A RAND NOTE

ASSESSING THE CAPABILITIES OF STRATEGIC NUCLEAR FORCES: THE LIMITS OF CURRENT METHODS

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PREFACE

This Note reviews current methods of assessing strategic force capabilities and evaluates the strengths and weaknesses of different procedures. The material is organized into sections associated with similar kinds of procedures in order to provide an easily referenced summary of the issues in each area. The work reported here was sponsored by the Director of Net Assessment, Office of the Secretary of Defense.

This Note should prove useful to those interested in how strategic force capabilities are measured and in how these measurements then get factored into assessments of the strategic balance.

SUMMARY

The purpose of this Note is to assess the nature and validity of the various procedures used in assessing strategic force capabilities. That process should illuminate the problems and the limitations of such procedures and indicate, in at least some cases, how more appropriate procedures can be used. The review also suggests the complexity involved in making such assessments and the difficulties of arriving at specific conclusions about force capabilities. Finally, the assessment should expose readers to the limitations of some of the procedures from which policy decisions may stem.

There are three ways to evaluate strategic force capabilities: The most basic is to determine the percentage of targets of any given type that could be damaged by a particular force. The second and more difficult approach is to assess the residual capability of a target type after an attack. Such an approach improves the assessment of strategic force capabilities by substituting for target damage a more meaningful measure of the implications of that damage. The third procedure is to evaluate the gross damage potential of strategic forces using aggregate measures. While considerably simpler, this third procedure often captures damage potential only in very vague terms.

Each of these procedures for assessing strategic force capabilities has substantial limitations that prevent the development of precise estimates. Even when there is agreement on the nature of the capabilities to be measured, it is not possible to model most of their aspects in sufficient detail to support an accurate assessment of them. Among the many procedures for comparing capabilities, each can lead to a different estimate with no single choice clearly preferable. In particular, when aggregate measures are used, the procedures employed are at best approximations and are in some instances completely misleading. Finally, few assessments of capabilities consider uncertainty, and when they do the uncertainty usually overwhelms the estimate.

This analysis is organized under six major headings. The first section develops the general background and bases of procedures for assessing strategic force capabilities. Sections II and III treat those procedures and the specific types of capability that they attempt to assess. The fourth section addresses the roles and uses of aggregate measures, and the fifth the implications of considering nonstandard scenarios. That discussion focuses on how such scenarios affect the procedures developed in the earlier sections and the different types of capabilities that must be considered. The final section presents a sample analysis of Soviet capabilities in the mid-1980s and considers some of the difficulties of trying to apply the methodologies described in the previous sections.

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I. BASES FOR EVALUATING STRATEGIC FORCES

There is today no generally accepted methodology for assessing the capabilities of strategic nuclear forces. The wide variety of measures and metrics that attempt to evaluate some aspect of these capabilities suffer from two types of problems. Some measures do not measure specific capabilities in any meaningful way. Others are of limited utility because they usually consider only one of the many dimensions that should be included in a general assessment. Both of these problems are aggravated by the uncertainty that degrades the precision of the assessments.

This section describes the general bases for assessing strategic force capabilities. It outlines the purpose and objectives of strategic forces and the capabilties generally associated with them. It also addresses flexibility and endurance in the strategic forces. Finally, it considers how to deal with uncertainties in estimating strategic capabilities. In the subsequent sections, specific procedures will be developed for addressing each capability discussed herein.

THE PURPOSE OF STRATEGIC FORCES

The fundamental purpose of strategic nuclear forces is deterrence. The relationship between this purpose and the requisite capabilities of strategic forces is described on pp. 5-6 of the *Fiscal Year 1981 Defense Department Report* (hereafter *1981 Defense Report*):

> We have recognized for years that our strategic nuclear capabilities could deter only a small number of contingencies. But there can be no doubt that these capabilities still provide the foundation on which our security rests. Without them, the Soviet Union could threaten the extinction of the United States and its allies. With them, our other forces become meaningful instruments of military and political power. With the growth of Soviet strategic capabilities, we have concluded that credible deterrence depends on our ability (1) to maintain the second-strike forces necessary to attack a comprehensive set of targets,

including targets of political and military as well as of economic value, (2) to withhold retaliation against selected targets, (3) to cover at all times a sizable percentage of the Soviet economic base, so that these targets could be destroyed, if necessary, and (4) to hold the elements of a reserve force for a substantial period after a strategic exchange.

Clearly, the "capabilities" of the strategic forces are tied to their ability to destroy several categories of Soviet assets. The *1981 Defense Report* also refers to maintaining flexibility and endurance in the strategic forces. While these specific requirements may vary from time to time, two basic concerns remain the same: (1) What classes of targets must strategic forces be able to destroy to "guarantee" deterrence, and (2) how flexible must those forces be in threatening that destruction?

OBJECTIVES FOR STRATEGIC FORCES

Military, political, and economic target classes have been associated historically with two targeting objectives: countervalue and countermilitary. Countervalue targets normally are located in urban areas. Countermilitary targets are primarily the military forces of an opponent but can also include the industry that supports the military and the political leadership that controls it. Such targets also tend to be located in or near urban areas. In short, the traditional targeting objectives cut across the target classes proposed in the *1981 Defense Report*.

Despite the clear definition of target classes in the *1981 Defense Report*, there is still no consensus in the United States on the appropriate objectives for strategic targeting. This lack of consensus contributes to the generation of a variety of very different assessments of strategic capabilities. While analytic techniques have often been blamed for the resulting differences, those differences more often derive from the assumptions made in applying the analytic techniques or the selection of techniques that reflect particular policy biases. It is therefore important to identify the general schools of thought on strategic targeting.

Perspectives on Countervalue Capability

Countervalue attacks seek to destroy the "value" assets of an opponent. Those assets are normally considered to be his industry and population.[1] Destruction of a large part of the opponent's industry and population is intended to cripple his economy, cancel his ability to support modern warfare, and destroy the viability of his society.

There are, however, two schools of thought on countervalue attacks. One school holds that countervalue attacks fulfill an "assured destruction" objective in deterring "a deliberate nuclear attack upon the United States or its allies by maintaining at all times a clear and unmistakable ability to inflict an unacceptable degree of damage upon any aggressor. . . . After careful study and debate, it was [Defense Secretary Robert] McNamara's judgment . . . that the ability to destroy in retaliation 20 to 25 percent of the Soviet population and 50 percent of its industrial capacity was sufficient."[2] In this view, the "unacceptable degree of damage" had to be sufficient to offset any potential gain that the opponent might seek to achieve by nuclear war. By posing this threat, then, a country deterred its opponent from ever starting a nuclear war.

The other school of thought holds that the magnitude of a countervalue attack should reflect the magnitude of the gains the opponent could hope to achieve by the actions that had to be deterred. Thus, if in a nuclear war the Soviet Union were to gain control of an undamaged Western Europe, the loss of half of Soviet industry might not offset eventual Soviet gains, and a higher level of damage would therefore have to be threatened. Similarly, Soviet limited nuclear attacks should be deterred by U.S. responses in kind, as the use of an assured destruction attack in such a context would be *inappropriate*. Finally, this school believes that if deterrence should fail and both

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[1]In the past this type of attack has often made the *civilian* population the specific object of attack. Although such attacks appear to be in violation of international law, the ability to kill civilians is almost universally included in assessments of strategic force capabilities and will therefore not be ignored here.

[2]Enthoven and Smith (1971), pp. 174-175.

sides deliver full countervalue attacks, the relative levels of damage would be an important determinant of the postwar relationships.

These two schools of thought view countervalue capabilities from very different perspectives. To the first, a countervalue capability exists if strategic forces can deliver an assured destruction attack. Therefore, the advocates of this school focus on the size of the strategic forces relative to assured destruction requirements. The second school views countervalue capabilities in a relative sense, focusing on asymmetries in the levels or types of damage that either side could cause. The importance of those differences will be discussed below.

Perspectives on Countermilitary Capability

Broadly defined, a countermilitary attack seeks to destroy the military capabilities of an opponent. In both classical military strategy and in more recent strategic thought, such attacks are said to have two basic purposes. First, the attacker wishes to destroy some of the opposing military capability to prevent its being used against his "value" (nonmilitary) assets. Since at least the early 1960s, the literature on strategic war has referred to that goal as "damage-limiting."

The second purpose is to destroy the opposing military forces or reduce them to a level at which they acknowledge defeat or withdraw from the war. This purpose more closely approaches the notion of "war-fighting," which is focused on in the contemporary literature on strategic war.

Among a wide variety of opinions on countermilitary attacks and their purposes, two are prominent. Stated simply, the first holds that damage-limiting is essentially impossible while U.S. and Soviet strategic forces remain at their present high levels of destructive capability. ("What is the difference between 150 million and 120 million fatalities?")[3] Further, since nuclear war would be the "end of the world" (as we know it), the outcome of nuclear war becomes

[3]Many who hold this view also believe that arms control should be used to reduce nuclear weapon arsenals to very low levels where, according to their logic, damage-limiting could again become a relevant capability.

irrelevant and war-fighting makes no sense. In short, proponents of that view believe that countermilitary capabilities are unnecessary, wasteful, and potentially dangerous, and that neither the United States nor the Soviet Union should develop them.[4] In this view, assessing the countermilitary capability of either side is worthwhile only to verify that the opponent could not, indeed, limit damage to himself by destroying the opposing forces.

The opposing point of view (espoused by the Soviet Union) acknowledges that nuclear war would be extremely destructive but maintains that many would survive the war and insists on trying to improve the lot of the survivors. In this view, the question of who wins the war is crucial, for the purpose of the war in the first place is to prevent subservience to the opponent. Further, while the war would be highly destructive, each side should seek to minimize damage to itself in order to improve the quality of what might otherwise be a truly meaningless postwar existence. In short, this view gives importance to both the damage-limiting and war-fighting purposes of countermilitary attacks, thus requiring a detailed assessment of the relative countermilitary capabilities.

These two points of view lead their proponents to assess strategic force capabilities in very different ways. Those who hold the first position often ignore countermilitary capabilities, assessing only countervalue capabilities. Those who hold to the second view tend to focus on countermilitary capabilities, in part because they are not greatly interested in the fate of assets not directly related to the military outcomes of a war.

STRATEGIC FORCE CAPABILITIES AND TARGET DESTRUCTION

Many analysts assume that the damage to an asset is proportional to the number of asset-related targets that have been destroyed. That

[4] Countermilitary capabilities are potentially dangerous in that, if one were to develop a damage-limiting capability, it would lead to instability by encouraging a preemptive strike whenever one party feared that his deterrent capability might be eroded by his opponent's damage-limiting capability.

is, if five of ten steel mills are destroyed, 50 percent of the capability to make steel is assumed to be lost. Even if all ten steel mills were exactly the same size, this conclusion does not immediately follow. The physical assets of a steel mill constitute only one factor in the production of steel; in this case, the potentially better availability of other resources (such as labor) might well allow steel production to recover to 60 or 70 percent of the original level. The more appropriate criterion for measuring strategic force capabilities is, therefore, the extent to which they can degrade the capabilities of an opponent (such as steel-making).

There are three types of relationships between the destruction of targets and the degradation of capabilities. In the first, if a capability is redundant the damage to that capability will not be proportional to the damage inflicted on the targets that make it up. For example, it may be necessary to sever 50 percent or more of the nodes of a communication system before communication between any two points is impaired. The second type of relationship involves capabilities that degrade much faster than the rate at which targets are destroyed. A power grid is a good example: The failure of one of several units in the grid will cause the entire area to lose power. Between these extremes there are capabilities that degrade more nearly according to the level of damage. Thus the loss of vehicles in a transportation system running at full capacity will degrade the ability to deliver goods in roughly a proportional manner. It is also possible for an asset to have combinations of these relationships. For example, the effectiveness of a military unit initially will degrade at a rate roughly proportional to the rate at which assets are being destroyed. When fatalities reach some break-point (usually less than 50 percent damage), the morale and cohesion of the unit disintegrate and its effectiveness falls nearly to zero.

While it is usually possible to estimate how many targets of a particular type will be destroyed in a specified attack, it is much more difficult to determine the effect of that attack on capabilities. That effect depends on the specific aim points, and analysis of that effect requires relatively detailed models of the functions of each

target type. This difficulty is further complicated when measuring countermilitary capabilities. This measurement becomes recursive: "My capability to destroy his capability to destroy my capability to . . ." To avoid these difficulties, most assessments of strategic force capabilities concentrate on target damage, often ignoring the possibility that there might not be a direct connection between target damage and the degradation of opposing assets. This Note focuses on the destruction of targets but also attempts to identify some of the issues involved in determining how an opposing capability degrades as it is damaged. Some simple models for evaluating some of those degradations are displayed.

STRATEGIC FORCE FLEXIBILITY

Relatively little analysis has gone into assessment of strategic capabilities in other than a few standard scenarios. Standard scenarios usually start with a countermilitary attack, followed almost immediately by a countermilitary/countervalue exchange that ends the war. But at least three circumstances not routinely considered could change conventional strategic force capabilities: an extended crisis or a period of conventional conflict that preceded the use of nuclear weapons; an initial resort to limited nuclear options; or protracted nuclear conflict. Whether or not strategic forces would have the flexibility and endurance to carry out their assigned mission through such "off-design" scenarios is, as earlier remarked, one measure of their capabilities. Procedures for measuring strategic capabilities in these off-design scenarios are examined in Sec. V.

UNCERTAINTY IN ASSESSING STRATEGIC FORCE CAPABILITIES

Every factor considered in assessments of strategic force capabilities is uncertain. Unfortunately, the typical approach is to ignore these uncertainties and to assign a single point estimate to each parameter. The resulting estimate is often referred to as an "expected" or "best" estimate, based upon the "most likely" or "best" values of the parameters used to calculate it. However, these estimates are usually neither "best" nor "expected" and therefore can

seriously mislead those who use them. A better approach is to account explicitly for these uncertainties (to the extent possible). To do so, analysts must both understand the nature of the uncertainties and include them in assessments.

