pulse [EMP] Attack, 2008), http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf.

7. There is a subcategory of effects that are, strictly speaking, physical in nature but are sufficiently unusual as to merit the designation “intangible.” For example, a 1979 Office of Technology Assessment study identified a synergistic effect in which the radiation deaths of birds and the destruction of insecticide factories would combine to affect the insect population in ways that might be devastating to agriculture. See Office of Technology Assessment, *The Effects of Nuclear War* (Washington, DC: US Congress, 1979), 12, https://ota.fas.org/reports/7906.pdf.
8. See Robert Vineberg, *Human Factors in Tactical Nuclear Combat*, Technical Report 65-2 (Alexandria, VA: Human Resources Research Office, George Washington University, under contract with the Department of the Army, 1965), https://apps.dtic.mil/sti/pdfs/AD0647838.pdf; G. R. Sessions, *A Summary of the Psychological Effects of Tactical Nuclear Warfare* (Colorado Springs: US Air Force Academy, 1984), https://apps.dtic.mil/sti/pdfs/ADP003256.pdf; and G. W. Baker and L. S. Cottrell Jr., eds., *Human Problems in the Utilization of Fallout Shelters*, Disaster Study No. 12 (Washington, DC: National Academy of Sciences, National Research Council, 1960).
9. Peter G. Nordlie, *An Approach to the Study of Social and Psychological Effects of Nuclear Attack* (McLean, VA: Human Sciences Research, Inc., prepared for the Office of Civil Defense, Department of Defense, March 1963).
10. Bernard Brodie, ed., *The Absolute Weapon: Atomic Power and World Order* (New York: Harcourt Brace, 1946), 76.
11. Fred C. Iklé, “The Social Versus the Physical Effects from Nuclear Bombing,” *Scientific Monthly* 78, no. 3 (1954): 182–187, https://www.jstor.org/stable/20949.
12. Johan Galtung, *On the Social and Cultural Implications of Nuclear War* (Princeton, NJ: Princeton University, April 1986).
13. Office of Technology Assessment, *Effects of Nuclear War*.
14. Office of Technology Assessment, *Effects of Nuclear War*, 775. Interestingly, Iklé cautioned against just this sort of speculation a generation earlier, warning that “we should not be misled by the awesome physical destruction to make occult predictions about the end of civilization.” He saw no reason to expect “large masses of city dwellers to suffer mental breakdowns or to fear that mankind would abandon technology and science.” See Iklé, “Social Versus the Physical Effects from Nuclear Bombing.”
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16. Richard Moyes, Phil Webber, and Greg Crowther, *Humanitarian Consequences: Short Case Study of the Direct Humanitarian Impacts from a Single Nuclear Weapon Detonation on Manchester, UK* (London: Article 36, February 2013).
17. See US Federal Emergency Management Agency, *National Planning Scenarios* (Washington, DC: Department of Homeland Security, 2006).
18. See, for example, Committee for the Compilation of Materials on Damage Caused by the Atomic Bombs in Hiroshima and Nagasaki, *Hiroshima and*

Nagasaki: The Physical, Medical, and Social Effects of the Atomic Bombings, trans. Eisei Ishikawa and David L. Swain (Tokyo: Iwanami Shoten, 1981).

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20. Robert J. Lifton, *Death in Life* (New York: Vantage Books, 1969), 31.
21. Robert J. Lifton, "Psychological Effects of the Atomic Bomb in Hiroshima: The Theme of Death," *Daedalus* 92, no. 3 (1963): 462–497, https://www.jstor.org/stable/20026792.
22. Mikihachiro Tatara, "The Second Generation of Hibakusha, Atomic Bomb Survivors: A Psychologist's View," in *International Handbook of Multigenerational Legacies of Trauma*, ed. Yael Danieli (New York: Plenum Press, 1998), 141–146.
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24. See Gaddis Smith, "Was Moscow Our Real Target?," review of *Atomic Diplomacy: Hiroshima and Potsdam: The Use of the Atomic Bomb and the American Confrontation with Soviet Power* by Gar Alperovitz, *New York Times*, August 18, 1985, Sunday Book Review, https://www.nytimes.com/1985/08/18/books/was-moscow-our-real-target.html.
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34. The Chernobyl Forum 2003–2005, *Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine*, 2nd rev. version (Vienna: Chernobyl Forum, 2006), 36, https://www.iaea.org/sites/default/files/chernobyl.pdf. Tellingly, a UN-commissioned report on the "human consequences" of Chernobyl found no reliable evidence of an increase in leukemia among the affected population, which had been widely predicted. Although rates of other cancers may have increased, much of the survivors' anxiety appears to be based on imagined rather than real health effects, underscoring the potency of psychological consequences. See *The Human Consequences of the Chernobyl Nuclear Accident: A Strategy for Recovery* (Commissioned by UNDP and UNICEF with the support of the UN Office for the Coordination of Humanitarian Affairs and the World Health Organization, January 25, 2002), https://www.iaea.org/sites/default/files/strategy_for_recovery.pdf.
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64. The Iraq War resolution contained the following passage, which clearly suggests a link between Saddam Hussein’s regime and the September 11

attacks: "Whereas members of al Qaida, an organization bearing responsibility for attacks on the United States, its citizens, and interests, including the attacks that occurred on September 11, 2001, are known to be in Iraq." See the Authorization for Use of Military Force against Iraq Resolution of 2002, Pub. L. 107-243, https://www.congress.gov/107/plaws/publ243/PLAW-107publ243.pdf. For polling on the public's belief in a link between Iraq and the attacks, see "Washington Post Poll: Saddam Hussein and the Sept. 11 Attacks," *Washington Post*, September 6, 2003, https://www.washingtonpost.com/wp-srv/politics/polls/vault/stories/data082303.htm.

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81. Kofi Annan, "A Global Strategy for Fighting Terrorism," keynote address to the closing plenary of the International Summit on Democracy, Terrorism and Security, March 10, 2005, https://www.un.org/sg/en/content/sg/speeches/2005-03-10/kofi-annan's-keynote-address-closing-plenary-international-summit.

82. The obvious exception would be Russian-origin material, in which case military retaliation would be unlikely given Russia's considerable capacity for counter-retaliation. Nevertheless, if Russian negligence were responsible for the loss of the material, relations between the wounded nation and Russia would deteriorate in ways that may be greatly destabilizing.

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87. B. R. Buddemeier, J. E. Valentine, K. K. Millage, and L. D. Brandt, *National Capital Region Key Response Planning Factors for the Aftermath of Nuclear Terrorism*, Report No. LLNL-TR-512111 (Livermore, CA: Lawrence Livermore National Laboratory, November 2011).

88. National Security Staff Interagency Policy Coordination Subcommittee for Preparedness & Response to Radiological and Nuclear Threats, *Planning Guidance for Response to a Nuclear Detonation*, 112.

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Chapter 8
Knowledge Integration

Jane M. Booker

For multifaceted problems such as assessing the risk of nuclear deterrence failure, data, information, and knowledge can emerge from many different sources involving diverse subject areas and in myriad qualitative or quantitative forms. Often the amounts of data, information, and knowledge are limited, apply to rare events or events that have never occurred, or both, necessitating the combined use of all sources. For example, sources include historical data on past events; expertise from authorities in different subject areas; and knowledge about past and current cultures, human behaviors, sociology, politics of people and states, as well as the theory or rules governing politics. Regardless of source and form, available knowledge has uncertainty attached. Some uncertainties can be significant, and the uncertainties themselves can be of different types. Depending on the type of uncertainty, quantification may not be feasible or the appropriate mathematical theory for it may be difficult to apply. Nonetheless, decision- and policy-makers need a final or top-level answer about nuclear deterrence failure accompanied by an understandable uncertainty. Knowledge integration methods address these needs and provide ways to tackle other difficulties encountered when combining all available data, information, and knowledge and their associated uncertainties to produce an assessment of risk. Some of the integration principles and methods are described in this chapter, especially those related to the challenges in assessing the risk of nuclear deterrence failure—a problem of significant uncertainties and poor data, information, and knowledge.

The first step in laying the foundation of the concepts for the knowledge integration required to assess the risk of failure of deterrence is to distinguish among data, information, and knowledge.

Data are observations of knowledge that are measured, recorded, enumerated, described, or numerically or symbolically represented. Data are generally considered analyzable, which implies a numerical, ordinal, or categorical form.[1]

Information is commonly defined as facts provided or learned and that which is subsequently conveyed or represented.[2]

Knowledge refers to a body of facts gathered by study, experience, or observation or inferred from those. Knowledge implies processing through the human brain. Thus, cognition, experience, memory, and mental processing are involved in the formulation of knowledge.

Simple examples may serve to clarify these concepts. For the problem of determining the risk of nuclear deterrence failure, data might be in the form of frequency counts of categories of historical events. For example, how many times was the nuclear alert level raised during an international crisis? An example of information would be an intelligence report on a missile test by a foreign state. A knowledge example would be the physics theory necessary to develop a nuclear weapon.

Inherent in the study of data, information, and knowledge is the uncertainty associated with it, for which probability is the most commonly used uncertainty theory with the longest history of use.[3] An uncertainty in the data example above is the possibility of an unknown raising of the nuclear alert level. For the information example, an uncertainty exists in the accuracy of the intelligence report. Even theory, such as nuclear theory, may not be exactly known, creating knowledge uncertainty.

Because the lines among data, information, and knowledge are often blurred, the term *knowledge* is used in this chapter title to represent all three. Additionally, knowledge is the most general, and it is what would be assessed in determining the risk of deterrence failure. Any necessary distinctions among the three, such as differences in applicable methods, are noted. The smallest unit or singleton of knowledge is referred to as a piece of knowledge, which could be a number, a word, or a phrase or statement sufficient to contain the fundamental knowledge.

Knowledge can be considered as having two forms: quantitative and qualitative. The distinction between these two categorizations is not precise (i.e., it is fuzzy).[4] Qualitative knowledge often involves the use of linguistics, some of which can be quantified. Examples include ordinal linguistics such as small, medium, or large and relative comparisons such as worse, the same, or better. The principles and methods for the mathematical combination and/or summarization of all forms of knowledge under uncertainty are referred to as knowledge integration.

With this terminology in hand, the first section of this chapter provides a history of better-known methodologies leading to knowledge integration. The second and third sections address the various aspects of the deterrence assessment problem that require combination and integration principles and methods, respectively. Because of its centrality to the problem, uncertainty combination is treated separately in the fourth section. Following that, the fifth section describes the challenges and benefits associated with knowledge integration. Finally, the sixth section summarizes key issues for the assessment of the risk of deterrence failure.

A Brief History of Knowledge Integration

One of the earliest data combination techniques—multiple frame sampling—came from statistical sampling theory.[5] A sampling frame can be thought of as a partial list of the entire population of interest. Data gathered from different sampling frames are combined, and uncertainties are combined by using probability theory. For example, a telephone survey uses the frame of the phone directory. The telephone-based sample could be combined with a mailed survey using the frame of addresses from the Census Bureau or local government records. The goals of multiple frame sampling are to ensure proper coverage of the population by using data gathered from different frames and to decrease the uncertainty (as variability) in the inferences made about the population. The latter is accomplished by an increased sample size from the combined frame samples.

This sample combination idea was later extended to combining entire studies. Because gathering data from studies (especially human studies) is expensive, meta-analysis was developed to combine different studies. Meta-analysis also has its foundation in statistics, again characterizing uncertainty with probability theory. Combining quantitative data from various sources (i.e., studies) has several advantages:[6]

1. Results from one study can be confirmed by others.
2. The sample size is increased, which reduces variability.
3. Additional effects of varying conditions can be determined.
4. The strengths of relationships between associated quantities can be determined.

As these reasons suggest, more than just data are considered in the combination. Information, in the form of relationships among quantities, is also combined from separate studies to achieve the fourth listed benefit. Application areas for meta-analysis include biology, medicine, social sciences, and education. Credit is given to Glass for pioneering work in this area.[7]

Data fusion[8] and data integration generally refer to the process of combining data from different locations, such as a sensor network or multiple geographical sites. The computational community is part of this field because of the need for managing data with databases and data structures. Data integration is sometimes associated with combining data from different studies, overlapping with meta-analysis. However, methods for data integration are not limited to statistical ones, as with meta-analysis. These integration methods also involve mathematical logic and computational algorithms.

Extending meta-analysis and data integration methods to a more general knowledge or information integration methodology began in the late 1990s with the PREDICT reliability methodology.[9] Before that, an enhancement of probabilistic risk assessment toward an information integration methodology was done in the NUREG-1150 study by merging expertise with data.[10] Four additional major extensions were developed for PREDICT, the first information integration methodology:

1. Formally elicited knowledge was integrated with sparse data and poorly validated theoretical calculations.
2. Knowledge and its uncertainties were quantified and combined using different theories (probability theory and fuzzy sets).
3. Expert knowledge was used to provide structure for a problem not suited to contemporary structuring methods.
4. Validation of the integration methodology was achieved by a simultaneous application to a problem where vital data eventually became available.

Knowledge integration extends the combination beyond data, studies, and relationships to all knowledge, information, and data and their associated uncertainties. For example, elicited knowledge from experts is integrated with what sparse data may be available. Knowledge integration enhances and generalizes many of the techniques from meta-analysis and data fusion. In particular, different types of uncertainties are analyzed using general information theories rather than just probabilistic uncertainty.[11] Knowledge integration methods are useful for combining the different quantities described in the following section.

Multiple Integrations

There is a need for integration methods that would be used to combine (1) all available knowledge from different sources and (2) different types of uncertainties associated with these. However, this is not the complete list of what requires integrating in order to assess the risk of deterrence failure.

Integrations for Risk and Deterrence

Assessing the risk of failure of nuclear deterrence involves assessing the two constituents of risk (likelihood and consequence) and the two constituents of deterrence (credibility and capability). Individually, each of these four constituents presents a difficult combination problem, involving multiple integrations of diverse knowledge sources, only some of which are quantifiable. In addition, integrating tools are lacking and uncertainties of various types are large, primarily because of lack of knowledge. None of these four constituents for assessing the risk of deterrence failure has sufficient knowledge available to use statistical risk analysis methods.

Traditionally, likelihood has been represented as probability. Probabilistic risk assessment has a long history of this practice. Consequence evaluation involves difficult-to-assess quantities such as the value of human life and property and the chaos or damage from destruction. Often multiplication is the mechanism for combining likelihood and consequence. The difficulty with multiplication stems from the fact that the same value of risk can result from a low-consequence–high-probability event as from a high-consequence–low-probability event.

Credibility and capability should be evaluated from the perspective of the party being deterred. Because perspective is involved, evaluation and determination of associated uncertainties of these two constituents are challenging.

Neither combining likelihood and consequence to assess risk nor combining credibility and capability to assess deterrence may be feasible because of these difficulties. To approach achieving a risk analysis capability for the problem of nuclear deterrence, what little knowledge that exists must be collected and put together, necessitating the use of knowledge integration methods for each constituent. Any connections or relationships discovered among the four during their individual assessments should be noted. However, the risk assessment may address the four constituents without an integration of them.

Integration of Experts' Knowledge

For risk assessment of the failure of nuclear deterrence, a major source of knowledge is going to be provided by experts from multiple and diverse subject areas. Drawing conclusions about or providing top-level answers for the four constituents is likely to require resolving differences among these various experts. While differences can originate from different subject areas, differences among experts in the same field are also to be expected. Any group of experts not exhibiting any disagreement is a warning sign that something is amiss with the elicitation or with the selection of experts.

Expert resolution elicitation techniques permit understanding of why disagreements occur and provide ways to resolve many forms of and reasons for differences.[12] As noted in chapter 3, reasons for differences include experts answering slightly different questions than the one posed, experts making different assumptions, and experts using different problem-solving processing in arriving at their responses. Any unresolved differences represent the inherent uncertainty in the current state of knowledge.

Integration of Scenarios, Conditions, and Problem Dimensions

An expert may be asked to provide knowledge about different versions of the problem. For example, different background conditions and/or scenarios leading up to a nuclear attack or war can be posed. The expert would then provide different (conditional) responses depending on the specified conditions and/or scenarios. An unconditional response is formed from conditional responses by using an aggregation method from the "Conditional Combination" subsection of the "Knowledge Integration Principles and Methods" section.

In addition to aggregating conditional responses for each expert, it may be necessary to combine responses across multiple experts from different subject areas. This is particularly true for the problem of determining the risk of deterrence failure, where no single individual has expertise in all subject areas and all problem dimensions. An example of ignoring different subject area expertise is the Lugar survey, in which respondents from different fields answered survey questions covering multiple subjects.[13]

Integrating Uncertainties

Portions of a complex problem that have less available knowledge tend to have larger uncertainties. In addition, different types of uncertainty may have been identified for specific parts of the problem. Those different uncertainties can have different mathematical theories to characterize them. Thus, knowledge integration involves the combining of uncertainties and uncertainty theories. Methods and issues for combining uncertainties are described in the "Uncertainty Combination" section.

Recomposition

In formal elicitation, it is vital to decompose a complex problem or system into manageable pieces for an expert. Such a decomposition must eventually be recombined to obtain an overall top-level answer, which a decision-maker or policy-maker expects. Recombination of different decomposed portions of the problem can involve integrating over different levels of detail, combining the specific with the general.

Difficulties with recomposition of the problem occur when different amounts and types of data, information, and knowledge exist for different parts. For example, historical data may exist for certain (more common) categories of events but not for unique (one of a kind) or never-observed events. The tendency (bias) is to focus on pieces of the problem that have more data, information, and knowledge because analysis and integration methods are easier to implement and uncertainties are easier to quantify. This biased activity is called pearl polishing.

An example of pearl polishing in nuclear deterrence during the Cold War is the US focus on exchange analysis and first-strike stability because those issues were better understood at the time and more analytically tractable. More attention should have been paid to the broader, more difficult issues regarding culture, psychology, and politics. Attention, analysis, and decisions based only on better-known portions of the deterrence problem will not make up for the difficulties resulting from, and lack of attention to, pieces of the problem that are less known or understood.

Recomposition involves utilizing the framework or structure of the problem. Structures can be networks, trees, diagrams, and specialized structures (such as might be supplied by experts consistent with their thinking). Methods for determining that structure are discussed in chapter 3 and include methods from risk analysis, decision analysis, graph theory, logic, and complex systems. Whatever the form of the structure and the nature of the connections between problem parts, it can provide the mechanism and/or rules for integration of parts to reach the top-level answer, such as the four constituents of risk and deterrence.

Knowledge Integration Principles and Methods

Although some tools and methods exist for knowledge integration, research and development of these continues, and many issues remain unresolved. Without presenting details of some of the complicated and esoteric methods, most of which apply only to data-rich problems, an overview of fundamental principles and methods follows.

Quality of Knowledge

Because data, information, and knowledge in the deterrence problem are sparse and/or have large uncertainty, quality of knowledge becomes an important issue. Quality of knowledge involves the use of established practices for gathering knowledge in a manner that properly represents the current state of knowledge.

Knowledge from validated theory, models, or computation is of good quality. Unfortunately, validation (matching theory, models, and computation with reality) requires sufficient data, information, and knowledge. Validation is highly improbable for the risk of deterrence failure problem.

Much of the knowledge for the deterrence problem will come from experts. The difference between using and not using formal elicitation methods is the quality of knowledge. Experimentalists are taught to practice good protocols to ensure the quality of their data, such as implementing controlled conditions and documenting every detail. Formal elicitation serves the same purpose, using techniques to monitor and minimize biases.[14]

In data fusion, care must be taken to understand the quality of the data before combination. Data from biased studies or data that are unrepresentative of the population are of poor quality and are not equivalent to data gathered under controlled conditions. Likewise, knowledge must be gathered that properly represents the population (the current state of knowledge). With experts being the major source of knowledge, expert selection becomes important, as discussed in chapter 3.

The risk of deterrence failure is one of the problems for which a portion of the current state of knowledge resides in the classified community. Studies conducted in an unclassified environment deal with the unclassified population, and results and conclusions are conditional on that population. If classified knowledge becomes accessible, the population is broadened. Whatever the population, the quality of knowledge depends on adequate representation of it, and the conclusions are conditioned on it.

Source Inventory and Evaluation

Integrating knowledge from different sources requires an inventory and some evaluation of the sources and types of knowledge that are available or accessible to anticipate integration difficulties and needs. Table 8.1 shows a simplified listing of knowledge sources (rows) for four discrete cases along a continuum of problems (columns). A common (and somewhat related) example is given for each case: case I concerns how to determine the energy yield of TNT explosive, case II is for determining the electrical power generation capability and safety of nuclear energy reactors, case III concerns the determination of nuclear weapon yield under a testing ban, and case IV is the risk of failure of deterrence problem.

The types and sources of knowledge are listed in the far-left column of Table 8.1. The availability and evaluation of these sources is shown in interior cells of the table for each of the four cases. In the Data row, the cases range from data rich (case I) to data poor (case IV). The History row describes the length of time of experience, including the number of realized events. The state of knowledge about theory or first principles that apply is represented in the third row. How much inference is required to interpret the knowledge, draw conclusions, and make decisions or policy is depicted in the next row. TNT explosive energy output is so well known that it is a National Institute of Standards and Technology standard, requiring no inference. The need for experts as a major source of knowledge is evaluated in the next row. How well calculations or models can be formulated and validated to make predictions is addressed in the Model row. Finally the degree of uncertainty present is listed in the last row. One might argue that uncertainty is not a source of knowledge; however, it is important in the evaluation process and in the knowledge integration.

According to the evaluations in Table 8.1, the risk of deterrence failure problem is the worst and most difficult on all accounts—not a surprising result. Available knowledge is biased because some sources (e.g., states) are not as open as others, and that bias is a form of uncertainty. Other sources are also poor, resulting in heavy reliance on experts and contributing to large uncertainty.

While experts do formulate their knowledge from these other poor sources, they also incorporate their own cognitive processing ability as a primary source. Understanding experts' thinking becomes even more important when combining expert knowledge with whatever other meager knowledge is available from other sources.

Table 8.1. Knowledge Source Evaluation

Knowledge Source	Case I: TNT Explosive	Case II: Nuclear Power	Case III: Nuclear Weapons	Case IV: Deterrence Failure
Data	Large	Moderate	Small	Sparse
History	Long	Short	Short	Short
Theory	Solid	Good	Moderate	Poor
Inference	None	Little	Much	Very much
Experts	Not needed	Some use	Greatly needed	Heavy reliance
Model	Great	Good	Some	Poor
Uncertainty	Small	Moderate	Moderate	Large

The paucity of knowledge in the deterrence failure problem necessitates a waste-nothing assessment approach that utilizes knowledge integration methods. The Table 8.1 evaluation also indicates the need for:

- formal expert knowledge elicitation methods, including techniques for understanding experts' thinking and problem-solving processes;
- integration methods that combine elicited knowledge with any data, information, and knowledge from other sources, such as history; and
- integration methods that focus on making inferences and dealing with large uncertainties.

Common Quantity

A fundamental principle of integration is to combine data, information, and knowledge having common units, common definition, common representation, or common structure. This principle is designed to avoid combining "apples with oranges," meaning unlike or disparate things. The common quantity is usually the quantity of interest in the study, such as risk or its constituents.

Often it is possible to transform or convert dissimilar quantities so that they have a common scale or definition. For example, one can use conversion factors to change foreign currency to US dollars or to establish common units (e.g., measuring every quantity in feet rather than a mixture of units). These conversions are well established and straightforward but will occur infrequently when assessing the risk of deterrence failure. Other less obvious, more frequently occurring, and more important conversions may require querying subject-matter experts. Term definitions must also be verified for consistency of use, especially when dealing with knowledge elicited from experts in different fields. For example, one expert may view consequence of a nuclear attack in terms of loss of lives and property, while another may also include changes in stability among states.