Table 1 lists some of the uncertainties that can affect capability assessments. They vary from physical unknowns or imprecise estimates to inherent unknowns about the actual conditions of a nuclear war.[5] Because these factors are uncertain, the results of any capability assessment that employs them will also be uncertain. Many analysts suggest that this uncertainty in results is neither important nor significant, since a major nuclear war would involve the use of thousands of large weapons and thus the uncertainties should "wash out." Yet the variance in estimates of strategic force capabilities so plentiful in the literature today strongly suggests that the uncertainties may not wash out.

Some of these parameters—weapon accuracy, for example—can be very uncertain. Figure 1 shows the results of simulated flight tests of a missile with a 900 ft CEP (circular probable error) and zero systematic bias (the distance between the target and the mean point of impact in the tests). Based on the assumed CEP, random numbers are used to generate the impact points. During the first ten or so tests, the estimates of both systematic bias and CEP are very different from their true values. A 90 percent confidence interval is shown around the estimated CEP; during the first 20 or so tests, this is also very broad. Indeed, even after 50 tests, it is still about 20 percent, making countersilo capabilities uncertain to within about 40 percent.[6] While most long-range ballistic missile systems are tested more than 50 times during their lifetimes, many of these tests necessarily concern hardware or software changes intended to correct flaws in the missiles. Any changes in configuration make the tests

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[5] Uncertainty in these factors results from limited test programs, imperfect intelligence, inability to predict the circumstances of a nuclear war, and other such problems.

[6] Countersilo capability, as developed in the next section, is proportional to the inverse of CEP squared.

Table 1

MAJOR UNCERTAINTIES IN ASSESSING STRATEGIC CAPABILITIES

Uncertain Weapon Performance	
Deployment/Availability	Height of Burst
Warhead Loadings	Reliability
Yield	Range
Accuracy	Footprint
--Dispersion (CEP)	Launch Rate
--Systematic Bias	Reprogramming
Uncertain Force Employment Parameters	
Prelaunch Survivability	Time-on-Target Control
Command and Control Connectivity	Fusing/Burst Height
Penetration Probability	Warhead Allocation
Uncertain Target Parameters	
Location and Altitude	Hardness and Shielding
Mobility	Value
Size and Shape	Climatic Conditions
Uncertain Scenario Conditions	
Warning	Attack Timing
Attack Objectives	Scale of Attack
Modeling Uncertainties	
Prompt Effects	Fallout Radiation Level
Fratricide	Fallout Distribution
Protracted War Uncertainties	
Interactions with Tactical Nuclear/Conventional Forces	Enduring Survival
	Enduring Availability

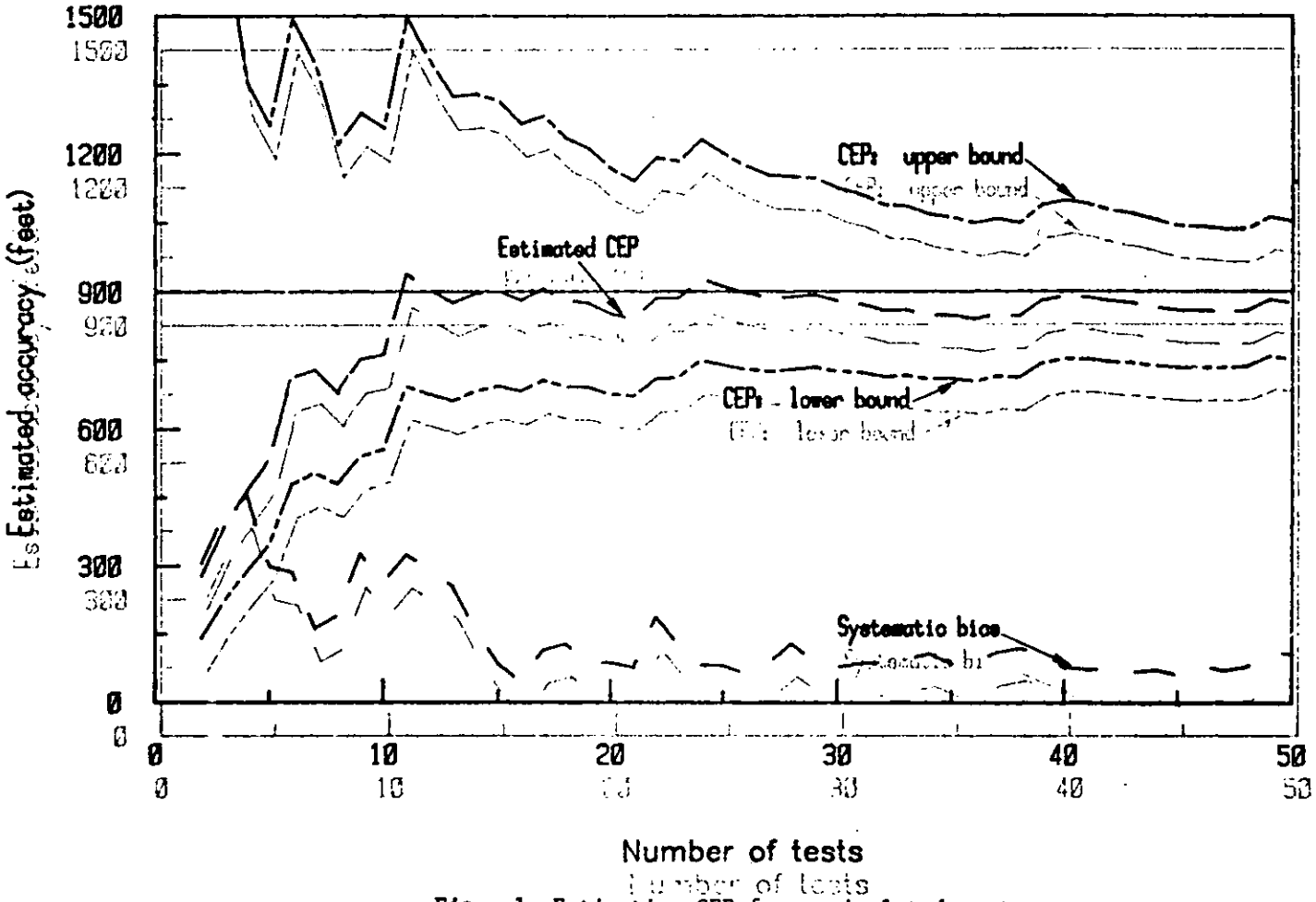

Fig. 1--Estimating CEP for a simulated test program

heterogeneous and only homogeneous tests can really be counted together in statistically estimating our confidence in CEP. Therefore, the amount of uncertainty shown in CEP here for 50 tests may not be unusual for many missile systems, and the accuracy of relatively new and untested systems will be far less certain.[7]

The other factors listed in Table 1 are associated with uncertainties that vary in scope and nature from those that concern weapon accuracy. Both systematic bias and fratricide are extremely uncertain because they cannot be tested directly.[8] On the other hand, missile range is known quite accurately. Any uncertainties that the United States faces in its own parameter values are enlarged when efforts are made to estimate comparable Soviet parameters. Therefore, there is little basis for the conventional confidence in assessments of strategic force capabilities. By not accounting for these uncertainties, analysts could severely misestimate strategic force capabilities.

It is worthwhile to distinguish between two types of uncertainties in strategic analysis. First, there are variations in the parameters around their mean value. For example, the yield of any given warhead might vary from the mean of the yield of that warhead type because of variations in the critical parameters of the warhead around its design specifications. Second, there is uncertainty in the mean value itself. For example, the yield of a warhead type may be estimated as 200 kilotons (Kt), though that estimate is uncertain because of limited testing and imprecise measurement techniques. In large attacks, variations tend to wash out and mean value uncertainties tend to persist. Since the basic attacks here considered are large attacks, variations need be discussed only occasionally, attention being focused on the uncertainty in the mean value of a parameter.

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[7] Since a 90 percent confidence interval is used here, the range of CEP values considered is much narrower than if a higher confidence interval were chosen. Also, the system in the example has a known CEP; in reality, the CEP will not be known and thus could be anywhere within the confidence interval.

[8] Fratricide can be tested only by examining multiple bursts in the atmosphere, a test prohibited by the test ban. The source of systematic bias is inherently unknown; it can be tested only on our test ranges and not over operational trajectories, as would be necessary to correctly quantify this bias.

Given the uncertainty in the mean value of parameters, there are five types of parameter values that can be used in assessments of strategic force capabilities. They are shown in Fig. 2, which takes as an example the probability distribution of the warhead yield of a Soviet weapon system. The most common procedure for dealing with the uncertainty in estimating this yield is to essentially ignore it by using the most probable value (1) as a "best estimate." Alternatively, one might wish to account for the bimodal nature of this particular distribution, by noting that there are two possible warhead technologies and acknowledging uncertainty about which is being used. In that case, one might choose a "best estimate" and an "alternative estimate" (2) in the analysis or, a "worst case" criterion (3) could be used in selecting parameter values. The worst case value represents the highest possible yield--irrespective of the probability of its being realized--on the basis that high confidence in U.S. strategic capabilities requires the ability to offset the worst possible threat. A fourth (and rare) method for selecting parameter values is to use both the highest and lowest values of the distribution to determine the range (4) of possible values. The final procedure uses values drawn by "Monte Carlo sampling"[9] (5) across the distribution to estimate both the range and the shape of the distribution. This method is not often used,[10] but in some cases it can improve standard capability assessments.

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[9] Ideally, analysts of strategic force capabilities would like to be able to develop analytic expressions that would integrate the damage functions across the various uncertainty distributions, yielding a simple distribution of results. Unfortunately, the mathematical techniques for integrating these functions do not exist. In their absence analysts turn to Monte Carlo simulations in which a series of estimates are drawn from each distribution and a result calculated for each of the various estimates. These results then serve to parameterize the uncertainty distribution of the outcome of the calculation.

[10] Even if a procedure existed for combining uncertainty distributions with damage functions, it would still suffer from the lack of knowledge about the distribution functions of the various parameters. However, analysts usually are willing to choose a "best estimate" even though they cannot determine how close that estimate is to the "real" value. While the distributions themselves are uncertain, making some estimate of them is undoubtedly better than ignoring them.

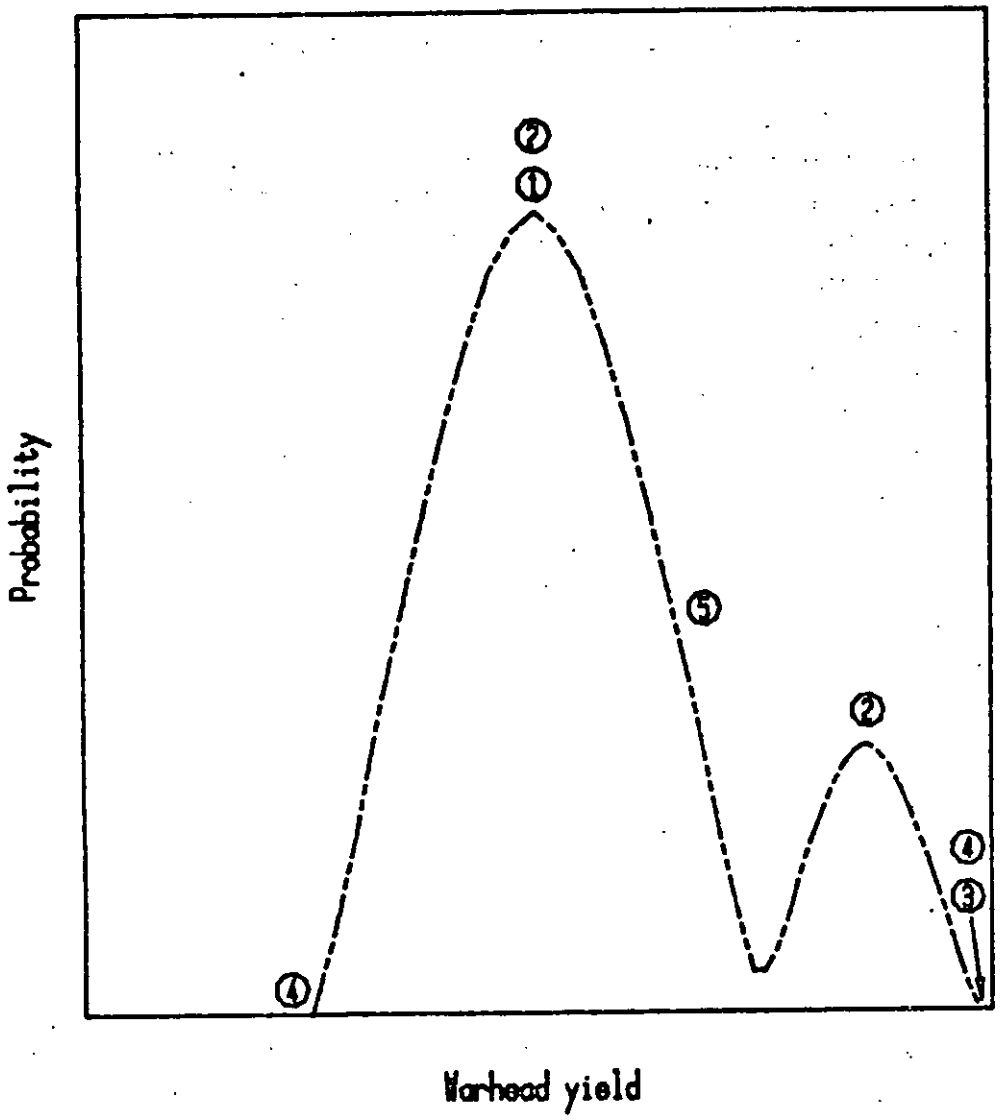

Fig. 2--Procedures for dealing with uncertainty/variability

II. ESTIMATING COUNTERMILITARY CAPABILITIES

This section considers some of the procedures used to estimate the damage that strategic forces can cause to military targets. Many analysts define countermilitary targeting as that aimed at destruction of the opponent's strategic forces (counterforce attacks). Some define countermilitary attacks even more narrowly to include only attacks on the opposing land-based intercontinental ballistic missile (ICBM) force. While this section focuses on counterforce attacks, it also includes attacks on other military forces. Different methodologies are used to assess the effectiveness of attacks against ICBMS, bombers, submarine-launched ballistic missiles (SLBMs), the strategic command and control system, and other military targets. For each type of target, the nature of potential attacks and their critical elements are examined, and some of the methods for assessing attack effectiveness are introduced. The potential importance of uncertainty in all of these calculations is also presented.

INTERCONTINENTAL BALLISTIC MISSILES

Attacks on ICBMs must focus on delivering warheads very close to the target. The critical factors are (1) the vulnerability of the target,[1] (2) the destructiveness of the warhead, and (3) the accuracy with which the warhead is delivered. Attack assessments must also consider (4) the effects of multiple warheads (including fratricide), and (5) the delivery probability of the warheads. In essence, then, these factors cover all aspects of the traditional hard target destruction problem.

Initially, the hard target destruction problem was analyzed using a relatively simple formulation, which assumed that target vulnerability

[1]A variety of weapon effects may contribute to the destruction or disabling of a hard target, as described in Appendix A. However, most of those effects are poorly understood. Therefore, vulnerability is normally represented as susceptibility to blast effects, which are relatively well understood.

could be measured by the lethal radius (LR)[2] at which a 1 Kt weapon could kill the target, that the destructiveness of the warhead was proportional to its yield (Y) taken to the one-third power, and that warhead impacts were circular normally distributed around the target with half of the warheads falling within the CEP. Given these assumptions, the survival probability (PS) of the target can be formulated as:

$$PS = .5^{(LR \cdot Y^{1/3}/CEP)^2}$$

This formulation assumes what is commonly called a "cookie-cutter" damage function: If the warhead lands at or within the lethal radius, the target is completely destroyed; if the warhead lands outside the lethal radius, the target is completely undamaged. For multiple warheads (n), this damage simply compounds,[3] yielding a survival probability (PS_n) of:

$$PS_n = .5^{n\ (LR \cdot Y^{1/3}/CEP)^2}$$

To account for delivery probability in this relationship, many analysts simply deflate the number of warheads by the delivery probability. Thus, a warhead with a lethal radius of 120 ft, a yield of 1000 Kt, and a CEP of 600 ft would have a PS of 0.0625. For two warheads deflated by an 80 percent delivery probability (n = 1.6), the compound survival probability would be 0.0118.

Several factors complicate this relationship. First, the lethal radius is a function of yield: A higher warhead yield increases the duration of the overpressure pulse that hits the target. In turn, an

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[2]See Appendix B for details of the lethal radius formulation.

[3]Damage "compounds" when the damage caused by each warhead is "independent" of the damage caused by every other warhead, and thus the survival probabilities can be multiplied together to determine the multiple shot survival probability. Damage would not be independent if (for example) the first detonating warhead failed to kill the target, but "softened" it, making destruction easier by subsequent warheads.

increase in pulse duration may make the target vulnerable to lower overpressures, thus enlarging the effective lethal radius of the warhead. But the effect of pulse duration varies across target types, making it impossible to include this effect in the yield term of PS. Instead, a modified system of measuring target vulnerability has been developed that explicitly includes sensitivity to pulse duration in the vulnerability assessment. It is called the vulnerability number system.[4]

The second complicating factor is the nature of the damage function. For a variety of reasons, damage does not take the form of a cookie-cutter.[5] Rather, the probability of damage falls below 100 percent well within the lethal radius and does not reach zero until well outside the lethal radius. A log normal damage function is commonly used to capture this kind of variation in target damage, with a "damage sigma" measuring the slope of the damage function. Use of this function changes the cookie-cutter PS by up to about 2.2 percent--not a very significant difference.

The third complicating factor is warhead accuracy (or rather, inaccuracy). While ideal warheads might fall in a circular normal pattern around the target, this kind of pattern usually forms around a "mean point of impact" that is some distance from the target.[6] The distance between the target and the mean point of impact is referred to as systematic bias, or gross miss. Thus systematic bias measures true inaccuracy, whereas the CEP measures the dispersion of potential impact points. Systematic bias invalidates the simple formula for PS shown above and makes any simple, analytic assessment of PS impossible. However, approximations have been developed that make calculation of PS possible while accounting for systematic bias. Depending upon its magnitude, systematic bias can significantly increase PS.[7]

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[4]See DIA (1974).

[5]These reasons include variability in target hardness, in warhead effects, and in the hardness of different target parts.

[6]Warhead impacts may also fall in elliptical or other more complicated patterns, but such variations are extremely difficult to model, are normally not significant in effect, and are therefore usually ignored. See Bennett (1980a) and (1980b, especially Appendix C).

[7]Foster (1978), pp. 34-38.

The fourth complicating factor is the proper representation of the probability of warhead arrival. While many analysts offset warhead arrival uncertainties by deflating the number of arriving warheads, that technique is clearly improper. In the example given above, the survival probability for two warheads having an 80 percent arrival probability was 0.0118. However, for two warheads with an 80 percent arrival probability, no warhead would arrive at least four percent of the time, making the expected survival probability at least 0.04. To arrive at the proper compound survival probability, the survival probability for the target when it is attacked by a single warhead must first be found. For the above example, it is 0.25.[8] For two warheads, then, the true compound survival probability is 0.0625, or more than five times larger than is sometimes calculated.

The fifth complicating factor is fratricide—the destruction of an incoming warhead by the debris or nuclear effects of a previous nuclear detonation in the same area. Because of fratricide, warheads that would otherwise reliably detonate on target could be lost. Unfortunately, there is no consensus as to the potential magnitude of this effect, though most analysts agree that it would limit the successful delivery of warheads to two or three per target in any given attack wave.[9]

A variety of other factors also might affect the simple formulation of PS, though most are less important than those described above. Among these factors are the choice of warhead burst height, the interaction between accuracy and height of burst errors, other nuclear effects (especially ground shock), and attack timing. Uncertainty also plays a significant role in a proper formulation.

It is not possible to solve all of these problems using the formulas developed above.[10] However, it is possible to account for the

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[8]The probability of survival equals the probability the warhead does not arrive (20 percent) plus the probability the target survives if the warhead does arrive (0.625 times 80 percent, which equals five percent.)

[9]While fratricide is seldom cited as the reason for limiting an attack to two warheads per target, this limitation is widely employed for that reason.

[10]A more complete description of the procedures for estimating damage to ICBMs is given in Bennett (1980a and 1980b).

fourth and fifth factors fairly easily. That is, arrival probability (PA) can be introduced by modifying the survival probability to:

$$PS = [1 - PA + PA \cdot 0.5^{(LR \cdot Y^{1/3}/CEP)^2 \cdot n}]^n$$

In turn, fratricide can be partially accounted for by limiting the value of n to 2. This formulation allows us to at least estimate the potential countersilo capability of strategic forces.

Table 2 displays some sample ICBM parameter values to be used in an exemplary analysis. For simplicity, it is assumed that the ICBM silos are all protected to 2000 pounds per square inch (psi) over-pressure and that the arrival probability of the warheads in a first strike is 80 percent.[11] Thus, although several of these systems can destroy opposing ICBM silos if the warheads arrive, the 80 percent arrival probability dilutes their effectiveness. It will also be assumed for the purposes of this example that no more than two warheads can detonate on any given target because of fratricide constraints.

The data in Table 2 presuppose that a Soviet countersilo strike on U.S. ICBMs would probably employ SS-C or SS-A missiles rather than SS-Bs, which have a lower kill probability. Because the SS-C warhead is so large, they presumably would not be numerous enough for a significant countersilo attack (such a missile would be more likely to be used against less numerous command and control assets). If two SS-A warheads were allocated to each U.S. silo, the foregoing formula indicates that roughly 87 percent of the U.S. silos would be destroyed. Such an attack, although not a "disarming blow," would

[11] The kill probabilities calculated equal one minus the single shot survival probability shown above using a cookie-cutter damage function (so as to allow readers to reproduce the calculations). The lethal radius is calculated assuming a groundburst. If airbursts were used, the kill probabilities would be somewhat higher; if a log-normal damage function were used, they would be somewhat lower. Since both differences are small and would tend to cancel each other, they are ignored for simplicity here.

Table 2

SAMPLE ICBM FORCES

System	Warhead Yield (MT[a])	CEP (n mi)	2000 psi Kill Probability P(arrival) 100%	2000 psi Kill Probability Equals 80%
United States				
US-A	0.20	0.10	0.613	0.490
US-B	1.00	0.20	0.500	0.400
US-C	5.00	0.60	0.202	0.161
Soviet Union				
SS-A	0.75	0.12	0.796	0.637
SS-B	3.00	0.36	0.359	0.287
SS-C	12.00	0.12	1.000	0.800

[a]Megatons.

affect the countermilitary capabilities of the U.S. ICBM force by reducing its delivery probability (without retargeting) to about 10 percent (assuming a force reliability of 80 percent). With this residual of perhaps 100 ICBMs (and ignoring other assets), the United States would be able to do only a limited amount of damage to either Soviet military or value targets, and even less without retargeting to allow the residual missiles to optimally cover opposing targets.

STRATEGIC BOMBERS

Attacks on strategic bombers are essentially time-urgent attacks. If bombers have adequate tactical warning, they can take off from their bases and avoid destruction. Further, since the bombers can be recalled, the decision to launch them does not have the serious implications associated with launching ICBMs on warning. Nevertheless, great care would have to be exercised in recalling the bombers to avoid making them vulnerable after they landed. Still, it will be assumed here that the bombers are launched upon tactical warning, and

therefore that the success of an attack on them will be critically dependent on its timing.[12]

Bombers will survive if they can outrun the nuclear effects of weapons detonated on or near their bases. Their ability to do this depends on several factors: (1) the amount of time needed to prepare for takeoff, (2) the flyout curve for the aircraft (relating distance to time during takeoff and acceleration), and (3) the time delay between planes trying to use the same runway. Also, since bombers and tankers must concurrently escape from some airfields, the numbers of each that survive depend on the priority given to each in the takeoff queue. The amount of time bombers have to reach a safe distance from their bases is roughly equal to the amount of time required for the attacking missile to reach the bomber base after its launch has been detected.[13] The safe distance from the base is a function of (1) the vulnerability of the aircraft, (2) the destructiveness of the attacking warheads, (3) the number of warheads allocated to the base, and (4) the pattern by which these warheads are allocated and the paths by which the bombers attempt to escape.

In the 1950s and early 1960s, SAC officials were initially worried about attacks on U.S. bomber bases by Soviet bombers. Later, Soviet ICBMs were of concern. In each case, the lack of a reliable tactical warning system was the prime reason for concern about those threats. Today's systems should generally provide at least 30 minutes of warning against attacks by either of these types of strategic

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[12] Actually, in normal peacetime circumstances there are two components to the bomber force. The first is the alert force, which is prepared for launch on warning. Attacks against this force are time sensitive. The second is the nonalert force, which normally requires hours to be made ready for launching and could therefore be attacked at a more deliberate pace, as could other basically immobile targets. But it must also be recognized that with reasonable strategic warning a much larger share of the total bomber force could temporarily be placed on alert, with obvious consequences.

[13] It is normally assumed that the first detected launch of an enemy missile initiates the launching of the entire bomber force. This procedure increases the time available for escape by allowing many aircraft to take off before the missiles fired at their bases have been either launched or detected.

weapons. But the flight times of Soviet SLBMs, especially those located directly off the U.S. coast, could be on the order of five to twenty minutes, posing a definite threat to bomber survival.[14] Therefore, only the Soviet SLBM threat to bomber survival is examined here.[15]

A simple example is used here to illustrate bomber survival calculations. The four bomber bases shown in Table 3 are to be attacked by a Soviet Yankee submarine located about 800 n mi off the Atlantic coastline. The bombers and tankers shown are on day-to-day alert. For simplicity, it is assumed that the submarine can place at most one warhead on each of these bases. Table 4 summarizes some nominal values for missile flight times and aircraft escape times, showing potential aircraft survival levels.[16] The flight time of the SLBM is calculated assuming the use of a moderately depressed trajectory as an extreme form of threat. Bombers and tankers perform equivalently. The bomber reaction time is for day-to-day alert; the bomber escape time is calculated assuming that a 1 MT warhead is detonated over the center of the runway and that the aircraft is protected to about 1.5 psi.[17] Subtracting the bomber reaction and escape times

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[14] SLBM flight time depends on (1) the distance between the submarine and the bomber bases, and (2) the trajectory of the missile (range and angle of depression).

[15] The nonalert bomber force, although not a time-sensitive target set, is of potentially very high value. Therefore, it is assumed that some combination of SLBMs, ICBMs, and bombers will attack the bomber bases after the attack on the alert bombers to ensure the destruction of the nonalert force.

[16] For this example, most of the parameter values come from Quanbeck and Wood (1976), pp. 44-50. Quanbeck and Wood indicate that a depressed trajectory SLBM could fly 1100 n mi in 530 sec, or 2.075 n mi per second. Inasmuch as the ranges in the example are from 820 to 1180 n mi, this speed will be used to calculate SLBM flight times. The time between SLBM launches is from Winnefeld and Builder (1971), p. 21. For the sake of simplicity, 15 sec is assumed as the interval between aircraft takeoffs.

[17] Quanbeck and Wood indicate that bombers are hardened to 1 to 2 psi. Using the optimistic assumption that the bomber could climb above the nuclear mach stem, the distance at which damage would be done depends on the free air overpressure. (The mach stem is the shock front formed by the merging of the incident and reflected shock wave.) The lethal radii of a 1 MT burst at 1 and 2 psi overpressures

Table 3

EXEMPLARY BOMBER BASES AND DEPLOYMENTS

Base	Latitude	Longitude	No. of Bombers	No. of Tankers
Griffiss	43.23	75.40	5	4
Rickenbacker	39.82	82.93	0	5
Seymour-Johnson	35.33	77.95	4	4
Wurtsmith	44.45	83.40	5	5

Table 4

SLBM FLIGHT TIMES AND BOMBER ESCAPE TIMES
(In minutes)

Base	SLBM Flight Time	Bomber Reaction Time	Bomber Escape Time	Net Escape Time	Possible Aircraft Surviving
Griffiss	6.62	5.50	2.30	--	0
Rickenbacker	9.26	5.50	2.30	1.46	6
Seymour-Johnson	7.85	5.50	2.30	.05	1
Wurtsmith	9.46	5.50	2.30	1.66	7

from the SLBM flight time gives the net escape time for all of the aircraft at the base; one aircraft can take off every 15 sec. Thus, with Wurtsmith's 1.66 min net escape time, the first bomber can take off at time zero followed by six more aircraft at 15 sec intervals; however, subsequent aircraft taking off can not escape the weapon effects. Depending upon the order of bombers and tankers in the takeoff queue, some mixture of each can survive at Wurtsmith; since bombers would probably be placed earlier in the queue than tankers on the average, a few more bombers than tankers would probably survive.