In some methodologies such as probabilistic risk assessment, reliability, or decision analysis, common quantities are well established, and all knowledge is transformed to those. In probabilistic risk assessment, probability is the common quantity, in reliability it is reliability, and in decision analysis it is utility. Experts may have to agree on formulae or functions (e.g., a utility function) to supply the mechanism for transformation between quantities.

In general risk assessment, likelihood is one common quantity that may or may not be defined as a probability. However, consequence is also a component of risk, and there have been various attempts at determining common definitions for consequence, such as providing equivalency of the dollar value for the loss of human life. It is difficult to assess the dollar value of things like physical damage; political stability; and emotional, cultural, and lifestyle changes of peoples as a result of deterrence failure.

Sometimes establishing commonality can be accomplished by changing the level of detail of the knowledge. In the apples with oranges example, although an apple is not the same thing as an orange, they are both fruit. If the common quantity level is broadened to be the more general fruit rather than the specific apple, one can combine apples with oranges. An example would be to categorize different types of weapons of mass destruction threats according to weapon type (e.g., biological, chemical, nuclear, etc.) rather than using specifics, such as a nuclear device manufactured by a terrorist group.

The sacrifice made by changing to a more general level is that detailed information is lost. Loss of detail induces a nonspecificity uncertainty when or if such detail is ever needed in the future. For example, it may become important later to know whether the more general fruit was originally an apple or an orange. If that original detail is lost, it is uncertain which fruit it was. Documentation of the original knowledge avoids this kind of nonspecificity uncertainty when transforming to a more general common quantity.

Obviously, one could carry the idea of generalization to a ridiculous extreme, losing all content and meaning of the original knowledge. Finding the appropriate level of generality to establish common quantity may require a group elicitation, including resolving differences among experts; this is especially true for experts in multiple and diverse subject areas.

Weighting Schemes

Any combination, aggregation, or integration procedure can be considered as the implementation of some sort of weighting scheme. Using this general definition makes weighting schemes the backbone of knowledge integration.

Knowledge integration of an established common quantity can essentially be accomplished by the choice of the appropriate weighting scheme.

The "Multiple Integrations" section described the various kinds of combinations necessary for the risk of deterrence failure problem; however, the means of formulating those aggregations was not addressed. Weighting schemes are the primary mechanism for those combinations. For example, most of the knowledge will come from experts. If more than one expert provides expertise for an issue or question, then a weighting scheme is required to combine their knowledge. Likewise, knowledge from other sources (e.g., historical data) would be combined with that from experts. Finally, knowledge about issues or portions of a problem is combined using a weighting scheme to form the top four constituents of risk and deterrence.

Before application of a weighting scheme (or any combination method), differences, inconsistencies, and disparities among the pieces of knowledge to be combined must be resolved. Chapter 3 provides guidelines on how to resolve these differences among experts, and most of those methods are applicable to resolving other differences. For example, if two pieces of knowledge are contradictory and nothing can be found to explain this, then the resolution becomes a matter of determining the combined uncertainty from the two pieces. Specifically, the uncertainty in both pieces of knowledge is so large that both realizations are possible. To illustrate, suppose a state leader claims that they will attack an adversary on one day, but their next speech talks about peaceful coexistence. This leader keeps alternating between these outcomes in other speeches and documents, for no apparent reason. The result is that the uncertainty regarding the leader's course of action is so large that their adversary must simultaneously prepare for both actions. Should the adversary prepare equally for both outcomes or favor one as more likely over the other? That answer is a matter for establishing the weights.

The weights for an integration scheme may be numerical, including ranks, or ordinal, including linguistic qualifiers or rules. Likewise, the knowledge being integrated, its uncertainty, and the uncertainty of the weights can be quantitative or qualitative. The quantitative schemes are introduced here, and the qualitative schemes are described in the "Logic and Rule-Based Combinations" subsection.

How to determine the quantitative weights is the first challenge. The easiest and most common choice is to consider the pieces of knowledge to be combined as having equal validity and applicability. This is the equal weights combination. Equal weights are recommended for combining knowledge from different experts, unless there are definitive reasons for weighting some experts more than others.[15] That same recommendation can be applied to any integration process for the same reason: differential weights require good reason and justification.

Assigning a weight of zero means that the piece of knowledge (or even the expert) is deemed incorrect, irrelevant, or inapplicable. Reasons for eliminating knowledge from combination should be documented in case that piece becomes relevant later. Elimination should be a rare occurrence.

A weight of zero is often calculated for weighting schemes based on an event's frequency of occurrence when the event has never happened. This is true for percentages, proportions, weight of evidence[16] and other ratio-based weights. For never-observed events, such as the number of times terrorist groups have used nuclear weapons, these weight calculations become meaningless. However, these weight formulations can be used when multiple data, information, and knowledge sources are combined if any source has a nonzero numerator. The section on "Bayesian Integration" illustrates.

The human brain assimilates knowledge in cognitive processing by using its own weighting scheme. Each of us determines the relevance and importance of the knowledge we acquire and how to combine new knowledge with existing pieces from our experience. This is why eliciting expert thinking is useful for determining weights and weighting schemes.

Weights, including equal weights, have uncertainty. The simplest way of capturing that uncertainty is to select a range of values or ordinal descriptions for each weight. For example, an expert comparing events may explain that event A is two or three times more important than event B. If the weight for event B is 1, then the weight for event A is somewhere between 2 and 3. The uncertainty for the weight of event B must next be determined. In doing so, the expert may also have to expand the interval for event A to maintain the factor of 2 to 3 between A and B.

The most fundamental weighting scheme is the average or mean. In calculating the mean of two or more pieces of knowledge, the combination is the sum of equally weighted pieces. The weights are defined as the fraction, 1 divided by the number of pieces.

Bayesian Integration

Because weights and their uncertainties are a challenge to determine, an automatic weighting process is desirable, which is one reason for the application of Bayes' theorem. No supplied weights are required to implement Bayesian integration because the mathematics within the theorem generates them automatically from the information contained in the supplied knowledge sources. Bayesian integration is important because many analysts consider it the premier data combination methodology; however, it has disadvantages and limitations of applicability.[17]

Bayes' theorem[18] is a convenient mathematical combination or weighting scheme for combining two sources of knowledge quantitatively expressed in functional form, called the prior distribution and the likelihood function.[19] The resulting combination of these two functions is another function called the posterior distribution.

Integrating expert knowledge with experimental or observational data using this theorem has been done for many decades and remains popular today. The expert-supplied knowledge is formulated as the prior distribution, and what little data may exist are formulated as likelihood functions.[20] This expert-with-data integration is useful for problems with phenomena that have not yet occurred, such as a failure. Thus, it is applicable to the risk of deterrence failure problem, where prior distributions could be formulated from experts to combine with the sparse historical record.

However, before the 1990s, Bayesian analysts did not concern themselves with formal elicitation methods until those methods were developed and applied. One of the first applications was NUREG-1150, probabilistic risk assessment studies of several nuclear reactors.[21] The Nuclear Regulatory Commission sponsored this massive study to replace the previous one, WASH-1400, in which formal elicitation methods were not used.[22]

For the risk of deterrence failure problem, Bayesian integration could be applied for combining different knowledge sources. For example, results from a previous study could serve as the prior for the results of a new study. This example also illustrates another advantage of using Bayes' theorem: updating or integration can be done on a continual basis. Whenever new knowledge becomes available, the previously combined knowledge (the posterior distribution) then becomes the prior distribution to be updated with the new knowledge. This updating feature would be useful for the deterrence problem because of the constant changes that occur in the available knowledge.

One disadvantage of the combination capability of Bayes' theorem is that the available knowledge must be captured and quantified in the form of functions—distribution functions for the prior and posterior, and likelihood functions and quantities (called parameters) associated with those. Critics of Bayesian methods cite this reason to argue against its use. Reverend Bayes' original form of the theorem contained probabilities instead of functions. However, this formulation is no easier to use for expert knowledge because humans are not good probabilistic thinkers.

Because of the way the mathematics of the theorem operates to weigh the two sources of knowledge, there are cases where the resulting combination (the posterior distribution) does not make sense. This is another disadvantage, limiting the utility of the theorem. One case arises when a large amount of knowledge—a body of evidence—is formulated into a prior that is inconsistent with a small amount or piece of knowledge formulated into the likelihood. For example, at the time of the Cuban missile crisis, military experts had considerable knowledge to support the idea for a land invasion of Cuba. However, their prior information would have been inconsistent with a new piece of knowledge—that the Soviet Union had placed tactical nuclear weapons in Cuba to repel an invasion—had such information been available. But Bayesian combination would have still supported invasion because the large amount of prior information would have outweighed the single new piece, as depicted in the top of Figure 8.1. Basing a decision to attack on the Bayesian combination would have been a bad idea. Instead, the single new piece of evidence in this example should outweigh all prior knowledge and drive the decision not to invade.

Another undesirable result from Bayesian integration arises when prior knowledge conflicts with near equal amounts of likelihood knowledge, as shown in the bottom of Figure 8.1. For this situation, Bayes' theorem produces a combination that lies between the two, in a region where knowledge from neither source is found. Returning to the state leader example in the "Weighting Schemes" subsection, the leader's first statement (prior) supported attack, while the second (likelihood) supported peace. Bayes' theorem produces a combination of half attack and half peace, an indeterminate result.

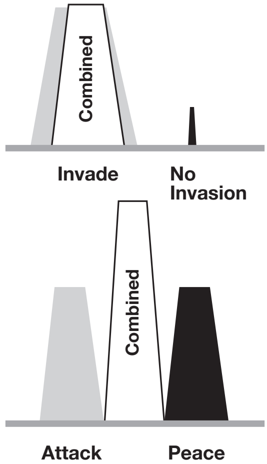

Figure 8.1. Bayesian integration issues. The top image depicts Bayesian integration ("combined" white trapezoid) of a large amount of prior knowledge (gray trapezoid) with new knowledge of nuclear weapons (black line). The bottom image depicts equal amounts of prior (gray) and likelihood (black) knowledge, resulting in a combination ("combined" white trapezoid) falling between, where no knowledge resides. Shapes are for illustration purposes and are not drawn to exact dimensions.

Redundancy and Dependency

Dependency between and redundancy among knowledge sources leads to double counting of the same knowledge, unless the overlap is identified and remedied. Figure 8.2 illustrates this knowledge integration principle. The top portion represents two independent sources of knowledge, perhaps information from two different experts. The bottom portion shows some of the same knowledge provided by both A and B in the white overlap area. If the A and B circles represent knowledge from different experts, then not recognizing the white overlap results in counting the same knowledge twice. A simple example of double counting occurs when gathering historical events on a particular subject and the same event is described in different documents. The event only happened once, regardless of how many times it is cited.

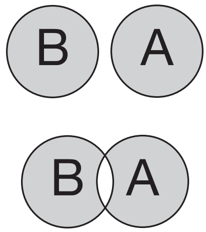

Figure 8.2. Double counting redundant knowledge. Nonoverlapping, independent information from A and B (top); double counting of information from A and B in the white area (bottom).

Recognizing dependency and redundancy is difficult, especially during or after an elicitation. Just because two experts provide the same answer to a question does not necessarily mean they are completely dependent or overlapping. Studies have shown that experts who use similar problem-solving processes produce similar answers—a correlation of cognition and responses.[23] However, correlation is not necessarily dependence, and small degrees of dependence do not result in significant overlap or double counting.[24]

A simple example of dependent experts that does matter is when expert A learns of expert B's answer and decides to copy it, rather than providing A's original answer. In this case, there is only one independent answer even though two experts responded. The dependence or redundancy among experts, as illustrated by expert A's response, primarily comes from expert A's deliberate decision to provide the party-line or community-established response. This social pressure bias can be detected and mitigated through formal elicitation methods.

Dependent relationships are similar to conditional relationships, which are common in most knowledge integration, as described next.

Conditional Combination

Underlying conditions attached to knowledge must be identified before knowledge integration to avoid mixing "apples" with "oranges." Assumptions and dependencies are conditions. Conditions are important because the knowledge can change when conditions change.

For example, history shows that no nuclear weapons were used since World War II. Thus, one might reasonably conclude that the likelihood of such use during that period (i.e., the end of the war to present day) was low.