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are about 23,000 and 37,000 ft, respectively. A 5 n mi average distance was thus chosen for the lethal effects. Further, it was assumed that aircraft start their takeoff 1 n mi from the center of the runway and thus must fly 6 n mi to escape the nuclear effects. See Glasstone and Dolan (1977), pp. 108-109.

The net escape times given in Table 4 are calculated assuming that each base is hit with the first SLBM from the submarine. Since SLBMs are fired one at a time, with roughly a 15 sec delay between firings, the attacker must choose the order in which he targets the bases. In this case, the attacker can kill none of the aircraft at Rickenbacker (since only five are based there and six could escape); therefore he might not target that base at all. Also, the attacker can destroy all of the aircraft at Griffiss as long as he does not delay the missile launch by 1.18 min or more. On the other hand, if the first SLBM is targeted on Wurtsmith, one more aircraft can survive at Seymour-Johnson (the 15 sec delay in hitting Seymour-Johnson allows one more takeoff), and vice versa. In this particular case, the seven aircraft that can escape from Wurtsmith may be all of the bombers, so that the marginal aircraft at Wurtsmith is probably a tanker; alternatively, the second aircraft taking off from Seymour-Johnson is probably a bomber. Assuming that the attacker prefers to destroy bombers, he might place his first weapon on Seymour-Johnson, his second on Wurtsmith, his third on Griffiss, and his fourth on Rickenbacker (if he places any on Rickenbacker at all). Thus, the surviving aircraft might be the five tankers at Rickenbacker, one bomber from Seymour-Johnson, and five bombers and three tankers from Wurtsmith.

In real attacks on the bomber forces, two other factors must be considered. First, not all of the weapons fired at the bomber bases will detonate on target, as they are less than 100 percent reliable. Assuming that the SLBMs in our example are 80 percent reliable, then, the *expected* survival from the four warhead attack increases from six bombers and eight tankers to about eight bombers and ten tankers. Second, the attacker can reduce survival by targeting more than one warhead per base. The extra warheads can offset reliability problems and also can expand the area covered by nuclear effects, decreasing the bomber escape time. The Soviets probably would use such a procedure, referred to as a pattern attack, given the relatively small number of U.S. bomber bases and the relatively large number of Soviet submarines available to attack them.

Bomber survivability can be assessed by a variety of computer programs. These programs vary in complexity from extremely simple approximations to very detailed simulations of the interactions discussed above. However, even in the very detailed simulations, the allocation of weapons for pattern attacks must be simplified by a number of assumptions because the timing and positioning of pattern attacks can be extremely complicated, making a truly optimal weapon allocation infeasible. Still, most of the detailed simulations provide allocations that are very close to optimal and thus produce reasonably accurate results.[18] However, the allocations are almost always calculated assuming that each side has perfect information about the actions and systems performance of the other; without perfect information, a suboptimal allocation of weapons is probable.

BALLISTIC MISSILE SUBMARINES

Like most other naval assets, SSBNs must be treated as mobile targets. Therefore, attacks against them progress through two stages. In the first (localization), the attacker attempts to determine the SSBN location within a small area. In the second (engagement), the attacker employs weapons in an attempt to destroy the SSBN. With a nuclear weapon, the probability of destroying the SSBN in the engagement is fairly high.[19] Therefore, localization is the key step in attacking SSBNs.

There are four ways to locate an SSBN. The first is to monitor SSBN ports and repair facilities. The second is to trail SSBNs as they leave port. The third is to search for SSBNs with any of a variety of systems. And the fourth procedure is to wait for an SSBN to give away its position by launching a missile, surfacing, or

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[18] However, simple bomber survival models, such as the one used by Quanbeck and Wood (1976), produce survival levels that can be off by up to 50 percent, since they fail to allocate weapons optimally and often misestimate the damage caused to escaping aircraft. Analysts should ensure that simple models are somehow validated against the actual dynamics of bomber survival.

[19] A barrage attack could be performed with ICBM warheads, or the attacker could use a variety of nuclear torpedos and depth bombs with sophisticated homing devices.

carelessly transmitting messages. These procedures may be used in any combination, though the method of attack resulting from each is somewhat different. That is, since some SSBNs are always in ports, SSBN ports will naturally be a target set for any nuclear attack. SSBNs can best be trailed only by other submarines and are likely to be attacked by those submarines. Submarines detected during search or after exposing themselves can be attacked by the detecting submarine, surface ship, or aircraft, perhaps with an area barrage of nuclear weapons.

Much of the present-day effort in antisubmarine warfare is expended in developing search techniques for localization. Two basic approaches are used in such searches. The first is acoustic search. While sonar and similar devices have been used for years for this purpose, acoustic search is a difficult and uncertain procedure because sea water is an imperfect carrier of sound. Acoustic search can be performed by area sensors (like SOSUS),[20] point sensors (sonobuoys), or sweeping sensors (mounted on naval craft, especially submarines). Area sensors provide continual surveillance of certain areas as long as ocean conditions are appropriate; point sensors search a circular area around the sensor, and sweeping sensors search a path defined by the range of the sensors (the path width) and the speed of the vessel (the path length in any given period of time). The area searched, when divided by the area available for SSBN deployment, gives the probability of a random encounter with a single SSBN.[21] Thus, that probability increases with the area that can be searched in any given amount of time and decreases with the amount of area in which the SSBN can be deployed.

Nonacoustic search is the other means of SSBN detection. Among the techniques suggested for nonacoustic search are ocean piercing lasers, wake detection, and magnetic anomaly detection. Such forms of search could also employ area, point, or sweep techniques.

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[20] The U.S. SOSUS (sound surveillance system) consists of a series of sensors for submarine detection mounted on the ocean bottom. See Aldridge (1978), pp. 34-36.

[21] SSBNs also have sound detection systems which (at times) allow them to detect an attacker and evade or attack first.

Attacks on SSBNs normally do not fit into most assessments of strategic capabilities, in part because many analysts treat SSBNs as invulnerable, or vulnerable only in the long term, given the lengths of time that might be required to find and destroy them. Another reason for ignoring attacks on SSBNs is that strategic weapon systems would have a small role in such attacks, and thus exchange ratios would not be meaningful.[22] However, these attacks could affect strategic capabilities in some scenarios[23] and should therefore be considered.

COMMAND AND CONTROL

The vulnerability of command and control systems is essentially a network problem. That is, such systems are usually designed with redundancy, which requires that an attack must cut many nodes or connections to be effective. Further, the attacker can never know for sure which levels of the command and control structure have already received authority for counterattacks. Thus, while damaging upper levels of the network might require relatively little effort, a prudent planner would probably attempt to damage several levels, including the more dispersed operational level.

While the public literature is relatively rich in detail on the vulnerability of strategic forces, the same literature has largely ignored detailed treatment of command and control vulnerability. Though single point vulnerability can be fairly well approximated on incomplete information, it is much more difficult to construct a

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[22] General purpose forces could also be used to destroy strategic systems other than SSBNs. For example, B-52s could be destroyed by hand-held surface-to-air missiles (SAMs) as they took off, and ICBM silos could be subject to paramilitary attack with conventional explosives. However, ICBMs and bombers are generally considered more susceptible to attack by strategic forces, whereas SSBNs are more susceptible to attack by general purpose forces. Thus bomber and ICBM prelaunch survival must be considered in assessing strategic force capabilities, whereas SSBN prelaunch survival is not as obviously relevant.

[23] Such scenarios might begin with a phase of protracted conventional war, during which SSBNs might be destroyed, or might include a strategic exchange that continued over some period.

network model without a good understanding of each node and connection, since the survival of but a single link may make the postulated attack unsuccessful. This type of problem is shown in the following simple example.

Each U.S. Minuteman squadron controls the launch of 50 missiles in that squadron. At this level, the command and control elements are referred to as launch control centers (LCCs).[24] Each squadron has five. Normally, the crews from at least two LCCs must give the order to launch the squadron's missiles; however, with outside help a single LCC sometimes can launch the missiles. Therefore, an attacker who wished to neutralize the missiles in any given squadron by attacking command and control sites would have to destroy at least four, and perhaps all five LCCs, in that squadron. The probability of LCC survival can be calculated using a binomial equation based upon the survival probability of each individual LCC, as shown in Table 5. For example, if each LCC has a survival probability of only 1 percent, there is a 95 percent probability that no LCC would survive and roughly a 5 percent probability that only one would. There is almost no chance that two or more LCCs would survive.

The results shown in Table 5 are typical of many network problems. Very high kill probabilities are needed against each node in a network to completely cut all links. Thus, in the LCC network, a kill probability against a single LCC of 90 percent results in only a 59 percent probability of disabling the entire network. Alternatively, if this network requires at least two links to stay open, the effectiveness of an attack against the entire network can exceed the kill probability against any individual node in the network (if the LCC survival probability is less than 0.131). Thus, while requiring two LCCs to launch a squadron's missiles reduces the probability of unauthorized launch, it could also substantially reduce the probability of effective command and control survival.

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[24]The operation of the LCCs is described in "Targeting Flexibility Emphasized by SAC" (1976).

Table 5

MINUTEMAN SQUADRON COMMAND AND CONTROL NETWORK SURVIVABILITY

Individual LCC Survival Probability (%)	Probability of the Survival of:		
	No LCCs	1 LCC	2 or More LCCs
1.0	95.1	4.8	0.1
2.0	90.4	9.2	0.4
5.0	77.4	20.4	2.2
10.0	59.0	32.8	8.2
13.1	49.6	37.3	13.1
20.0	32.8	41.0	26.2
30.0	16.8	36.0	47.2
50.0	3.1	15.6	81.3

OTHER MILITARY TARGETS

There are various other military targets, the vulnerability of which depends on their size, mobility, and "hardness." In general, many of these targets are associated with "soft," relatively small, and immobile military bases that can be destroyed by a single nuclear warhead. Damage to these targets is determined by the number of warheads that can be delivered against them.

This type of formulation has some obvious difficulties. If the military capabilities themselves are either mobile or capable of dispersing on warning, destruction of the fixed facilities associated with a military capability may have very little effect on the capability itself (at least in the short run). Further, many military facilities are quite large and more than a single warhead might be required to cover the entire target. If these facilities are hardened, damage must be assessed as for ICBM silos, above. Also, because the attacker will not know which warheads will arrive, he y be forced to assign more than one warhead to each target to ensure at least one arrives. Some other military targets may be so close to each other that more than one can be destroyed by a single warhead.

In summary, then, damage to other military targets is difficult to evaluate. Even for fixed military facilities, analysts must use detailed weapon allocation procedures and must know the actual location, size, and vulnerability of these facilities and the arrival probability of the attacking weapons. Damage to mobile or dispersable military units cannot readily be assessed without considerably more information. These difficulties cause many analysts to ignore other military targets in assessments of countermilitary capabilities, even though in some scenarios they may be the most important targets.

UNCERTAINTY IN COUNTERMILITARY CAPABILITIES

Like all other aspects of nuclear war, countermilitary attacks involve large uncertainties. While it is difficult to precisely rank the types of military targets by the amount of uncertainty associated with attacks against them, it seems likely that the ranking today would be (from highest uncertainty to lowest): command and control, other military targets, bombers, ICBMs, and SSBNs.

Attacks on command and control should be treated as having the most uncertain effects for a variety of reasons. An opponent can never be entirely confident that he knows the precise nature of the command and control network. The network also can change rapidly, and is likely to do so if an attack is not quick enough to catch airborne command elements before they escape their airfields. Also, the reliability of the various communication procedures, especially in a nuclear environment, is extremely uncertain. Finally, both sides know that once nuclear war has begun, lower level commanders may be able to continue attacks regardless of the condition of large command and control networks.

Uncertainty exists in attacks on other military targets because the attacker can feel confident only of destroying the fixed installations associated with those targets. In a surprise attack, he may also catch many units still at their bases, though he is unlikely to know their exact locations. Even if units are damaged their effectiveness thereafter remains uncertain; partial attrition may destroy a unit's cohesion or motivate it to fight harder. Finally, no attacker

can be certain of the short- or long-term effects of having destroyed the fixed installations associated with particular military units.[25]

With attacks on bombers, the primary uncertainty is timing. Will there be enough warning? Will the aircrews and aircraft respond quickly? How quickly will the opponent's SLBMs reach their targets? The defender can not accurately anticipate SSBN targeting plans, and the attacker will not assuredly know where the bombers are based. Last, the destructiveness of the warheads and the vulnerability of the aircraft are imperfectly known.

The uncertainty associated with countersilo attacks has been widely studied.[26] Perhaps the primary sources of uncertainty in those attacks are accuracy, fratricide, and weapon effects. Some of these uncertainties can have large consequences, as will be demonstrated.

Most analysts feel that SSBN survival probabilities are very high and that the uncertainty of that survivability very low. They insist that U.S. SSBNs are almost certainly invulnerable and will be safe for years to come. Indeed, almost all discussions of SSBN survivability suggest that only a major technological breakthrough in SSBN localization would make them vulnerable, and that breakthrough must certainly be less probable, at least in the near future, than are the various threats to the other forces.

The potential effect of some of these uncertainties is shown by calculating the uncertainty in U.S. ICBM survivability, assuming a Soviet attack as discussed above (using the data from Table 2). In this attack, it is assumed that two SS-A warheads arrive at each of 1000 U.S. silos (and therefore arrival probability is not a

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[25] With airfields, for example, the fixed installations tend to be the aircraft repair facilities and the stores of petroleum, oil, and lubricants. Without these assets, aircraft sorties may be limited to only one or two per aircraft. If, however, similar facilities exist at an undamaged airfield close by, aircraft sorties may be limited only when extremely complicated or specialized maintenance problems arise.

[26] This subject is developed in considerable detail in Bennett (1980a and 1980b).

problem).[27] The multiple-warhead PS formula given earlier is used to calculate survivability, so that the only variables are the target hardness, the warhead yield, and the CEP.[28] The results of this calculation are displayed in Fig. 3, where the number of surviving U.S. ICBMs is plotted against the cumulative probability that as many or fewer survive. Thus, there is only a 25 percent chance that 20 or fewer U.S. ICBMs survive, and a 50 percent chance that 47 or more survive. The "expected" survival calculated from the nominal parameters is 42 U.S. ICBMs—less than the median level of survival.[29] Even with the limited uncertainties considered here, and assuming that two warheads detonate on every target, this curve shows that the number of U.S. ICBMs surviving could range from essentially zero to over 400, making impossible any precise numerical estimates of strategic force capabilities without also specifying a confidence interval. Further, as stated above, ICBM survivability can probably be estimated with greater confidence than the survivability of any other military force element except SLBMs. Therefore, while a basic pattern of countermilitary capabilities can be established, a point estimate of those capabilities is very hard to justify.

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[27] If arrival probability were actually considered, the expected value for survival should increase (unless a large number of warheads are used to guarantee arrival), and the uncertainty would be enhanced (since arrival probability is itself uncertain).

[28] Thus fratricide and systematic bias, two of the major determinants of uncertainties in ICBM survival, are not included in this calculation, decreasing the overall survival estimates, and reducing the uncertainty shown in survival. In doing this calculation, yield is assumed to have a standard deviation of 10 percent (75 Kt), hardness a standard deviation of 250 psi, and the CEP is assumed to be determined from 25 tests. It is further assumed that the yield and CEP are determined by 10 tests each, and that the lethal radius calculated for blast effects has a standard deviation of 5 percent. Student's t distributions are used for each of the variables except the CEP, which is determined from a chi-square distribution.

[29] In most cases where the "expected" survival is quite low, the median or the average survival (accounting for uncertainties) tends to be higher than the "expected" survival because a slight degradation in any of the factors tends to increase survival more than a slight improvement in the factors decreases survival (the mathematician's problem of averaging across a concave surface).

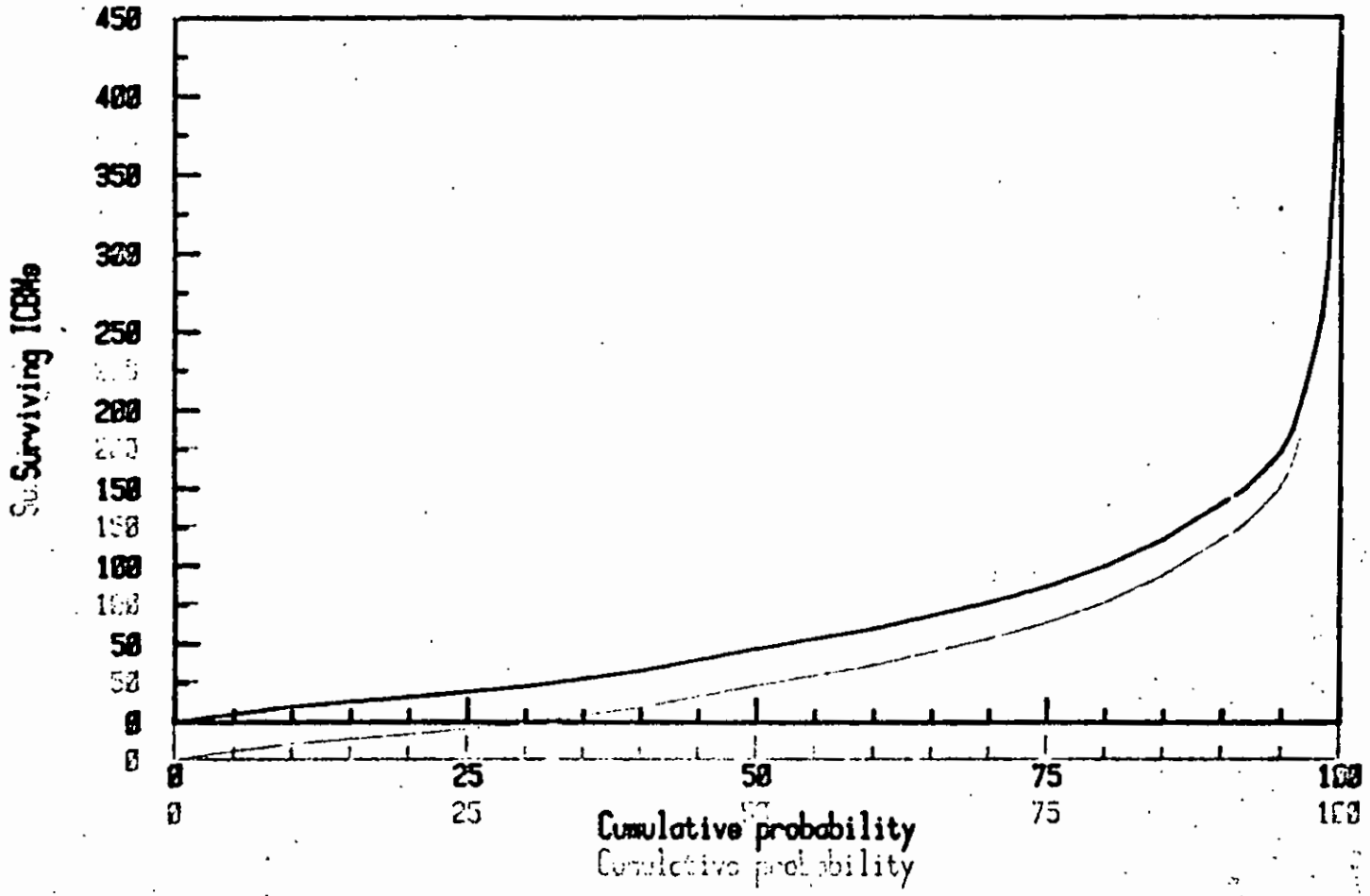

Fig. 3--Exemplary uncertainty in ICBM survivability

Fig. 3--Exemplary uncertainty in ICBM survivability

III. ESTIMATING COUNTERVALUE CAPABILITIES

The purpose of countervalue attacks is usually stated as the destruction of the opponent's industry or society. This section discusses the nature of such attacks and some methods for evaluating them, first by differentiating the vulnerability of industry and the population, then by considering procedures for attacking collocated area targets and how countervalue attacks could affect industrial capabilities in the postwar period. Fallout damage is also assessed, as is the potential influence of civil defense, which is designed to offset such damage. Finally, this section considers how various uncertainties can affect countervalue assessments.

THE VULNERABILITY OF POPULATION AND INDUSTRY

Nuclear weapons affect industry and population in various ways. (It is not U.S. policy to attack population.) As with military targets, the weapon effect most often used to assess damage to both of these types of assets is overpressure or "blast." An overpressure of between 5 and 10 psi is normally fatal to either industry or population. Within the 5 psi distance from a nuclear explosion, fire may destroy many of the structures that survive blast effects.[1] For a groundburst 1 MT weapon, the 5 psi lethal radius is about 2.5 n mi (15,000 ft); it is about 3.8 n mi for an optimal airburst. The comparable distances for 10 psi are 1.7 and 2.4 n mi, respectively.[2]

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[1] Damage criteria for both blast and fire effects are given in ACDA (1978), pp. 7-9.

[2] The lethal radii are calculated from Glasstone and Dolan (1977), pp. 112-115. The details of these nuclear weapon effects are discussed in Appendix A. It is important to note that the optimal height of burst for 10 psi and for 5 psi differ significantly. Thus, at the optimal height of burst for 5 psi (about 10,000 ft for 1 MT), the 10 psi lethal radius is only about 1.3 n mi because the weapon is detonated above the 10 psi mach stem region. At the optimal height of burst for 10 psi (about 7,000 ft), the 5 psi lethal radius is reduced only about 10 percent.

Population is also sensitive to radiation effects. Prompt gamma and neutron radiation is emitted by a nuclear weapon when it explodes. For 1 MT or larger weapons, the lethal radius for prompt radiation is smaller than that for comparable blast effects, and so blast is the effect from which fatalities should be calculated. For weapons smaller than 1 MT, the prompt radiation lethal radius is the larger and thus is the determinant of fatalities.[3] Thermal radiation can also be lethal for those in line of sight of the explosion. Usually only people who are outdoors at the time of an explosion would ordinarily be so exposed, but for them thermal radiation could be the most lethal.[4] Finally, fallout produced by nuclear weapons spreads downwind from the explosion. People downwind would receive radiation dosages as long as they remained unsheltered in contaminated areas; accumulation of a sufficient radiation dosage can be fatal.[5]

Industrial activities can also be damaged by other nuclear effects. Almost all kinds of modern electronics are vulnerable to electromagnetic pulse (EMP) effects, which may either temporarily disable or permanently destroy electronic circuitry. Also, if fallout covers industrial establishments, access to them may be denied for weeks or months after a nuclear explosion.

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[3]There is an intermediate region between about 100 Kt and 1 MT in which both effects are significant and cause a net lethal radius larger than the lethal radius of either effect by itself. This relationship exists because blast effects scale with yield to the one-third power, whereas radiation effects scale with yield raised to somewhat lower powers (e.g., around .15).

[4]The effect of prompt radiation is greatest against people who are outdoors and unprotected. However, prompt radiation is probably less lethal than thermal radiation to people outdoors, except from very low warhead yields (below about 10 to 20 Kt).

[5]In determining the total radiation dosage received, prompt radiation dosages must be added to fallout radiation dosages. However, the protection against radiation afforded by structures is not the same for both. In general, structures provide less protection against prompt radiation than fallout radiation. See Appendix A for more information on these effects.

ATTACKING TARGET CONCENTRATIONS

A lethal radius for prompt nuclear effects can be estimated against any type of target. Attacks against isolated point targets will destroy the target if the weapon arrives and detonates and if the detonation occurs within the lethal radius from the target.[6] However, both population and industry tend to be located in highly concentrated urban areas, collocated with other industry and urban population;[7] also, many industries are actually area targets. Attacks against industry or population[8] must account for these factors. While a variety of approximations are available for assessing damage to these area targets, the real difficulty in formulating such attacks is in determining where weapons should be placed and the priorities between locations. A solution to these problems is known as a weapon allocations procedure.[9]

To establish an allocation procedure, most analysts employ a value system for urban and industrial targets. Such a value system facilitates the comparison of targets of different types, allowing the analyst to decide, for example, where to target a weapon in an area containing both a steel mill and an oil refinery. The value of each populated area is related to the number of people who live within that area. The value of each industrial plant can be the manufacturing value added (MVA)[10] or some similar measure. Assigning a value to

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[6] Alternatively, for a normal damage function (not a "cookie cutter"), the probability that the target is destroyed by an arriving and detonating weapon is calculated by integrating the damage function with the warhead impact distribution.

[7] "Urban" areas are cities of 25,000 population or more, as defined in ACDA (1978), p. 3.

[8] Attacks against population are discussed herein because of their frequent mention in the strategic literature—especially in connection with assured destruction—despite the distaste of the author for a strategy that would allow such attacks.

[9] A weapon allocation procedure can cover a variety of targets besides "value" assets, but is essential to formulating a meaningful countervalue attack.

[10] MVA is the difference between the values of the outputs and inputs of a firm; i.e., its net increase.

each target provides a basis for allocating a given number of weapons to maximize the damage they do.[11]

Two basic procedures can be used in allocating weapons against urban and industrial assets.[12] The first and simpler procedure examines all possible locations for placing the first weapon, and allocates it where it can destroy the greatest value.[13] The procedure then allocates weapons sequentially to the locations where the next greatest value can be destroyed. This procedure allows the analyst to determine a roughly optimal laydown for any number of weapons, and to draw a tradeoff curve between value destroyed and weapons used.

The second procedure begins with a specific number of weapons that must be allocated to a given target set. It then finds a "feasible" allocation for those weapons, often in the sequential manner of the first procedure. Finally, it attempts to modify the various aim points to increase the amount of damage done. For example, if only two industrial facilities are being attacked, and if they are separated by somewhat more than one weapon radius but somewhat less than two weapon radii, then the first weapon and the second weapon might be aimed so as to impact between the two. If this allocation

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[11] In performing such weapon allocations, only the value of objective targets is considered. If some type of industry is not to be attacked (e.g., clothing manufacture), its value is not included. Also, some assets can be specifically avoided by negatively weighting their value. Similarly, though the units of population and MVA are different, "optimal" attacks against both (to simultaneously accomplish the dual goals of assured destruction, for example) can be produced by appropriately weighting the values of each.

[12] A third procedure allocates a single warhead to each objective target, and then searches for overlaps in weapon coverage, removing as many overlapping weapons as possible while leaving every target covered. The locations chosen become the aim points of the attack, and weapons are then allocated to these locations either uniformly (one or two per aim point) or by maximizing the marginal damage done. This procedure is not usually employed because the exclusion is generally done by hand and is thus very slow.

[13] The procedure for finding the optimal location can be complicated, because the value surface for destruction of targets often has a variety of local optimums, some of which do not occur directly over any target. Some allocation procedures search the entire space for the global optimum, whereas others consider only the damage that could be done by directly attacking any given target.

does not completely destroy either target, then the final step of this procedure might well move one weapon to each target, guaranteeing their destruction (if both weapons arrive and detonate). In short, the sequential procedure can actually yield a suboptimal allocation for more than the first weapon in any given area, and this second procedure seeks to improve the allocation to an optimum.[14]

Figure 4 displays a product of the first procedure.[15] In this figure, 1 MT warheads with an 80 percent arrival probability were assigned to U.S. industry.[16] Thus, one hundred warheads could destroy slightly more than 20 percent of U.S. MVA, whereas nearly 900 warheads would be required to destroy about 60 percent of U.S. MVA. As shown, the data base employed (for 1977) contains only 79.28 percent of all U.S. MVA, and thus the destruction of MVA approaches that value as a limit.