However, that statement is conditioned on the assumption that close calls have been nonexistent or irrelevant. Because there have been a number of crises in which nuclear use was contemplated (i.e., close calls), and if nuclear use was a high-probability outcome of at least one of these crises, then one might reasonably conclude that the likelihood of nuclear use since World War II was high. The knowledge changed from “low” to “high” when the condition of close calls was considered.

Accounting for all assumptions, conditions, and caveats attached to knowledge is challenging. Conditions inherent in the knowledge may not be readily identifiable. Even an expert supplying the knowledge may not be fully aware of the conditions attached or the assumptions being made. Integration requires care not to combine knowledge having differing conditions. A simple example comparing estimates for the likelihood of nuclear war published in the literature illustrates this (see chapter 3). The authors supply their estimates in different units (different conditions): some provide a per-decade value, some a per-event or scenario value, and some a value without description. These different values cannot be compared or combined until they are all based on common ground, that is, common units. In addition, some of these authors may not be experts. Being an expert in the relevant subject area is a condition for combining expert knowledge.

This example illustrates only a couple of conditions encountered in the risk of deterrence failure problem. Others include scenario description, groups of people or nations involved, time frames, event sequences, subject areas involved, political environments, socioeconomic factors, and human factors.

Some conditions may not be influential and hence do not have to be considered; however, making that determination in a knowledge-poor environment is difficult. The degree of influence or effect of some conditions may not be determinable. In that case, risk assessment is done with a caveat stating that it is unknown what effect, if any, this condition has on the results.

A risk assessment can be done with every quantity conditioned on a particular assumption, such as a chosen scenario. Often risk assessments list these caveats as a caution that the results may differ if the conditions are changed. A simple example of one such condition is a specified time frame for the risk analysis, such as the risk within the next decade.

An implicit condition for all analyses is that the results depend on the knowledge and analysis method used therein. This knowledge includes how the problem was structured, its scope, what knowledge was used in the analysis, how uncertainties were handled, what theory or first principles were applied, and what analysis methods or models were chosen. However, as important as these conditions are to understand, one rarely sees such a detailed statement accompanying a risk assessment.

Inconsistency

Inconsistencies can be found in any form of knowledge. Inconsistencies must be identified and understood before integration to decrease uncertainty and to correct any errors or mistakes. Some inconsistencies are easily detected because they make no sense and are simply errors. For example, the number of member nations in the nuclear club is not one hundred, but it might be ten.

Sometimes an apparent inconsistency is not an actual one because conditions or assumptions have changed. For example, an expert may respond that there are two ways to construct a weapon and then later state there is only one way. After probing, it is discovered that the expert was assuming a certain material was available for the first case but not the second.

Sometimes an apparent inconsistency comes from the failure to recognize the effect of high uncertainty. For example, one expert claims an event will almost surely happen, while another claims that event is nearly impossible. Both experts arrived at their responses using different problem-solving processes, but both responses are valid given the high degree of uncertainty about the likelihood of the event. This high uncertainty is a nightmare for the analyst when presenting results to a decision-maker, as well as for the decision-maker who has to determine a course of action when none is clearly apparent.

In eliciting knowledge from experts, care must also be taken to query why and how an expert apparently switches a reason or response. For example, an expert may state that they cannot answer a particular question because they simply do not know about that subject but then may supply information about that subject later, even to the point of answering the original question. Resolving this and other inconsistencies is done using formal elicitation methods.

Whatever the reason or source of inconsistencies, they must be understood, resolved or remedied, and noted before knowledge integration.

Categorization and Enumeration

Categorization and enumeration can be used for quantification and subsequent integration, analysis, and assessment. When the majority of knowledge for a topic is in qualitative form and involves linguistics, as may occur in the risk of deterrence failure, it is difficult to combine verbal descriptions. However, in some cases essay responses from experts or historical records can be categorized. If that is possible, then counting the pieces of knowledge for each category is a form of quantification. This activity is also an integration method. In addition, it provides numerical results for analysis because enumerations can produce percentages or proportions relative to all categories. Categorization and enumeration are commonly used in the data analysis of surveys.

Both categorization and enumeration activities can involve uncertainty. Figure 8.3 shows how two kinds of uncertainty are involved in making a decision about a terrorist state: is it manufacturing weapons of mass destruction or not? The preponderance of existing knowledge about this state tips the scale and seesaw toward the weapons of mass destruction side. However, a new piece of knowledge emerges about this state acquiring uranium. Because the amount and which isotope(s) were obtained are unknown, it is not certain where the white block belongs: on the weapons of mass destruction (WMD) scale or the No WMD scale. The white block may partially belong on each of the scales, as illustrated with dashed arrows at the top of Figure 8.3. The uncertainty involved in making the categorization can be handled by probability. The probability that the uranium acquisition is for the WMD scale is 0.7, and the probability that it is for other purposes is 0.3. In probability theory, those two assignments sum to 1.0; however, for other uncertainty theories, such as possibility, that is not a requirement.

The second kind of uncertainty is illustrated at the bottom of Figure 8.3—the uncertainty in forming distinctively concise categories. The continuous seesaw at the bottom of Figure 8.3 depicts the inability to precisely distinguish between activities pertaining to the manufacture of a weapon of mass destruction and legitimate related activities (e.g., nuclear power and research reactors). The indeterminacy of the exact (crisp) boundaries of the categories WMD or No WMD makes those two categorizations fuzzy sets.[25]

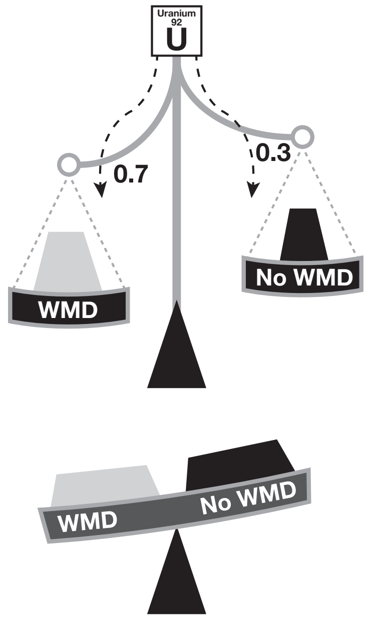

Figure 8.3. Enumeration and categorization uncertainties. Illustration of uncertainty in assignment of knowledge (white block) to two crisp sets (top) and determining the boundaries of two fuzzy sets (WMD and No WMD) (bottom).

Logic and Rule-Based Combinations

Alternatives to mathematical integration formulae are logic and rule-based combinations. Rules and logic are the ways to combine qualitative and linguistic knowledge. These describe the relationships existing among the issues, events, knowledge, experts, etc., involved.

Related to conditional integration logical rules are if–then rules. For example, the statement "If A occurs then B does not occur" is an if–then relationship that describes how to combine A and B. A string or series of if–then rules dictates which items or statements coincide and which are unrelated.

Other logical rules offer the same benefits—providing guidance on how pieces of knowledge are or are not related and dictating how they are combined. For example, logic dictates that there are some minimal requirements for constructing and delivering a weapon of mass destruction. Each of these steps or acquisitions must be included; otherwise weapon construction is not possible. For the problem of constructing and delivering a weapon of mass destruction, knowledge must be gathered about each of those steps and combined according to how that weapon of mass destruction can be produced and delivered. This is an example of the use of the AND logic operator, where each step must be accomplished for an achieved goal.

An example of the OR logic is when alternatives or options are present such that any one is all that is necessary. For example, a dirty bomb requires that some radioactive material be dispersed. However, there are multiple types and sources of radioactive material that can be used, and only one is minimally necessary.

Logic operators such as AND, OR, and NOT are used to connect and combine. In addition to these common crisp logic operators, there are also fuzzy logic counterparts.[26] Fuzzy logic[27] is useful for relationships and combinations that are uncertain, usually because of a lack of knowledge. Often these relationships involve linguistic descriptions rather than numbers. For example, an expert may answer a question about a terrorist group as follows: "Well, *if* this group gets more radical in its beliefs than it is now, *then* it would provide sufficient funding for making a nuclear device." The words *more radical* and *sufficient funding* are fuzzy quantities in this if–then statement. Fuzzy sets and logic provide the mechanisms for how to quantify linguistic statements and descriptions and how to compare and/or combine statements or rules from multiple experts.[28]

Inference-Based Combination

In keeping with the theme of providing some fundamental integration methods, inference-based combination provides a way to combine multiple sources of knowledge at any level of detail. The sources being combined are related to each other by some degree of inference, such as a similar problem or scenario (analogical inference); a related quantity (proxy inference); a relevant model, theory, or computation (validation inference); or a prediction (prediction inference).[29]

A simple example, using estimates and data for nuclear weapon use, illustrates how to combine knowledge from multiple sources. Figure 8.4

depicts four sources of knowledge available: two sources from history (top row) and two sources of estimates made by experts or authors found in the literature (bottom row).

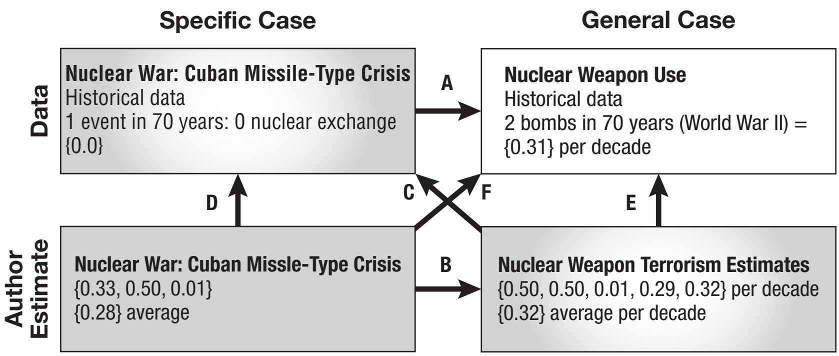

Figure 8.4. Four-box inference technique for nuclear weapon use: combining specific and general historical data with author estimates.

The boxes in the right column refer to the general case of nuclear weapon use in war or terrorism, while the boxes in the left column contain information for a specific event leading to a nuclear exchange—a Cuban-missile-type crisis. The three gray boxes contain knowledge that is “similar” but not identical in quality or relevance to the sparse data in the white box. The white box contains what little, if any, knowledge exists for the problem at hand. If sufficient amounts of knowledge were available for this box, there would be no need to combine that knowledge with the sources in the other boxes. Thus, using the knowledge in the gray boxes to represent the white box is making an inference about its degree of applicability to the white box. The arrows A–F indicate the inference being made and point toward the more important or relevant box from the supporting boxes.

The goal is to combine the knowledge in the three gray boxes with the white box, accounting for the inferences and their uncertainties. This is done using a weighting scheme where the weights for the knowledge in each box are determined based on the degree of inference (the arrows) between boxes. Experts are usually the resource used to determine the degree of inference (the similarity of each box relative to another) for each of the six arrows. Experts assign a value for the degree of relevancy using a numerical comparison scale modified from the pairwise comparison scale developed by Saaty.[30] A simple example for how to apply Saaty’s method to determine the weights for combining the boxes is provided in Langenbrunner et al.[31] Quantifying and combining the corresponding uncertainties for these arrows and for the knowledge in the boxes are more complicated.

Expert-Supplied Integration

Subject-matter experts are often the best sources for determining how knowledge is combined, what combination approach is appropriate, what weights should be used, and what uncertainties apply. However, experts may not be aware of some of the methods for these determinations. Thus, it is the responsibility of the interviewer and analyst to inform experts and to recognize what methods may apply, based on the experts' descriptions. For example, an expert may be thinking about a complicated functional combination method but is unable to write down the formula. The analyst or interviewer recognizes this and provides the expert with some formulations and explanations to determine whether any of these are consistent with the expert's thinking.

It is common for experts to be unaware that they are expressing an uncertainty, especially a nonprobabilistic one. Again, it is the job of the interviewer or analyst to recognize the uncertainty and to clarify its meaning with the expert.