THE EFFECT OF INDUSTRIAL DAMAGE

The quantity of MVA destroyed does not necessarily measure the damage done to industry by a nuclear attack. For a variety of reasons, the surviving industrial facilities may produce at either higher or lower levels than before the attack. Also, the composition of the surviving industry determines the viability and usefulness of the economy. Many analysts, concerned about the capacity of the industry to recover its prewar capabilities, measure industrial damage by this recovery time.

Production at surviving industrial plants after a nuclear attack could differ from preattack production primarily because the inputs

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[14] While the second procedure destroys more value than the first for any given number of weapons allocated, it involves potentially changing everything about the allocation including aim points at different levels of attack.

[15] This allocation assumes that warheads can be aimed only at the center of each target data area. The target data are specified as MVA clusters ranging in radius from a few tenths of a nautical mile to about 7 n mi. Target hardness is assumed to be 10 psi.

[16] Data for this analysis are projected from the National Military Command System Support Center (1973).

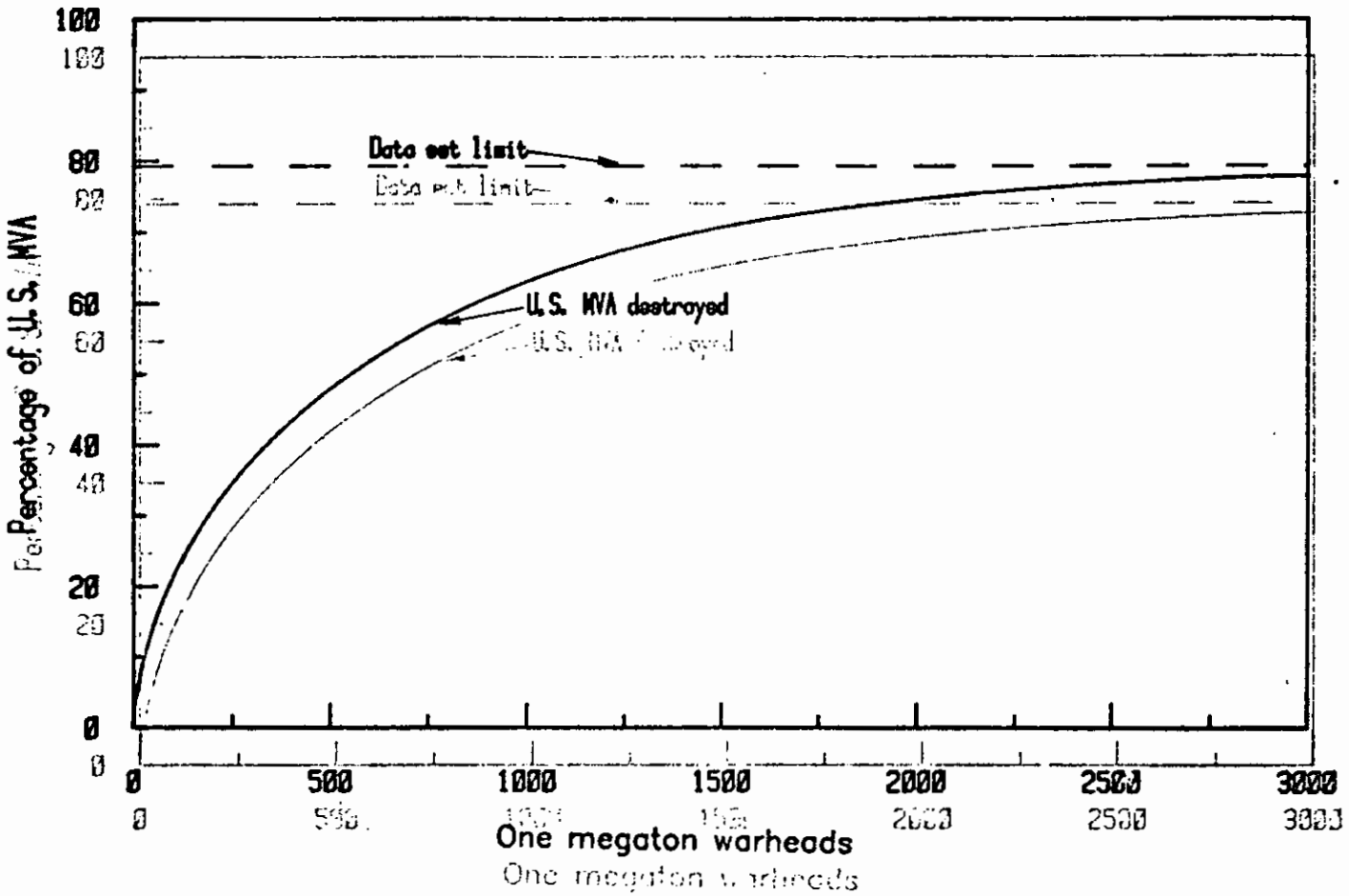

Fig. 4--Destruction of U.S. MVA by attacks of different sizes

Fig. 4--Destruction of U.S. MVA by attacks of different sizes

to the production process may well change.[17] If, for example, some important inputs were in very short supply, production might be greatly curtailed. If, however, some inputs could be increased, then production would also increase. In this latter event, some analysts argue, a larger work force could probably be mobilized after an attack, thus increasing the labor inputs to production.[18] However, much of this added labor would likely be unskilled, and therefore its marginal productivity might not be very high. On the other hand, it is reasonable to assume that many important inputs such as steel and energy would have received higher levels of damage than the manufacturing firms that depended on them, and therefore would indeed be in short supply (especially given the expected interruptions of the transportation network). Further, some industrial processes resemble the power sector, in which even a slight degradation in productive capacity could cause a complete failure of that process in a given area. Thus, it seems more likely that the destruction of MVA would underestimate the loss in short-term industrial capability.

While most analyses do not identify the MVA destroyed in terms of the industry affected, industrial damage by sectors is a critical determinant of industrial viability and usefulness. Thus, though the civilian population would greatly suffer if all of the MVA destroyed produced finished civilian products, the effect of an attack could be much greater if similar levels of destruction (in terms of MVA)

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[17] Industrial plants may be only partially damaged, leaving some parts of their productive activities still intact. If the buildings that house a facility are destroyed while many of the machine tools within those buildings survive undamaged, extra labor will have to be drawn away from other productive activities to uncover the surviving equipment.

[18] In the assured destruction concept considered above, the goal is to destroy 50 percent of industry and 25 percent of the population. Thus, many analysts immediately assume that relatively more labor will be available after the attack. However, half of the Soviet population is urban, constituting the majority of both the labor force and the fatalities. About 50 percent of the present Soviet industrial labor force would probably be killed; thus increases in labor would primarily come from either the rural population or the urban population that was not in the labor force, both groups consisting mainly of untrained labor.

affected the energy or heavy industry sectors. For a country engaged in a military conflict, perhaps the most important issue would be the amount of war-supporting industry that survived, though even this element could be partly or wholly useless if, for example, surviving petroleum product storage and refining capacity could not support the surviving industry.

Concern about the composition of industrial assets that survive an attack has led some analysts to look for "bottle-neck" sectors which, if heavily damaged, could disrupt the entire industrial economy. Petroleum, steel, and electrical power are traditional candidates. However, it is difficult to disrupt an entire economy because substitutes for the products of any given sector can usually be found, although they may not perfectly replace the original products.[19] It is also difficult to predict the degree of substitution possible in any given case, and thus the effectiveness of an attack on a bottleneck is extremely uncertain.

Over the past several years, many analysts have measured industrial damage by the time required for industrial or economic recovery. Such estimates tend to ignore the composition of the resulting industrial base or the production potential of individual firms under adverse conditions. Instead, they focus on the time required to recover prewar gross national product (GNP)[20] or MVA, assuming that all postwar production relationships are like prewar cases.[21] These analyses also ignore the tradeoffs between initial

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[19]Thus, aluminum or other metals might replace steel, and petroleum or steel could potentially be obtained from areas captured during the war.

[20]GNP is essentially the economic value of all goods and services produced by an economy. It is much greater than MVA, since it includes service, commercial, agricultural, and other nonindustrial sectors of the economy.

[21]That is, no substitution is allowed, and all factors are assumed to retain their prewar productivity. Often the prewar production relationships are captured in an "input/output" table, which gives the relationships between inputs required and outputs produced in the peacetime economy.

postwar industrial capabilities and longer-term recovery.[22] Thus, even if industrial or economic recovery time is a useful measure of industrial damage, the procedures presently being used to calculate this time cannot be relied on because they oversimplify a complicated phenomenon.

In summary, then, industrial damage is normally equated to MVA destroyed. However, MVA may not be a good measure of industrial capability because it fails to capture the dynamics of economic processes and also ignores the composition of the surviving industry and the recovery potential of that industry. Yet because it is difficult to accurately account for each of these factors[23] many analysts return to the simple MVA metric.

FALLOUT PATTERNS

Fallout was one of the first weapon effects recognized during the development of nuclear weapons. Since that time, probably more research has gone into modeling fallout than any other nuclear weapon effect. Despite this effort, no model available today can reliably reproduce the fallout patterns observed at nuclear tests. In part, this is due to the difficulty in modeling the atmospheric transport of fallout particles,[24] and in part to other atmospheric and geographic factors that cause variations in the size and composition of fallout clouds. Even when these factors are held constant, the most

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[22]Accordingly, a U.S. attack on Soviet heavy industry might maximize the amount of time "required" for Soviet industrial recovery, though it may not significantly affect essential production of war-supporting industries in the short term, production that could help determine the actual outcome of the war.

[23]The difficulties in predicting changes in peacetime economic activity are well known to most people. It is far more difficult to predict economic performance after the severe changes wrought by nuclear war.

[24]Once a fallout cloud is formed, it is carried by the winds until the individual particles fall from the cloud. While very detailed wind models are used in some fallout calculations, these models require too much time for practical estimation of fallout effects from large-scale nuclear attacks.

commonly used fallout models still vary considerably in their predictions of fallout pattern and intensity.[25]

Despite these difficulties, several aspects of fallout are well understood. First, warheads that detonate at ground level produce substantial fallout near the point of detonation, whereas airbursts, especially above a critical height, produce almost no close-in fallouts.[26] This observation is important because many warheads that would be detonated in populated areas are likely to be airbursts.[27] Second, groundbursts produce extensive fallout of varying intensities over large areas. The radioactivity in such areas would be far greater than the levels at which people express concern about nuclear reactor accidents; yet only in small areas would either casualties or fatalities be certain.[28] For standard wind speeds, these lethal areas would tend to be long but not very wide. Third, fallout is carried mainly by extremely small airborne particles of dirt and debris (thus the importance of atmospheric transport). Fourth, fallout decays fairly rapidly but exponentially,[29] so that some areas would still be significantly radioactive for weeks and even months after a nuclear attack. This residual radioactivity would be especially intense where

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[25]This problem is described in Bennett (1977), pp. 6-8.

[26]Unless the nuclear fireball touches the ground, no real crater is formed, and thus few "heavy" particles are raised into the fallout cloud. Then, the radioactive material does not "fall," but circles the earth at high altitudes until most of the radioactivity decays. Analysts disagree on the minimum height required for negligible fallout, though for a 1 MT burst above about 1800 ft, close-in fallout almost certainly will be negligible (this height scales with yield to the one-third power).

[27]Airbursts have larger lethal radii against industry and population and thus would tend to be used against those targets.

[28]A dosage of one rem, a thousand times the millirem dosage of concern in industrial accidents, could cover tens of thousands of square miles for a single 1 MT ground burst. However, the mean lethal dosage of 450 rem (integrated over time) would cover an area measured in hundreds of square miles.

[29]Fallout is usually measured by the dosage that would be delivered one hour after a nuclear explosion (referred to as the h+1 hour dosage). Thereafter, fallout decays with time (in hours) to the -1.2 power, so that the dosage is one-tenth as much at about 7 hours, one-hundredth as much at about two days, and one-thousandth as much at about two weeks.

fallout patterns from several nuclear weapons overlap. Fifth, the prevailing winds tend to blow from west to east, though the average wind direction depends on location and season and the specific wind can differ considerably from the average. Finally, almost any kind of structure or building can provide some protection from fallout; however, people must stay within that structure to remain protected.

These observations help to clarify the damage potential of fallout. In a standard nuclear attack, most of the fallout damage would occur in thin strands downwind of groundbursts. Since prompt effects damage occurs first, the fallout damage would become significant only beyond the lethal radius of the warhead. Fallout from warheads detonated in cities probably would take its toll in areas immediately surrounding the cities (areas that are often densely populated). Most of the fallout damage from warheads detonated away from cities would affect the rural population downwind of the burst.

Many analysts have noted that fallout is potentially much more damaging to people than are prompt effects because of its much larger lethal area. They have sometimes assumed that these effects could be exploited to maximize fatalities by placing fallout patterns fairly accurately over populated areas.[30] In general, the thin shape of the lethal fallout area and the variability of winds would make it difficult to so utilize the fallout from a single nuclear detonation. However, by appropriately patterning warhead detonations, a fairly large area could be subjected to fallout;[31] of course, this would require accurate prediction of the precise wind conditions. To give

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[30] See, for example, Boeing (1977), pp. 48-58.

[31] Boeing (1977). This report suggests placing the detonations along a line perpendicular to the wind direction to increase lethal fallout area (with overlapping dosages that are, by themselves, sublethal) by 35 percent. The results of our experiment described in the footnote below suggest that the lethal fallout area could be increased by perhaps as much as 100 percent if the overlaps were appropriately arranged. The resulting areas would also be much wider than that from a single detonation.

an idea of the lethal area produced, Figs. 5 and 6 show the percentage of a presumed lethal area that would actually be covered (based on a 30 kn wind), assuming errors in the prediction of either wind direction or speed.[32] While the actual wind direction tends not to reduce the lethal area very much, it determines whether or not the target is within the lethal area; for errors of 45 deg or more, it would be very difficult to actually cover a target with fallout unless a large number of weapons were used to produce a very wide pattern.[33] Alternatively, errors in the wind speed could dramatically reduce the lethal area because of a loss in optimal pattern overlap, leaving the lethal patterns either much shorter or with many sublethal "holes" within them. Thus, while it is remotely conceivable that fallout patterns would be used in attacks on populations, the technique has limited real-world utility because it depends on detailed local weather data that would be very difficult to acquire and evaluate in time to be useful.