Knowledge integration often requires the cooperation and coordination of different experts: subject-matter experts, experts on elicitation, experts on knowledge integration methods, and experts on uncertainties. Previously noted integration efforts among experts include agreement on common quantities necessary for risk assessment and on how to transform various forms of knowledge into those quantities. Experts may also have to provide and agree on the conditions for the problem structure, such as a given scenario, and the types of uncertainties inherent in the knowledge and in relationships among problem issues.

For quantities or issues that have indeterminate relationships yet require combination, it is possible that no expert is be able to identify an appropriate integration method. In cases in which no one knows how to combine things, a decision can be made to assume some simple combination scheme with the realization that a better integration approach may be available in the future. The inability to find an integration method may be due to a lack of knowledge about the subject or to a lack of good choices of integration methods currently in existence. Either way, this shortcoming and the assumptions made to circumvent it should be clear caveats accompanying any final answers or conclusions presented to decision-makers.

Uncertainty Combination

Throughout this chapter, different types of uncertainty have been mentioned that arise when doing knowledge integration: imprecision, inconsistency, nonspecificity, probability, the unknown, fuzzy, and likelihood. Because uncertainty is common to all knowledge throughout a risk assessment problem, it can be considered a common quantity. The precedent for this is in probabilistic risk assessments where probability (probabilistic uncertainty) is a common quantity for determining the likelihood component of risk.

In the past decade, risk assessment tools have expanded to include other mathematical theories of uncertainties. For example, possibility theory has been used to assess the risk of terrorism.[32] The advantage of using possibility theory over probability theory is that the axioms for possibility are more general, and less restrictive, than those for probability theory. Possibility is better suited to rare-event estimation, as evidenced by the common expression "That is possible but not probable." The disadvantage of using an alternative to probability theory is that most experts and decision-makers will be unfamiliar with it and how to interpret it. For all its faults, probability theory has a long history; many experts and decision-makers have at least heard about it, and some even understand it (although far fewer truly understand it than those who think they do).

Ideally, analysts would be able to work with experts to quantify each type of uncertainty with its appropriate mathematical theory, propagate and combine these uncertainties for an uncertainty estimate attached to the final or top-level answer, and then explain what it means to a decision-maker. However, insufficient research has been done to understand how to mix and match different uncertainty theories, let alone how to explain them to experts and policy-makers. An example of one such difficulty is when the integrated result of different uncertainty theories is desired to be in a familiar form, such as probability, for conveyance to a policy-maker. An uncertainty from a general uncertainty theory combined with an uncertainty from a more restricted one (e.g., probability) can force the combination to follow the more restricted theory. That result changes the interpretation and reason for using the more general theory in the first place.[33] In other words, a false sense of precision may be imposed on the integrated uncertainty that is not warranted given its constituent uncertainties.

Currently, research and experience of application is available for linking fuzzy membership functions with probability distribution functions.[34] Short of other uncertainty theory mixing techniques and experience, the familiar probability theory continues to be used for every uncertainty as is done in probabilistic risk assessment.

An alternative strategy for handling different kinds of uncertainties would be to select one of the most general uncertainty theories, such as imprecise probability,[35] and to characterize every uncertainty and integration by using that theory. An advantage of choosing imprecise probability is that this theory has a probabilistic nature, meaning it can be explained to experts and decision-makers. However, such use of imprecise probability theory would be breaking new application ground. Another theory to consider applying to the entire problem is information gap decision theory.[36] This theory has some history of application and can mathematically accommodate the use of multiple uncertainties within its framework, including probability.[37] Either of these two general uncertainty theories would be worth considering for integrating the different types of uncertainties inherent in the risk assessment for the failure of deterrence problem.

Managing Uncertainties

With no clear solution about how to combine uncertainties, the key may be to manage uncertainty.[38] The first step to managing uncertainties is becoming aware of the uncertainty types; of what knowledge is available; and of the limitations of the experts, analysts, and decision-makers in dealing with uncertainties. One tool that is currently being used is creation of an uncertainty inventory.[39] A quick uncertainty inventory for the risk of failure of nuclear deterrence problem could well reveal something like the following:

- Uncertainties of many types will exist.
- The most common uncertainty will be lack of knowledge—that is, "we just don't know." Unfortunately that type of uncertainty is not the kind that probability theory is designed to quantify.

- Another common uncertainty would be fuzzy from the use of linguistic terms.
- Applying available knowledge to the problem will require making inferences.[40]
- Reliance will be placed on experts as a source of knowledge, uncertainty, and integration methods.
- Not every uncertainty can be quantified, even using ordinal measures.
- Clear choices for handling and combining uncertainties do not exist, and application experience of the more exotic uncertainties is lacking. However, uncertainties cannot be ignored.

The goal is to get an integrated answer to the top-level question: What is the risk of deterrence failure? An integrated answer that ignores uncertainties will be incorrect, as shown in Figure 8.5. The real answer, denoted by an asterisk, is captured only when the uncertainties of the seven data points are considered. An integrated answer using overly large (e.g., anything is possible) uncertainties will be indeterminate. The risk would be anywhere from zero to doomsday. The best that can be done is to make every attempt to utilize all available knowledge and document how and why uncertainties were determined. This is managing uncertainty, and there are some simple methods and ideas for management.

Most humans (experts and decision-makers) can understand the uncertainty involved as expressed in an interval of values and in relative comparisons. Interval arithmetic can be used for combining intervals.[41] Combining comparisons is not as straightforward, but techniques from decision analysis may be useful, such as the pair-wise comparisons used in Figure 8.4.

Using defined words and concepts such as likelihood (rather than probability) prevents tying the expert or the analyst to any particular uncertainty theory. In probabilistic risk assessments and other probability-based analyses, combinations are often done with simulations of probability distribution functions. Similarly, simulations can be used to combine likelihood functions.

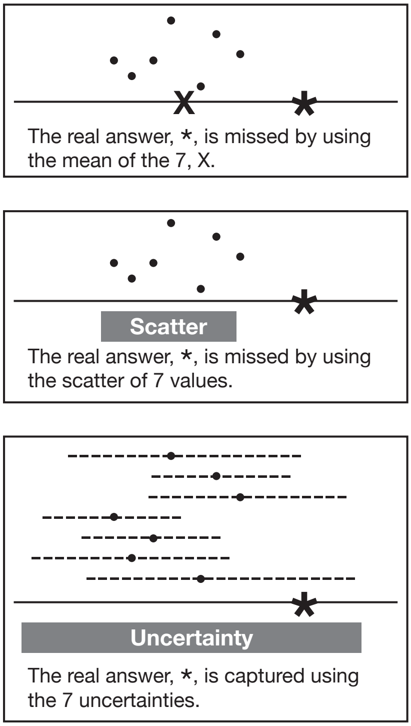

Figure 8.5. An integrated answer must consider uncertainties. Top box: no uncertainty for seven values. Middle box: use scatter of seven values for uncertainty. Bottom box: use uncertainties for all seven values.

One of the tenets of formal expert knowledge elicitation is to reveal uncertainty in the terms used and understood by the expert. That rule applies to integration with the addition that integration across experts may require thorough understanding of any subtle differences in definitions of terms describing uncertainty.

Experts are useful for providing a reality check for an integrated answer and corresponding uncertainty. Either or both may end up unreasonably distorted if an inappropriate integration was done. Often a large uncertainty for the integrated answer can be traced back to one or a few large individual uncertainties. Large uncertainties preclude definitive decisions and result in broad ranges of values of risk and its constituents. When sources of large uncertainties are identified, the decision-maker can be informed of where invested resources can reduce them, and hence reduce the large uncertainty in the final answer. It helps to show decision-makers how this can occur through a what-if demonstration: *What if* a dominant uncertainty is reduced by half? *Then* the final uncertainty is reduced by one-third; therefore, investing time and money for this reduction is valuable.

Managing uncertainty also involves understanding how it relates to making predictions and to inconsistencies among knowledge sources. Some mathematical relationships—trade-offs—between uncertainties and prediction have been established and may prove useful for combining and managing uncertainties.[42]

Rather than quantifying potentially large uncertainties, it may be prudent to assume some reasonable value (usually provided by an expert). This assumption is then identified as a placeholder unless and until more knowledge becomes available that would provide a better uncertainty estimate. That assumption is also a condition (caveat) on which the entire analysis and conclusions rest.

Regardless of the care and documentation implemented in characterizing and combining uncertainties, there will be criticisms and questions about them. Constructive criticisms are welcome because they offer a source of additional knowledge and potential alternative methods. Questions should be answerable from the complete and traceable documentation that has been created.

Knowledge Integration Challenges and Benefits

Some of the challenges and benefits of knowledge integration applied to the assessment of risk of deterrence failure are described below.

Challenges

One of the biggest challenges is that knowledge is constantly changing; today's prediction is tomorrow's historical data. Complete documentation of the knowledge and analysis of it are important for updating that documentation when new knowledge becomes available, necessitating a new integration.

Another challenge for assessing the risk of deterrence failure is the heavy reliance on experts as a primary source of knowledge, including using them to determine how to integrate that knowledge and how to characterize its uncertainty. However, formal elicitation methods are available to aid in this endeavor. Because of the lack of data for this problem, statistical methods are of limited use for analysis, summarization, integration, prediction, and drawing conclusions.

Uncertainties of different types abound for the risk of deterrence failure problem, with lack of knowledge being a major type. Although probability is the common theory for uncertainty, it is not appropriate for many uncertainty types and is not suggested when eliciting uncertainty from experts. Alternative uncertainty theories exist; however, application for many of these is limited.[43] Additional research is needed to provide methods for mixing different theories within a problem.

Care must be taken to identify and accommodate the conditioning factors of the knowledge when applying integration methods or principles. Included in these conditionings are dependence and double counting of the same knowledge.

Existing knowledge integration methods and studies that have been developed were applied to problems involving physical systems. The extent to which these methods are applicable to the ill-posed structure of the deterrence problem has yet to be determined.

Benefits

The goal of a risk assessment is to convey the risk and its uncertainty to decision-makers. That goal does not require the integration of likelihood with consequence, per se; however, it necessitates integration of the likelihoods and consequences over all the parts of the problem. For the deterrence failure problem, where data are sparse, all sources of data, information, and knowledge must be utilized and combined, requiring integration methods. The unique challenges presented for this problem make it difficult to apply traditional risk methods such as probabilistic risk assessment; however, the principles and methods presented here offer some solutions for assessing risk. It should not be too difficult to explain these fundamental methods to the decision- or policy-maker.

As with any thorough assessment process, the risk assessment for this problem will provide the opportunity to learn about aspects of the problem not obvious from a cursory examination. Lessons learned about how to manage uncertainties should produce insights about making decisions in the sparse knowledge environment. Risk analysts may need to work more closely with the decision-maker in order to convey the impact of these uncertainties on conclusions and decision choices.

The integration required for this problem may also require experts from different subject areas to work together or at least understand how their knowledge fits inside the larger problem covering various disciplines. Insights are gained through this process as well.

Understanding where the gaps in knowledge and placeholders are is a planning tool for the experts, analysts, and decision-makers. These "holes" are areas where improvements can be made, perhaps with investment of resources.

Having an updatable integration methodology permits demonstration of how results (and decisions) can change if/when new knowledge surfaces. The benefit of careful and complete documentation is that the knowledge can be used in the future and all the participants (e.g., the experts, the decision-maker, the analyst) can have a productive experience and speak favorably of their involvement in a well-designed and implemented, defensible study. Some examples of integration methodologies exist, for problems with uncertainties of different types, where heavy reliance is placed on expertise as a knowledge source and where different sources of data, information, and knowledge are combined. The methods and principles presented in this chapter have their origins in those studies:

- Reliability methodology, Performance and Reliability Evaluation with Diverse Information Combination and Tracking (PREDICT), 1999[44]
- Yield estimation prediction protocol, 2006[45]
- Inference uncertainty integration methodology (the four-box approach), 2010[46]

Summary

Once problem structure(s) have been determined and knowledge-gathering activities are ongoing or have been completed, knowledge integration becomes the critical step for achieving the goal of providing top-level answers, summaries, and conclusions to policy- and decision-makers.

Knowledge integration extends data-based and multiple study combination analysis methods in new directions. One extension is to combine all forms of data, information, and knowledge. Another is to characterize and combine different types of uncertainties, most of which are not appropriate for probability theory. Finally, a risk assessment for the deterrence failure problem involves additional combinations such as different experts (providing knowledge), different subject areas, and different scenarios or problem formulations.

Accommodating all these integrations brings new challenges not previously addressed by traditional risk assessment methods such as probabilistic risk assessment. Some of the research necessary to do these integrations has yet to be developed. Yet, timely integrations are necessary and must also be conveyed to policy- and decision-makers, as well as to experts involved in providing the knowledge. Therefore, some fundamental principles and methods are provided for present use.

Among the principles involved is the use of formal expert knowledge elicitation methods because experts are valuable resources for providing the knowledge, characterizing the uncertainties, and determining appropriate integration rules or schemes. Another principle is to waste nothing—gather and utilize all available data, information, and knowledge because of its sparseness and high uncertainty.

Following the integration principles and methods should provide the desired top-level or problem solution in terms conveyable to a decision-maker. In addition, these methods are designed to permit the necessary traceability to answer inquiries and update as new knowledge becomes available.

Acknowledgments: Thanks go to James Scouras, Andrew Bennett, Edward Toton, and James Langenbrunner for their constructive thoughts, knowledge, and comments regarding the planning and drafting of this chapter.

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Chapter 9
Reflections

James Scouras

Motivated by the importance of the perceived risk of nuclear deterrence failure in national security policy formulation, we began our study by asking whether more structured analytic approaches could improve on the highly intuitive manner by which the risk of deterrence failure has generally been assessed. For the likelihood dimension of risk, each of the approaches included in this book—case study, elicitation of expert judgment, probabilistic risk assessment, and application of complex systems theory—has something unique to offer. However, none of these approaches can do the job by itself. Rather we have reinforced the notion that multiple disciplines can each shed limited light on the question. We must extract from each of them whichever valuable insights they offer and do our best to synthesize these insights, using the art and science of knowledge integration, into a policy-relevant assessment. However daunting this task, discernible research paths hold significant promise. As for the physical consequences of nuclear use, it is clear that our knowledge base, derived primarily from concern about the military effectiveness of nuclear weapons, is inadequate to assess the potential consequences from the broader array of nuclear uses that now appear possible or from intangible consequences that could exceed even the physical consequences. This lack of knowledge is easier to address from an analytic perspective but requires an adequately funded research program. The dim prospects of such a program are yet another consequence of the complacency induced by our intuitive sense that nuclear weapon risks have largely abated.

It is remarkable how rapidly perspectives on nuclear risk have changed over the three post–Cold War decades. In the incredulity of our good fortune after the end of the Cold War and the demise of the Soviet Union, concern with the residual nuclear threat from Russia plummeted. Nuclear war was deemed highly improbable, and all things nuclear were relegated to much lower priority in national security planning. A decade later, after the attacks of September 11, 2001, terrorism—including nuclear terrorism—ascended to the top of the threat priority list and remained there until about five years ago. More recently, the emerging nuclear threat from North Korea, the rebuilding of the Russian nuclear arsenal, and the gradual rise in the Chinese nuclear threat, all three of which have been accompanied by belligerent international behaviors, have emplaced interstate nuclear crises and war with these actors as the primary nuclear risks.

Beyond the question of the extent to which this shuffling of the deck accurately reflected international realities, several points are worth making. First, perspectives on nuclear risk have been almost always focused on likelihood. Consequences have been rarely considered as a coequal component of risk. This is most obvious in the elevation of nuclear terrorism after 9/11 to higher concern than global nuclear war with Russia. While the arsenals of the United States and Russia had dropped significantly by then from their Cold War levels, they still numbered in the thousands of weapons. There remained the possibility—perhaps remote, perhaps not—that deterrence might fail and these arsenals would be used. Thus, while the likelihood of nuclear terrorism appeared to be growing, a global conflagration that involved the US and Russian nuclear arsenals was—and remains—among the more horrific catastrophes we could imagine.

Second, long-term (a decade or more, for argument's sake) projections of nuclear risk are inherently suspect. The world has changed and can reasonably be expected to continue to change too rapidly to justify confidence in risk assessments beyond the short to intermediate term. Thus, those mathematical calculations that suggest any nonzero and nondecreasing annual risk of nuclear war compounded over many years will inevitably lead to catastrophe need to be reconsidered in light of the improbability of the assumptions about nondeclining future risk.

As this discussion suggests, this work has been motivated in large part by the concern that the conventional wisdom regarding possible nuclear weapon use—from global nuclear war involving the arsenals of the nuclear superpowers to terrorist nuclear use of a single weapon—has not been adequately challenged. Are there analytic approaches that will allow us to move beyond intuition and overly simplified analyses to a more rigorous basis for assessing the risk of deterrence failure?

What Have We Learned?

Clearly, each of the approaches included in this study that contribute to our understanding of the likelihood of nuclear use—historical case study, elicitation of expert judgment, probabilistic risk assessment, and the application of complex systems theory—has something unique to offer. Because none of these approaches is by itself a silver bullet, we must extract from each of them whatever valuable nuggets (or morsels) of insight they offer and do our best to synthesize these insights, using the art and science of knowledge integration, into a policy-relevant assessment. Then, utilizing a risk assessment framework, likelihood must be combined with an analysis of the prospective consequences of nuclear use, for which there is a very large body of accumulated knowledge but also large uncertainties and enormous gaps.

Historical Case Study

Knowledge of the history of actual use of nuclear weapons in World War II and close calls of potential use during the Cold War and the post–Cold War period provides the essential foundation for any assessment of future risk. This history helps to identify paths to close calls and use as well as to assess past risks and contemporaneous perceptions of those risks. Without an awareness of the history of close calls, it is difficult to appreciate the myriad and unexpected ways in which nuclear war could be triggered. The unanticipated and idiosyncratic nature of many of these close calls, such as the 1995 Norwegian meteorological rocket that Russia briefly considered to be a possible US nuclear attack, should also engender an appropriate humility in any prognostications about the future.[1]

Extracting historical lessons relevant to the future is not straightforward. Fundamentally, the future is not the past. History is easily misused, and it is difficult to generalize from diverse and infrequent close calls. Facts are limited and those known may be biased, and historians often differ in their interpretations. Most important, case study must be combined with expert input to assess future risks, and therein lies further opportunity for subjectivity and disagreement. Nevertheless, to know how nuclear weapons might be used, we must know how they could have been used. Thus, study of close calls provides a necessary, but incomplete and uncertain, guide to the future.

Our work suggests two primary directions for further historical research. First, past close calls should be revisited as new source materials become available. For example, the Center for Naval Analyses conducted a fresh study of the 1969 Sino-Soviet border conflict utilizing newly available primary and secondary sources.[2] Beyond understanding the roles of nuclear weapons and policies in the progression and outcome of past crises, the goals of such studies should include an evaluation of the potential applicability of lessons extracted from these experiences to current and future nuclear challenges. Second, because lessons from history are applied mainly through the use of analogy, a greater appreciation of the historical record, limitations, and legitimate usage of analogies when applied to nuclear close calls would be immensely helpful in avoiding the more common misuses of history by policy-makers and others.[3]

Elicited Expert Knowledge

For data-sparse, theory-poor problems such as assessing the risk of nuclear deterrence failure, heavy reliance is placed on knowledge from experts. Formal elicitation methods to extract the best-quality knowledge from experts have been developed and successfully applied to diverse problems over the past several decades. Moreover, expert elicitation is an active research field with techniques continuing to improve. Awareness of the biases peculiar to assessing the risk of deterrence failure with its rather unique aspects (e.g., the challenges of thinking about the unthinkable) should allow elicitation methods to also be successfully tailored to that problem.

Unfortunately, formal elicitation methods are time consuming and expensive to employ. They have not been applied in past analyses of the risk of nuclear deterrence failure, resulting in data with dubious quality and suspect conclusions. Major improvements in the utility of elicited information would result from such simple practices as not relying on self-elicitations and capturing experts' thinking and their uncertainties. In addition, elicitations that directly ask for experts' estimations of the risk of nuclear weapon use suffer from assuming that a single "expert" can make informed judgments across the entire scope of the problem, rather than parsing the problem into smaller pieces that can be addressed more authoritatively by different experts.

Notwithstanding the potential of utilizing elicited knowledge, a fundamental limitation of formal elicitation must be recognized. Formal elicitation at its best can only extract knowledge that exists or that elicitations can provoke experts to develop by thinking through a question. Many of the issues in assessing the risk of deterrence failure are beyond experts' knowledge and analytic capabilities. This reality is not an argument against using formal elicitation methods; rather it a caution that should be reflected in the uncertainties associated with experts' judgments.

Probabilistic Risk Assessment

As with formal expert elicitation, probabilistic risk assessment is being applied to an ever-broader range of problems. However, its major successes have been in assessing risks associated with engineered systems such as nuclear power plants and the space shuttle.[4] Probabilistic risk assessment is far less mature for problems involving complex human interactions, where the range of possible decisions and actions cannot be identified in advance and actors are adaptive. An elaborate attempt to apply it to such a problem, the Department of Homeland Security's Bioterrorism Risk Assessment, has been sharply criticized as fundamentally flawed in a National Academy of Sciences report.[5]

Two other challenges of utilizing probabilistic risk assessment—one real and one that is more accurately characterized as a misguided concern—derive from the quantification of likelihood using probability. The real challenge is that many subject-matter experts are not particularly adept at estimating probabilities and tend to underestimate associated uncertainties.[6] Somewhat surprisingly, this observation is valid for experts both trained and untrained in mathematically based disciplines, including even statisticians.[7] On-the-spot training and practice at the front end of an elicitation do not seem to help much.[8] The misguided concern is that a well-executed probabilistic risk assessment, with experts' uncertainties in their judgments accurately captured, would not be helpful because many experts' uncertainties could be very large and, consequently, the probability of deterrence failure would have significant nonzero values across a very broad range of possibilities. However, rather than being uninformative, such a result would support two critical considerations for policy: experts are highly uncertain as to the risk of deterrence failure and the probability could be high or low. This, of course, helpfully undermines unwarranted confidence in the conventional wisdom that we can rest assured that the risk of global nuclear war is low. More precise conclusions may simply not be supported by our current state of knowledge.

While probabilistic risk assessment cannot be relied on to provide a definitive analysis when applied to the risk of nuclear deterrence failure, it does have important uses. In particular, it requires defining outcomes (e.g., global nuclear war between the United States and Russia, regional nuclear war in south Asia, or terrorist use of a single nuclear weapon in a European city) and identifying paths to these outcomes, each path starting with a triggering event and progressing step by step to an outcome of concern. These intermediate products are valuable even if all possible outcomes and paths are not identified and even if probabilities are not assigned to the various (or *all* the various) steps along each path. Developing these products in the context of a probabilistic risk assessment facilitates clarity in thinking and dialogue among experts to identify points of agreement and disagreement. To adapt the oft-quoted wisdom of George Box, essentially all probabilistic risk assessments are wrong, but some are useful.[9]

Finally, while not (yet) ready for prime time, probabilistic risk assessment has significant potential for improvement, as discussed in Martin Hellman's chapter. Focusing on historical examples of accidents and close calls should provide useful bases for both scenario development and expert elicitation of needed probabilities, however uncertain.

Complex Systems Theory

Our work has established that deterrence is an example of a complex system in operation. Thus, complex systems theory offers a vantage point for thinking about the potential failure of deterrence. However, like probabilistic risk assessment, while complex systems theory has had success in a variety of realms ranging from physical to biological and economic systems, relatively little research has focused on applications to international relations. The challenge lies in developing meaningful psychological and sociological behavior models for the human components of nuclear deterrence systems.

Nevertheless, general principles from complex systems theory can be applied to the risk of deterrence failure. Among them is the notion that system behaviors are not always presaged in component behaviors, which results in so-called emergent behaviors. Conventional systems assessment approaches inevitably miss rare, high-consequence events that must occur in complex systems. Complex systems theory also reinforces the importance of defining system boundaries carefully lest important interactions be excluded, giving rise to unintended consequences of deterrence policies and actions.