CIVIL DEFENSE AND OTHER POSTURE VARIATIONS

Calculations like those shown in Fig. 4 are made assuming that the attacker knows where the opposing urban-industrial assets are and how vulnerable they are. In many circumstances the location and vulnerability of these assets can change. Population is mobile and in various ways the vulnerability of either population or industry

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[32]These results were obtained by placing five 1 MT warheads, at eight mile intervals, along a line perpendicular to the direction of the wind (to produce the maximum total lethal area). The WSEG fallout model, the most widely used model in the defense community, was used to simulate the fallout patterns (see the description of this model in Bennett (1977)). The basic lethal dosage of 450 rem on the ground was used to define the lethal area. While part of the loss in lethal area from wind direction errors can be offset by staggering the warhead aim points (rather than putting them all in a line), this procedure can make the total pattern less effective for some direction errors.

[33]Even with the five warhead pattern used in this experiment, the lethal area is at most 40 n mi wide, though it is up to 154 n mi long. With large errors in predicting wind direction, the rectangular nature of this pattern could cause it to miss targets some distances from the detonations.

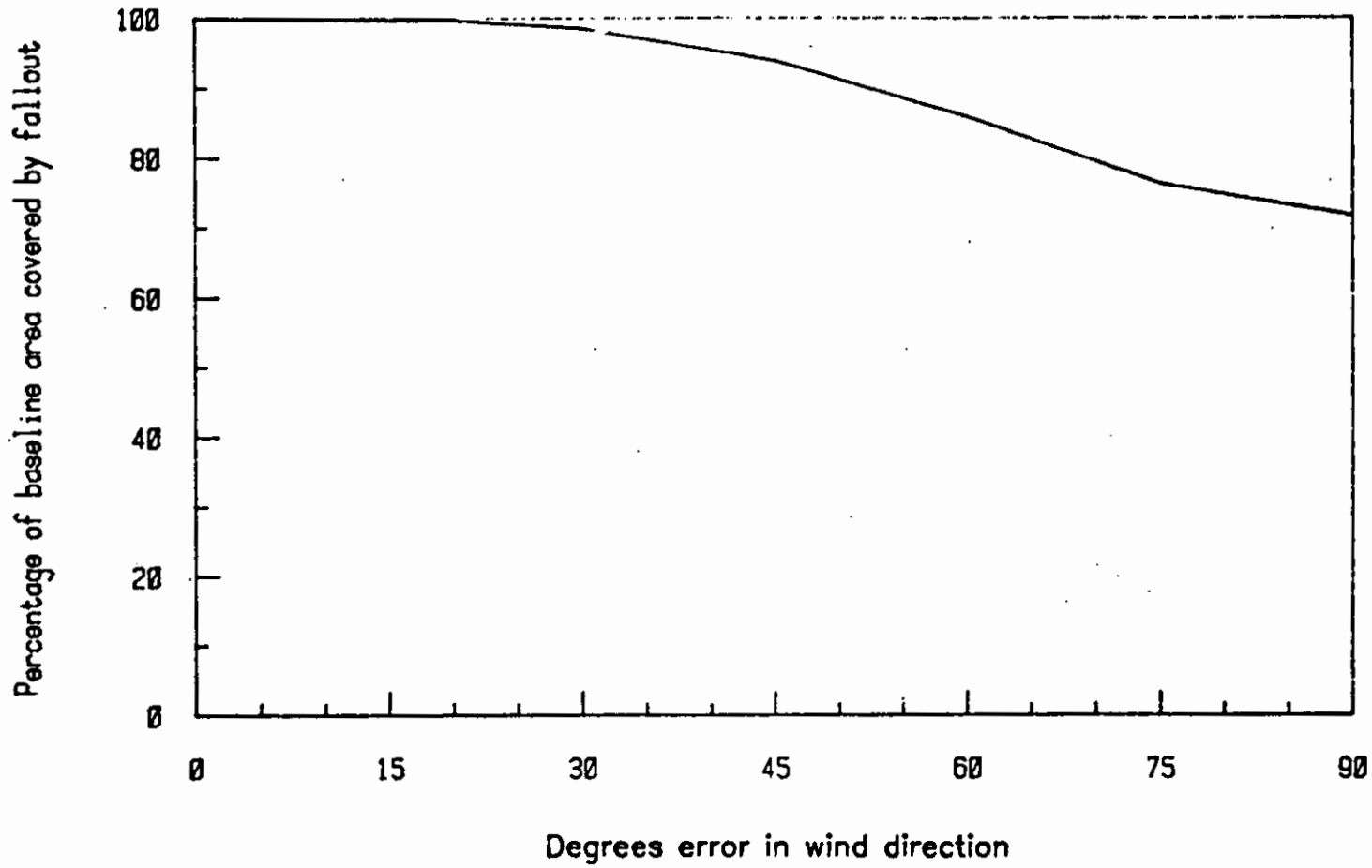

Fig. 5--Impact of error in wind direction on area covered by fallout patterns

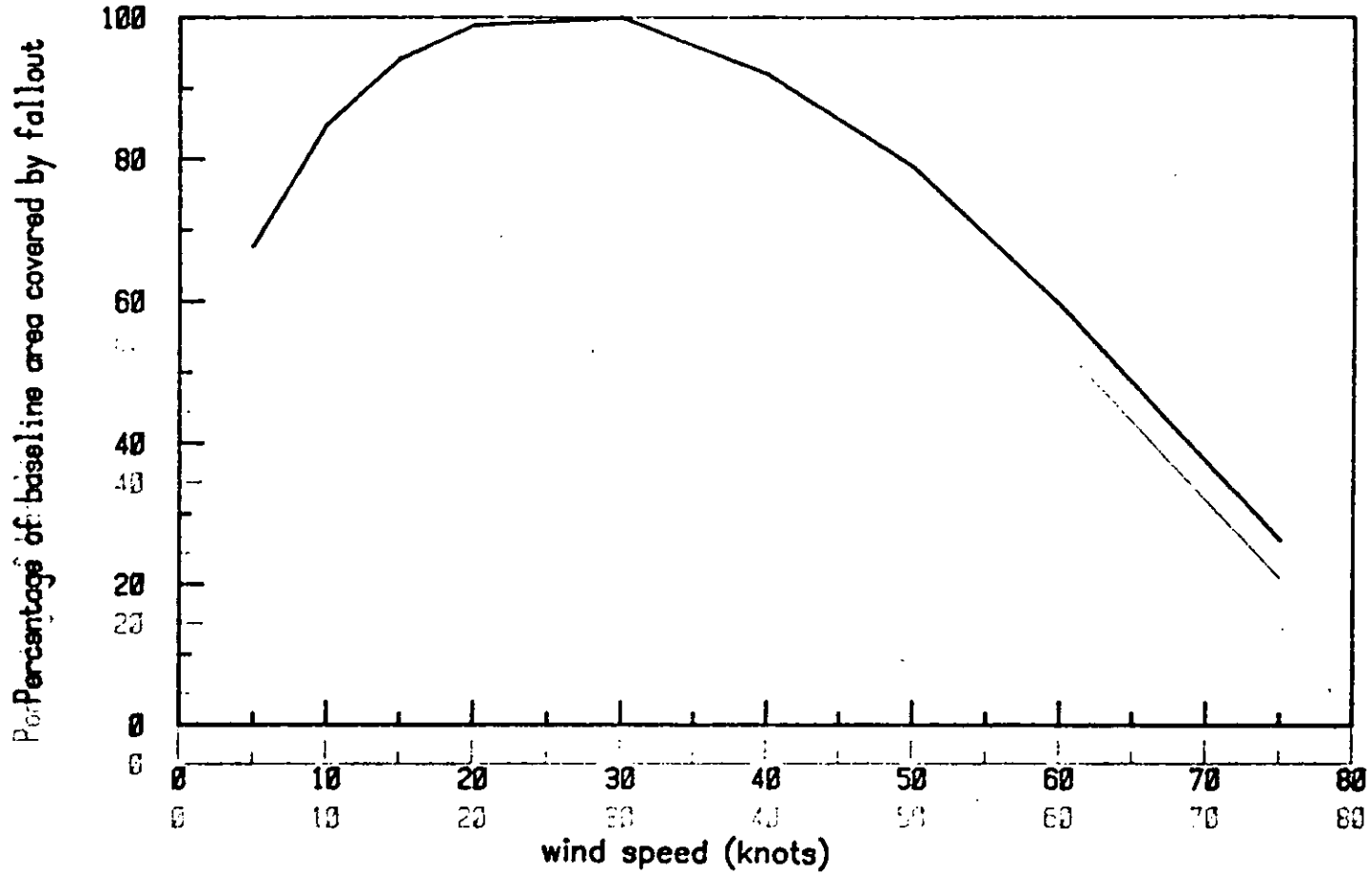

Fig. 6--Impact of wind speed on area covered by fallout patterns

can be lessened. The term "civil defense" refers to the purposeful actions taken along either of these lines to reduce urban-industrial damage potential.

Reducing population vulnerability usually involves some form of sheltering. While special shelters can be built to protect people from nuclear weapon effects, almost any structure, and especially the basement of any structure, tends to provide some shelter. In particular, most structures offer some protection against radiation, especially fallout radiation, and purposeful shelters can markedly increase that protection. Most structures offer slight protection against blast effects, though specially designed shelters can protect against tens to hundreds of psi of overpressure. Blast shelters may actually provide complete protection against blast effects in urban attacks, as those attacks would tend to use optimal airbursts against unprotected assets, detonating so high that the maximum overpressure generated on the ground may be 40 psi or less.[34]

No matter how a nuclear war began, many people on both sides would not be in their assumed locations. In part, this is because the census data employed in locating the population give the "night-time, bed-down" locations of people. While the populations of the Soviet Union or the United States could be in those locations when a war started, time differences and the locations of the two countries opposite each other on the globe mean that both countries would not be in such a condition at the same time. Some people in both countries would be at work, and thus probably more susceptible to attack because industrial sites are more likely to be targeted than residential

[34] At the optimal height of burst for 10 psi (7000 ft for a 1 MT warhead), the maximum overpressure on the ground (directly under the detonation) is about 40 psi. At the optimal height of burst for 5 psi, the maximum overpressure hitting the ground is about 15 psi. Thus, people protected to at least these levels would not be injured. Many analysts asume that if the Soviets were to shelter their people, U.S. warheads could be groundburst; but to do so would require a retargeting capability (since the trajectory would have to be different to hit the ground at the same place), and would significantly reduce damage to unprotected targets (since groundbursts reduce the lethal radius).

neighborhoods. On the other hand, if sufficient warning of the attack were received, the population could well evacuate probable target areas, greatly increasing chances of survival.

In evacuating the urban population, a civil defense program faces several tradeoffs. Perhaps the most important decision that must be made is where to put the evacuees. Provisions must be made to feed and support them and to provide some shelter against both fallout and the weather. One of the easiest solutions is to make each rural resident responsible for a small set of urban evacuees. The ratio of evacuees to rural residents is referred to as the hosting ratio; a hosting ratio of two to one is normally considered difficult but feasible to maintain. While hosting may ease problems of shelter and food distribution, it could increase the population density in some already heavily populated areas, thus making evacuees targets for a population attack. To avoid this, they could be sent to sparsely populated areas, but such regions generally lack shelter and food distribution capabilities.[35] Also, by evacuating the population, the civil defense program moves urban residents away from the majority of the good shelters, thus trading distance from weapon effects for the level of protection provided. Finally, during an evacuation, evacuees would be extremely vulnerable to attack. An effective civil defense program would have to minimize this extra vulnerability while completing the evacuation as quickly as possible. In short, an evacuation plan is extremely complicated and its effectiveness in reducing fatalities would be highly dependent on the choices planners made in deciding how to proceed with it.

Industry is neither as mobile nor as easily protected as people. The fraction of industry (especially basic industry) that

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[35] Several other tradeoffs would exist. First, moving evacuees into relatively unpopulated areas would probably take longer, because those areas have inferior transportation facilities. Second, because people will be concerned about their welfare in such areas, authorities may have difficulty in persuading them to evacuate. Third, the difficulties in providing food and shelter in such areas would undoubtedly lead to some fatalities over time from exposure, disease, or other related problems.

could be dispersed on warning is small.[36] Therefore, analysts focus on the possibilities of protecting industrial equipment in place rather than trying to move it.[37] Various procedures have been developed for such protection, almost all of them essentially involve burying the machinery. Such procedures provide good protection, but machinery so protected would be out of service for weeks even if the order to unearth it were given as soon as the burial was completed. The resulting loss in production would be substantial, so such procedures would not be lightly undertaken. Also, much of industry is not susceptible to "burial" (e.g., blast furnaces) and could not be significantly protected. In short, while some protection could probably be provided for industry, this protection would be far from comprehensive and would be extremely costly.

UNCERTAINTY IN COUNTERVALUE CAPABILITIES

Many analysts believe that there is very little uncertainty about the damage that could be inflicted by countervalue attacks. Thus, little has been done to assess that uncertainty. Part of the reason is that countervalue targets tend to be large and soft, leading many analysts to believe that the uncertainties of a massive attack would "wash out" because so many weapons are involved. If no more were involved in countervalue attacks than random variations about the mean values of parameters, the uncertainties might, indeed, be insignificant. But even countervalue attacks include a substantial number

[36] New industry could be built in dispersed areas. While this tactic would reduce the vulnerability of industry, there would usually be strong economic incentives not to do so. That is, dispersed industry has higher transportation costs and fairly high "start-up" costs, incurred in moving trained labor to the facility and training other new labor. Thus, economic incentives tend to push the construction of new facilities into the same areas where old facilities are located.