Progressing beyond discussion of general principles from complex systems theory will require development of a model of the nuclear deterrence system. Given the criticality of the continued success of deterrence, it is somewhat surprising that such a model has apparently never been developed—or possibly even attempted—except at a high level of abstraction with a narrow focus on damage calculations in stylized scenarios of strike and counterstrike (so-called exchange analysis). If carefully constructed and continually improved, a complex systems model of deterrence would enable the analytic tools (e.g., simulation) of complex systems analysis to help identify otherwise hidden failure modes, anticipate the impact of alternative deterrence policies and strategies, and perhaps even estimate the overall risk of deterrence failure.

Knowledge Integration

We have seen that while each of the four approaches examined in this study has something of value to contribute to assessing the likelihood of deterrence failure, that value may be difficult to extract. Casting such a wide methodological net creates yet another challenge: how to summarize knowledge obtained from such diverse approaches. To illustrate, historical case studies may provide some evidence that, for example, the progression of close calls to their final resolutions has been unpredictable and may support the inference that the outcomes of future close calls are also likely to be so. Elicitation of experts on the risk of deterrence failure may provide a sampling of opinion, qualitative and quantitative, and supporting thought processes. Probabilistic risk assessment, if all goes well, may provide quantitative probability distributions of the likelihoods of various paths to nuclear use. And considering the risk of deterrence failure from the perspective of complex systems theory may provide insights into limitations of more traditional systems analyses. Combining such diverse forms of knowledge from multiple approaches, all with uncertainties and both confirming and conflicting data, interpretations, and conclusions, is the challenging objective of knowledge integration.

We cannot evade this challenge. Knowledge integration allows us to summarize and draw conclusions, facilitating policy-making and communication. Without integration and summary, we are free to cherry-pick only those facts and arguments that support our preconceived notions. The process is not dissimilar from what we ask trial jurors to do without the benefit of much guidance from judges' instructions. We can learn something by thinking through how a reasonable juror might approach the problem.

While the more esoteric mathematical approaches that characterize some of the advanced research in knowledge integration have their place, it might also be helpful to focus on fundamental principles and practical approaches that emphasize simplicity, completeness, traceability, and transparency. Structures for assessing the quality of evidence, arraying it in support of and opposed to a hypothesis, and presenting the chain of logic that connects the evidence to a hypothesis would be immensely helpful. Uncertainties, contradictory evidence, and alternative hypotheses must be included as well. Such a disciplined, structured process would facilitate constructive dialogues among experts, policy-makers, and the public. And then it is up to fallible human beings, relying on neither mathematical exotica nor intuition, to render final judgments.

Consequences of Nuclear Weapon Use

Finally, we have concentrated on the likelihood component of risk, but a complete risk assessment of deterrence failure must also address the consequences of nuclear weapon use. While assessing the likelihood of nuclear use may be daunting, assessing the consequences is not a trivial task either. Despite more than one thousand US nuclear tests between 1945 and 1992 and extensive analyses of the effects of the Hiroshima and Nagasaki atomic attacks, there remain significant uncertainties with regard to consequences of nuclear weapon use. These uncertainties derive from inadequate data and study of those nuclear weapons effects, such as fire, that are not the primary mechanisms for destroying targets of interest to military planners; from phenomena, such as electromagnetic pulse, that were discovered only late (and by accident!) in the US nuclear testing program; from insufficient understanding of environmental effects, such as climate change, and societal effects, such as the robustness/fragility of economies and political institutions; and from a limited ability to model global, cascading, and/or long-term consequences of all types. In truth, we have only an inkling of the full scope of consequences of nuclear use, whether such use involves only one weapon or thousands. Military consequence assessments focus on damage to specific targets and miss the larger impacts of nuclear use on society and the environment. Ironically, it is these broader effects that will undoubtedly weigh most heavily on the minds of national leaders who must ultimately authorize nuclear weapon use.

It might be argued that it is enough to know that the consequences of even a single nuclear explosion would be horrific. While appealing in its simplicity, this perspective provides an inadequate basis for policy-making. Some nuclear wars will lead to 10,000 or fewer deaths; others to 1,000,000,000 or more. Beyond the 999,990,000 survivors of the smaller war who might take issue with the notion that all nuclear wars are essentially indistinguishable, there are other distinctions of importance. Some nuclear wars will bring about the demise of the United States as a political entity; others will not. Some nuclear wars will lead to a severe and long-term curtailment of civil liberties in the United States; others will not. Some nuclear wars will induce atmospheric changes that affect agricultural production across the planet, leading to mass starvation of hundreds of millions of human beings far beyond the borders of the belligerents; others will not. Some nuclear wars will encourage proliferation; others will not. Some nuclear wars will strengthen the nuclear taboo; others will not. While even the smallest nuclear war threatens consequences far worse than many calamities we can imagine, casting a blind eye to the varying degrees of horror across the spectrum of possible nuclear wars is simply irrational.

The perspective that the consequences of alternative potential nuclear wars are essentially indistinguishable in their horror is also not without policy dangers. In particular, it encourages the simplistic notion of independence between the likelihood of deterrence failure and the level of destruction threatened by nuclear retaliation. On the contrary, the relationship is complex. If the anticipated consequences to a would-be initiator of nuclear war are not perceived to be horrific enough—a criterion that depends on both the damage the initiator expects to inflict on the enemy and the damage the initiator expects to suffer in return—deterrence is undermined because such consequences may not be intolerable to the initiator. This is more than a purely theoretical point. Concern with the inadequacy of damage threatened by retaliation drove the Cold War arms race and in the future may, for example, impede significant further reductions in nuclear arsenals. It is also possible that a more comprehensive understanding of consequences could enable deeper reductions in nuclear arsenals. If more of the effects of nuclear war are included in the calculus, fewer weapons might be required to inflict whatever is perceived to constitute intolerable damage. The point of this discussion is that successful nuclear policy development, employment strategy, and crisis management depend on an understanding of consequences more nuanced than that all nuclear wars would be bad.

Similarly, the notion that we need not delve into the details of the consequences of nuclear war encourages the dangerous belief that deterrence can be maintained with a small arsenal even in the face of an adversary with a much larger arsenal. There is a substantial historical basis for this belief. For example, during the Cuban missile crisis, President Kennedy was deterred from bombing nuclear ballistic missile sites because of his fear that not all of them would be destroyed and at least one American city would suffer a nuclear attack in response. And, he was deterred from attacking the Soviet Union for the same reason. As expressed by Robert McNamara:[10]

> During a recent visit to the Soviet Union I was asked by several Russian political and scientific leaders to define nuclear parity. I replied that parity exists when each side is deterred from initiating a strategic strike by the recognition that such an attack would be followed by a retaliatory strike that would inflict unacceptable damage on the attacker. I went on to say: "I will surprise you by stating that I believe parity existed in October 1962, at the time of the Cuban missile crisis. The United States then had approximately five thousand strategic warheads, compared to the Soviet's three hundred. Despite an advantage of seventeen to one in our favor, President Kennedy and I were deterred from even considering a nuclear attack on the USSR by the knowledge that, although such a strike would destroy the Soviet Union, tens of their weapons would survive to be launched against the United States. These would kill millions of Americans. No responsible political leader would expose his nation to such a catastrophe."

Notwithstanding recent increases in China's nuclear arsenal, another example is provided by China's relatively small nuclear deterrent, which is justified on the basis that threatening only a few American cities is enough to deter US nuclear attack and prevent US intimidation.

However, there are historical counterexamples, as well. As McNamara noted, during the Cuban missile crisis the United States enjoyed an overwhelming nuclear superiority over the Soviet Union. That superiority was important in motivating the Soviet Union to place missiles in Cuba in the first place and also important in inducing the Soviets to ultimately remove their missiles.[11] As another example, in the Soviet–China border dispute of 1969, Mao Zedong had little confidence in the ability of China's small nuclear arsenal to deter a preemptive Soviet nuclear attack.[12] Finally, recognition of the importance of maintaining a *balance* of terror, even at absurdly high levels, helps explain the otherwise inexplicable buildup of US and Soviet arsenals to staggering heights during the Cold War. Again we see that reality is more complex than simplistic notions about deterrence and the consequences of nuclear war might suggest.

One might also argue that beyond a certain point, the law of diminishing returns will apply. So, while the first ten million fatalities might ruin your day, the next ten million would make it only slightly worse. That is, beyond a certain level of destructiveness, deterrence will not be further enhanced by threatening even greater damage; we can stop concerning ourselves with a careful assessment of consequences beyond that level. Unfortunately, even this does not seem to be a valid conclusion. As nuclear war increases in destructiveness, and depending on the nature of the targeting, the possibility of an environmental catastrophe increases. Ground bursts of sufficient yield can loft smoke and soot created by fires ignited by nuclear thermal radiation into the stratosphere, where they can remain for years, circulate around the globe, and attenuate sunlight. The reduced level of sunlight penetrating to the surface can significantly reduce surface temperatures for long periods of time, thereby harming agriculture on a global scale. While not completely understood and still the subject of some debate among scientists, this phenomenon could cause casualties far in excess of those caused by the more direct nuclear effects. So, rather than diminishing in incremental destructiveness as nuclear wars get larger, they can actually increase as they traverse the domain where global climatic effects are produced. Of course, the deterrent effects and policy implications of this depend on awareness of this phenomenon; it is not clear that official policies reflect such awareness.

In summary, a nuanced and comprehensive understanding of the consequence dimension of the risk of deterrence failure is essential but not easy. Target damage, the primary basis for evaluating nuclear war plans, provides only a very small piece of the knowledge we need. A comprehensive consequence assessment that includes the broader psychological and societal impacts of nuclear weapon use is beyond the reach of current analytic capabilities. Simplistic arguments that attempt to circumvent the need to assess these broader consequences can be dangerous. Finally, we cannot redress current deficiencies without a rejuvenated nuclear weapons effects enterprise.

Conclusions and Recommendations

The introduction to this study concluded by posing two questions: Is a risk assessment of deterrence failure worth pursuing? And, if so, what is the most promising path forward? This final section provides responses to these questions.[13]

Is an assessment of the risk of deterrence failure worth pursuing? Note that this question is not the same as asking whether the risk of deterrence failure is worth knowing. We should not presume that an attempted assessment will be successful. The main argument for trying boils down to this: Nuclear deterrence is a high-stakes strategy, gambling with hundreds of millions of lives and perhaps even with the survival of civilization. Prudence dictates doing all we can to reduce the risks associated with that strategy. Assessing those risks is the first step toward this end.

Risk assessment is a prerequisite of risk management. Without assessing the risks of deterrence failure, we are flying blind with respect to the need to reduce them. If a risk assessment finds risks are "unacceptably" high, we can more vigorously pursue risk reduction policies and programs. If significant risk abatement is not feasible, we might consider giving greater consideration to developing long-term alternatives to deterrence as our central strategy for preventing nuclear war and brinkmanship for managing nuclear crises.

If the assessment fails to come to any conclusion at all on the risk of deterrence failure, that too could be a useful result. While decisions and policies would undoubtedly continue to be made based on intuitive assessments of risk, it would perhaps help recalibrate the confidence we have in our intuition and motivate further research. Finally, in terms of further research, a well-executed risk assessment could set an appropriately high bar for the quality of such work, a welcome departure from many analyses conducted to date.

The arguments against pursuing an assessment of the risk of deterrence failure are perhaps more straightforward, but not as persuasive. First, *a risk assessment will cost money;* $10 million is not an unreasonable estimate for a comprehensive assessment using and improving state-of-the-art methods. Even in this era of high deficits and high national debt, this is clearly affordable and could result in significant savings if we develop a clearer understanding of the requirements for deterrence.

A more compelling counterargument is that it just cannot be done. *We are simply not able to develop a credible quantitative estimate of the risk of deterrence failure.* This presumption may or may not be valid, but it misses the broader picture. Related alternative goals that might be more achievable could result in useful policy-relevant insights. Such goals include:

- **Assessing the utility of determining the risk of deterrence failure.** How might the results inform policy-making? What form of answer would be useful for what decisions?
- **Assessing whether the question is researchable.** Can we come up with an analytic approach to the question? What is a practical research path forward? Our work has only scratched the surface on this.
- **Evaluating past analyses,** which could restore some balance to the current uncritical citation of such analyses in the literature.
- **Understanding risk perceptions,** including the question of how to judge risk acceptability. How much risk is too much and how should we decide?
- **Evaluating risk management policies** without an actual assessment of the risk of deterrence failure. Are we doing all we should to reduce risk?
- **Assessing future risk relative to past risk.** Is the risk of nuclear use increasing or decreasing? Is it larger or smaller than in past times?

- **Providing a lower bound on the risk,** which solves the objection to probabilistic risk assessment that it cannot possibly identify all paths to nuclear use.
- **Making qualitative judgments** without trying to quantify the risk.

While quantification of risk may represent the holy grail of risk assessment, accomplishing—or even just making progress toward—these objectives would be extremely useful and would be important steps toward this ultimate goal.

A third argument against performing a risk assessment is that we do not want to know the risk of deterrence failure. A determination of higher than "acceptable" risk could undermine deterrence with no practical alternative available. This position is not irrational but does not consider the more constructive reaction of pursuing a less-riskier variant of deterrence.

If a risk assessment of deterrence failure is worth pursuing, why hasn't it been done? The primary reason lies in the nature of the federal bureaucracy. First, there has been no leadership push for analysis on this question. In fact, independent analysis can be a dangerous thing to political leaders; one can never be sure how it will turn out. Analysis is too often just another weapon in the arsenal to promote an agenda, useful only to the extent it promotes preconceived views. Moreover, political leaders, in general, see nothing wrong with intuition, or at least *their* intuition. And the propensity to surround themselves with like-thinking advisers only reinforces their intuition.

Second, no single government agency—including the Departments of Defense and State—has purview over this question. It is not explicitly in the charters of the US Strategic Command, the Office of Net Assessment, the Defense Threat Reduction Agency, or any other component of the federal government to address the risk of nuclear deterrence failure. So, why would any of these organizations choose to expend scarce resources on it? While $10 million may be a rounding error in the entire federal budget, it is not a minor portion of the discretionary research budget of many government agencies.

Finally, it requires some nontraditional thinking to even pose the question. Most government agencies are too busy fighting daily fires to think long term or out of the box. An agency runs the risk of criticism both for stepping outside its lane of responsibility and for wasting money, as well as potential ridicule for tackling such a seemingly esoteric problem. Failing to take the initiative in this area will not ruin anyone's government career.

If an assessment of the risk of deterrence failure is worth pursuing, what is the most promising path forward? While the National Academies of Science, Engineering, and Mathematics (NASEM) is conducting a study of analytic methods for assessing the risks of nuclear war and nuclear terrorism, it is not actually performing a risk assessment, nor is it well suited to do so. Follow-on studies that actually do try to assess nuclear risks conducted by other competent organizations (e.g., federally funded research and development centers or university affiliated research centers) would be a logical follow-on.

The important concept is to undertake *several* independent studies. Absent collusion, it seems unlikely they would come up with the same answer, and whatever disagreement exists will inspire further thinking and evaluation. Several independent studies will also reduce the risk of mindless recitation of the results of a single study, as has been the case with the Lugar survey.

As an alternative to a mega-study or mega-studies, what could be even more worthwhile over the long run is to make this subject a more respectable topic for academic and government-sponsored research. Not many scholars have pursued it, and not many government or private funding sources have recognized its importance. Smaller studies tackling portions of the problem could result in a significant improvement in understanding and could pave the way, eventually, for a mega-study. Smaller studies also enable foundation support and even individual academics to pursue research without any external support at all.

One mechanism to kick-start interest in such studies is a community workshop that involves academics, think tanks, government agencies, and foundations. Ideally, multiple disciplines would be included, including physical and social scientists; political scientists, international relations experts, and nuclear strategy analysts; weapon designers, weapons effects experts and weapons operations experts; and experts in the methodologies addressed in this study and others. Beyond providing a forum for exchanging ideas, one objective could be to craft the outlines of a research agenda.

Such a research agenda might be usefully divided into studies that could be undertaken using current methods and advancement in methodologies that would enable future studies. The former category includes:

- Selected historical case studies and studies looking across the broad spectrum of close calls designed to draw lessons for assessing past and future risks

- A state-of-the-art expert elicitation to assess contemporary perspectives on current and future nuclear risks
- Development of a taxonomy of alternative paths to nuclear use
- A comprehensive assessment of the physical and social consequences of various scenarios of nuclear use

Given the consequences of even the smallest nuclear war and given the challenges of assessing nuclear risks, taking prudent steps to reduce the risk of nuclear war should not await a definitive risk assessment. Thus, many research topics will naturally blend risk assessment and risk management. While there are myriad potential topics for such studies, one example of particular importance relates to the three-quarters-of-a-century-long tradition of nonuse of nuclear weapons. We do not fully understand the dynamics of this unexpected phenomenon, nor the extent to which it has been the result of wise policy or good fortune, nor its cultural dependencies, nor how robust or fragile it is, nor how we can nurture its continuance. As Thomas Schelling argues in his Nobel Prize lecture in 2005:[15]

> This attitude, or convention, or tradition, that took root and grew over these past five decades, is an asset to be treasured. It is not guaranteed to survive; and some possessors or potential possessors of nuclear weapons may not share the convention. How to preserve this inhibition, what kinds of policies or activities may threaten it, how the inhibition may be broken or dissolved, and what institutional arrangements may support or weaken it, deserves serious attention. How the inhibition arose, whether it was inevitable, whether it was the result of careful design, whether luck was involved, and whether we should assess it as robust or vulnerable in the coming decades, is worth examining.

Research to advance methodology development has significant potential over the longer term. In this area, three advances would be particularly important:

1. An improved ability to model human behaviors and estimate probabilities in probabilistic risk assessments
2. A complex model of the nuclear deterrence system
3. Improved methods to assess social, economic, and political effects of nuclear weapon use

In addition, preliminary examination of myriad approaches to assessing the risk of deterrence failure not examined in this study should be undertaken.

A Final Thought

While we have tried to make the case for structured multidisciplinary analysis as an improvement over intuition in assessing the risk of nuclear deterrence failure, we have also come to appreciate that as much depends on the quality of the analysis as on the methodology employed. Too much of what little analysis on this topic has been produced is arguably deficient. In particular, many analyses are plagued by lack of transparency in assumptions or reasoning, inadequate treatment of uncertainties, failure to apply state-of-the-art elicitation techniques, or all these. Until such problems are addressed, it should not be surprising that analyses of the risk of nuclear deterrence failure continue to change few minds.

Notes

1. Peter Vincent Pry, *War Scare: Russia and America on the Nuclear Brink* (Westport, CT: Praeger Publishers, 1999).
2. Michael S. Gerson, *The Sino-Soviet Border Conflict: Deterrence, Escalation, and the Threat of Nuclear War in 1969* (Alexandria, VA: Center for Naval Analyses, 2010), https://www.cna.org/cna_files/pdf/d0022974.a2.pdf. The author of this chapter was involved in defining the objectives for Gerson's research, which was sponsored by the Defense Threat Reduction Agency's Advanced Systems and Concepts Office.
3. Richard Neustadt and Ernest May, *Thinking in Time: The Uses of History for Decision-Makers* (New York: Free Press, 1986), 58–62. See also Yuen Foong Khong, *Analogies at War: Korea, Munich, Dien Bien Phu, and the Vietnam Decisions of 1965* (Princeton, NJ: Princeton University Press, 1992).
4. George E. Apostolakis, "How Useful Is Quantitative Risk Assessment?" *Risk Analysis* 24, no. 3 (2004): 515–520, https://doi.org/10.1111/j.0272-4332.2004.00455.x. See also Elisabeth Pate-Cornell and Robin Dillon, "Probabilistic Risk Analysis for the NASA Space Shuttle: A Brief History and Current Work," *Reliability Engineering and System Safety* 74, no. 3 (2001): 345–352, https://doi.org/10.1016/S0951-8320(01)00081-3; and J. S. Wu and G. E. Apostolakis, "Experience with Probabilistic Risk Assessment in the Nuclear Power Industry," *Journal of Hazardous Materials* 29, no. 3 (1992): 313–345, https://doi.org/10.1016/0304-3894(92)85040-8.

5. Committee on Methodological Improvements to the Department of Homeland Security's Biological Agent Risk Analysis; Board on Mathematical Sciences and Their Applications; Division on Engineering and Physical Sciences; Board on Life Sciences; Division on Earth and Life Studies; National Research Council, *Department of Homeland Security Bioterrorism Risk Assessment: A Call for Change* (Washington, DC: National Academy Press, 2008), https://doi.org/10.17226/12206.
6. Mary A. Meyer and Jane M. Booker, *Eliciting and Analyzing Expert Judgment: A Practical Guide* (Philadelphia: Society for Industrial and Applied Mathematics, 2001), 44.
7. Meyer and Booker, *Eliciting and Analyzing Expert Judgment*, 44.
8. Meyer and Booker, *Eliciting and Analyzing Expert Judgment*, 44.
9. George Box, Professor Emeritus of Statistics at the University of Wisconsin, said this of models. See George E. P. Box and Norman R. Draper, *Empirical Model-Building and Response Surfaces* (New York: John Wiley & Sons, 1987), 424.
10. Robert McNamara, *Blundering into Disaster: Surviving the First Century of the Nuclear Age* (New York: Pantheon Books, 1986), 44–45.
11. Not all historians agree on the latter point, but one need only imagine a counterfactual replay of the crisis in which the Soviet Union, rather than the United States, enjoyed an overwhelming advantage in nuclear weapons. Could Kennedy have credibly delivered his threat that "it shall be the policy of this Nation to regard any nuclear missile launched from Cuba against any nation in the Western Hemisphere as an attack by the Soviet Union on the United States, requiring a full retaliatory response on the Soviet Union"? Even more to the point, the emplacement of missiles in Cuba in the first place might not have been necessary from the Soviet perspective had the nuclear balance favored them at the time.
12. Gerson, *The Sino-Soviet Border Conflict*.
13. Several of the thoughts presented in response to these two questions were articulated earlier by Hellman and were refined through further private conversations between Hellman and the author. See Martin E. Hellman, "Risk Analysis of Nuclear Deterrence," *The Bent of Tau Beta Pi* 99, no. 2 (2008): 14–22, https://ee.stanford.edu/~hellman/publications/74.pdf.
14. Hellman, "Risk Analysis of Nuclear Deterrence," 18.
15. Thomas C. Schelling, "An Astonishing Sixty Years: The Legacy of Hiroshima," Nobel Prize Lecture (Stockholm: The Nobel Foundation, 2005), https://www.nobelprize.org/prizes/economic-sciences/2005/schelling/lecture/.

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While careful analysis of the likelihood and consequences of the failure of nuclear deterrence is not usually undertaken in formulating national security strategy, general perception of the risk of nuclear war has a strong influence on the broad directions of national policy. For example, arguments for both national missile defenses and deep reductions in nuclear forces depend in no small part on judgments that deterrence is unreliable. However, such judgments are usually based on intuition, rather than on a synthesis of the most appropriate analytic methods that can be brought to bear. This work attempts to establish a methodological basis for more rigorously addressing the question: What is the risk of nuclear war? Our goals are to clarify the extent to which this is a researchable question and to explore promising analytic approaches. We focus on four complementary approaches to likelihood assessment: historical case study, elicitation of expert knowledge, probabilistic risk assessment, and the application of complex systems theory. We also evaluate the state of knowledge for assessing both the physical and intangible consequences of nuclear weapons use. Finally, we address the challenge of integrating knowledge derived from such disparate approaches.

Cover: The Oracle at Delphi by the Kodros painter, c. 440–430 BCE. The oracle, speaking for the god Apollo, was known for providing authoritative, yet enigmatic, responses to questions regarding power, religion, and war.

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