[37] Even if the industrial machinery could be protected in place, industrial buildings could not. They would eventually have to be replaced after an attack. In places with bad weather, they may have to be replaced before production could be resumed.

of parameters whose mean values are unknown, thereby contributing significantly to the uncertainty in such attacks.[38]

Four uncertain parameters condition the immediate damage caused by countervalue attacks. First, warhead destructiveness (especially yield) is uncertain within certain bounds, especially for the defender in a countervalue attack.[39] Second, the arrival probability is uncertain even in a first strike because limited testing prevents the attacker from precisely determining the reliability of his weapons, though arrival probability is considerably more uncertain for the side attacked in a first strike. Third, the vulnerability of industry and population is uncertain, even though blast damage falls generally in the range of 5 to 10 psi (as discussed above). Fourth, the models used to predict prompt weapon effects generate uncertain findings because they are based on a limited number of tests with variable outcomes.[40]

The potential influence of these uncertainties has been estimated by calculating the uncertainty associated with a Soviet assured destruction attack against U.S. industry, using the data from Fig. 4 and assuming that uncertainty in these factors could be captured by modifications to the lethal area.[41] The results of this analysis

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[38]This subsection considers uncertainty in the damage estimates but ignores the inherently much greater uncertainty in the viability of industry or the population after a nuclear attack.

[39]The determination of an opponent's warhead yield usually begins by estimating the weight of that warhead and then guessing the warhead technology employed. Because this technology can vary greatly, estimates of yield also vary greatly. For example, estimates of some Soviet ICBM warhead yields were recently cut about in half. See Pincus (1979).

[40]The influence of civil defense, which could completely overwhelm any of the uncertainties shown here, is also ignored.

[41]In this example, the following assumptions were made: the warhead yield was 1 MT with a 10 percent standard deviation, the hardness was 7.5 psi with a 1 psi standard deviation, the reliability was 80 percent with uncertainty based on 25 tests, and a 5 percent uncertainty was assumed in the weapon effects. In each case, a lethal area was calculated using the Monte Carlo values of yield, hardness, and weapons effects, and the ratio of this lethal area to the 10 psi lethal area was used as a multiplier times the number of warheads to obtain 1 MT, 10 psi equivalent warheads.

are shown in Fig. 7, in the same framework used to express counterforce attack uncertainty in Fig. 3. Basic target hardness is assumed to be 7.5 psi, as opposed to the 10 psi in Fig. 4. The use of 550 MT warheads in the "basic," first-strike attack generates a 90 percent probability that at least 50 percent of MVA would be destroyed. In turn, the assumption of 50 percent attrition of the Soviet forces by a U.S. first strike is associated with the premise that the Soviets would double their attack size to 1100 warheads in a second strike. In both cases, an optimal laydown is assumed in the calculations given here. The second-strike curve does not overlap the basic attack curve because some uncertainty was assumed in the amount of attrition suffered by the Soviets in the U.S. first strike, therefore increasing the uncertainty in their countervalue attack.[42]

The choice of the attack size (550 warheads in the basic attack) was predicated on the desire to generate high confidence of reaching the 50 percent damage level required by assured destruction. As a result, the nominal damage level (based upon most likely estimates of the parameters) is about 56 percent. Even so, there is a 10 percent probability that this level of attack would not meet the assured destruction requirement; to increase to 99 percent the confidence of obtaining 50 percent damage, over 700 warheads would be required (and even then a one percent chance of failure in assured destruction would exist). These 700 warheads are considerably more than the number required to obtain a nominal damage level of 50 percent (about 400 warheads in the nominal case), showing the considerable effect of only these basic uncertainties in countervalue capability.

In a second strike, even though an optimal laydown is assumed, the added uncertainty in warhead survivability decreases to 80 percent the confidence of achieving assured destruction. Further, the low side of the distribution is now very low, falling to about 30 percent damage. Merely to overcome the uncertainty in survivability and increase the confidence in assured destruction to 90 percent, the

[42] Soviet attrition was assumed to be 50 percent with a standard deviation of 10 percent.

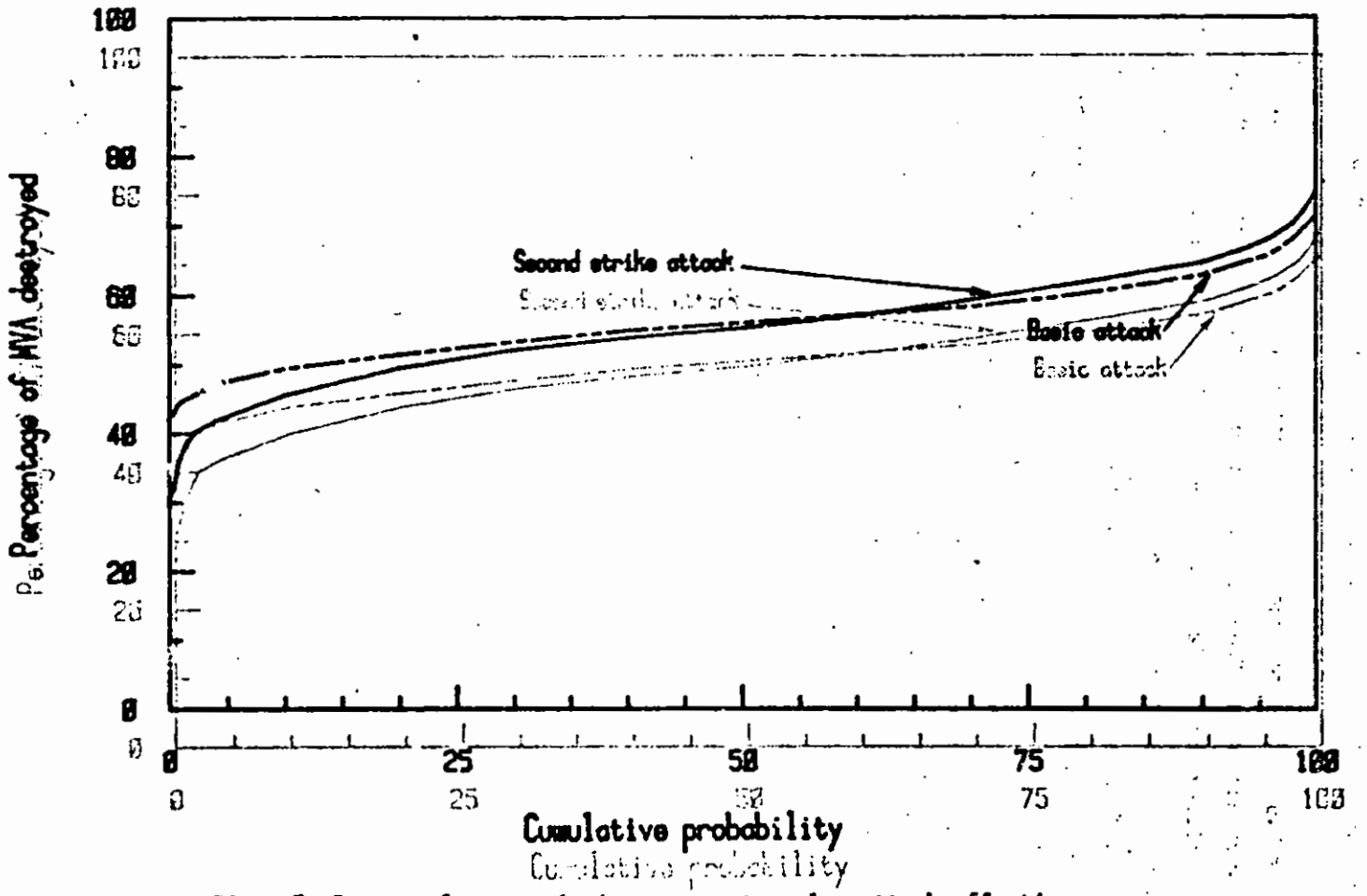

Fig. 7--Impact of uncertainties on countervalue attack effectiveness

Fig. 7--Impact of uncertainties on countervalue attack effectiveness

attack would have to be increased to 1300 warheads, and even then the lower bound would still be well below 40 percent damage. In short, in a second strike, high confidence in an assured destruction capability is difficult to achieve without expending a very large number of weapons.

IV. AGGREGATE MEASURES

As shown in the previous two sections, estimating countermilitary and countervalue capabilities for either the United States or the Soviet Union can be a fairly complicated process. Further, since such capabilities vary across weapon systems, there is generally no clear procedure for combining these capabilities into a sirgle measure. To deal with this, so-called aggregate measures were developed. These measures simplify the detailed calculations of force capabilities and provide a way to aggregate capabilities across an entire strategic force. However, some widely used aggregate measures completely misestimate strategic force capabilities, and most others dc not accurately represent the capabilities they are supposed to measure. Therefore, in reviewing the aggregate measures, this section explores both their rationale and limitations. To make these presentations meaningful, the aggregate measures are grouped by the capabilities they are supposed to measure: countermilitary, countervalue, and combinations of both.

AGGREGATE MEASURES OF COUNTERMILITARY CAPABILITIES

Aggregate measures of countermilitary capabilities are intended to provide a simple metric of those capabilities by capturing some aspect of a countermilitary attack. Ideally, the measure itself should scale directly with countermilitary capability. However, analysts have not been successful in simplifying the dynamics of bomber, SSBN, or command and control survivability; therefore, no aggregate measures exist that allow analysts to evaluate attacks on such targets. For countersilo capabilities, a wealth of measures have been developed, the most widely used of which will be described hereafter. For attacks on other military targets, the one aggregate measure that has been widely used will be discussed here as well.

Hard Target Kills

Over the years, countersilo capability has often been measured by the number of hard targets that a given force could kill. For simplicity, though, it has usually been assumed that each attacking warhead is assigned to a single target and that all targets have the same hardness. Because of this second assumption, this metric has most recently been referred to as 2500 psi kills, because 2500 psi probably represents an extreme of deep underground super-hardened targets.[1] Since it is assumed that each warhead is placed on an individual target identical to all others, this measure is calculated by determining the kill probability against that target for each type of warhead and summing it across the entire strategic force.

Clearly, this measure does not adequately reflect countersilo capabilities. For this procedure to provide reasonable estimates of actual capabilities, it must be assumed that the number of hard targets on the opposing side is equal to or greater than the number of weapons available,[2] that the hardness of all targets is approximately 2500 psi, and that all weapons are used in countersilo attacks. If there are fewer targets than weapons, or if target hardnesses are greater than 2500 psi, this measure will systematically overestimate hard target kill capabilities. If target hardness is less than 2500 psi, the opposite bias occurs. More specifically, if the hardness of U.S. and Soviet silos is different, this metric will be biased against the side that has the harder silos.

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[1]The name of this measure has been variously known over time as "1000 psi kills," "2000 psi kills," and "2500 psi kills."

[2]To overcome this limitation, this index has occasionally been modified to (1) limit the number of warheads used, and (2) allocate more than one warhead per target. (At present, both the United States and Soviet Union have at least five times as many weapons as such targets). Thus a recent variant, which is not widely used, placed two warheads each on at most the number of opposing silos (choosing the highest value warheads first). This type of modification approaches the methodology outlined in Sec. II in both accuracy and complexity.

Throwweight

Nitze (1976) has suggested that missile and bomber throwweight be employed as a measure of countersilo capabilities. (Throwweight is the weight of the payload that can be delivered to targets by either missiles or bombers.) Most payload weight is made up of warheads, and thus, for a single missile, throwweight establishes the number of warheads of any given size or the size of warheads that can be employed. Larger warheads have a higher countersilo capability and also serve to hedge against uncertainty in some of the other parameters involved in silo destruction.[3] Within limits, more warheads allow either more silos to be attacked or more warheads to be targeted against each silo.[4]

Today, throwweight is not a particularly significant measure of countersilo capabilities because the primary determinant of such capabilities is accuracy, and throwweight has very little effect on accuracy. Further, throwweight normally includes bomber payload and as such really does not measure simply the potential for bigger or more warheads.[5] Thus, while throwweight may indeed indicate something about the number and size of warheads available for countersilo attacks, there is no direct relationship between throwweight and countersilo capability.

Countermilitary Potential

The most widely used aggregate measure of countersilo capabilities is countermilitary potential (CMP).. CMP is widely used because it is simple to calculate and seems to relate directly to the ability

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[3]See, for example, Foster (1978).

[4]At some point, very little extra damage can be inflicted largely because of fratricide, which limits the number of warheads detonating at each target to about two.

[5]For example, when bomber payload includes a short-range attack missile (SRAM) or an air-launched cruise missile (ALCM), it includes a lot of weight besides warhead weight (e.g., missile motor, fuel, and guidance). Nitze factors that weight out in calculating the weight of a comparable ICBM warhead payload; nevertheless, that extra weight could be used instead to carry more bombs, but for good reasons, such a choice was not made.

to kill a hard target. Recalling the formula for silo PS, CMP is simply part of the exponential term:[6]

$$CMP = Y^{2/3}/CEP^2$$

Thus, CMP includes both the warhead yield (Y) and part of its accuracy (the CEP). To aggregate CMP across the strategic forces, the CMP of all weapons is simply added together, reflecting the procedure used in calculating the multiple shot survival probability (PS_n) above.[7]

Unfortunately, CMP can be biased in several respects. First, in aggregating the CMP of the total strategic force, weapons are included that are far too inaccurate or too small to be effective against very hard targets. On the other hand, as CMP values become relatively large (especially as accuracy increases), a point is reached where additions to CMP do not significantly increase the kill probability of a warhead; including CMP values beyond that point results in an overestimation of aggregate countersilo capabilities. In other words, CMP does not scale linearly with hard target kill probability, but rather shows decreasing marginal returns because it relates to hard target survivability through the exponent of the PS formula. As a result, doubling the CMP value of a weapon less than doubles its countersilo capability against a fixed target set.[8]

These considerations are illustrated in Fig. 8, which relates CMP values to the kill probability for 1000 psi and 2000 psi targets. In both cases, CMP values beyond about 120 add little or no benefit as the kill probability for that CMP value is virtually 100

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[6]For CMP, yield (Y) is measured in megatons and CEP in nautical miles. The accuracy of CMP as an aggregate measure depends upon the accuracy of the assumptions in the PS formulation: a "cookie-cutter" damage function, no systematic bias, a circular normal impact distribution, etc.

[7]See Tables 6 to 8 below for sample CMP calculations.

[8]Naturally, a force with double the CMP should be able to achieve the same kill probability as a basic force does if it is used against twice as many targets, but this is really only true if the CMP is equally divisible among all targets.

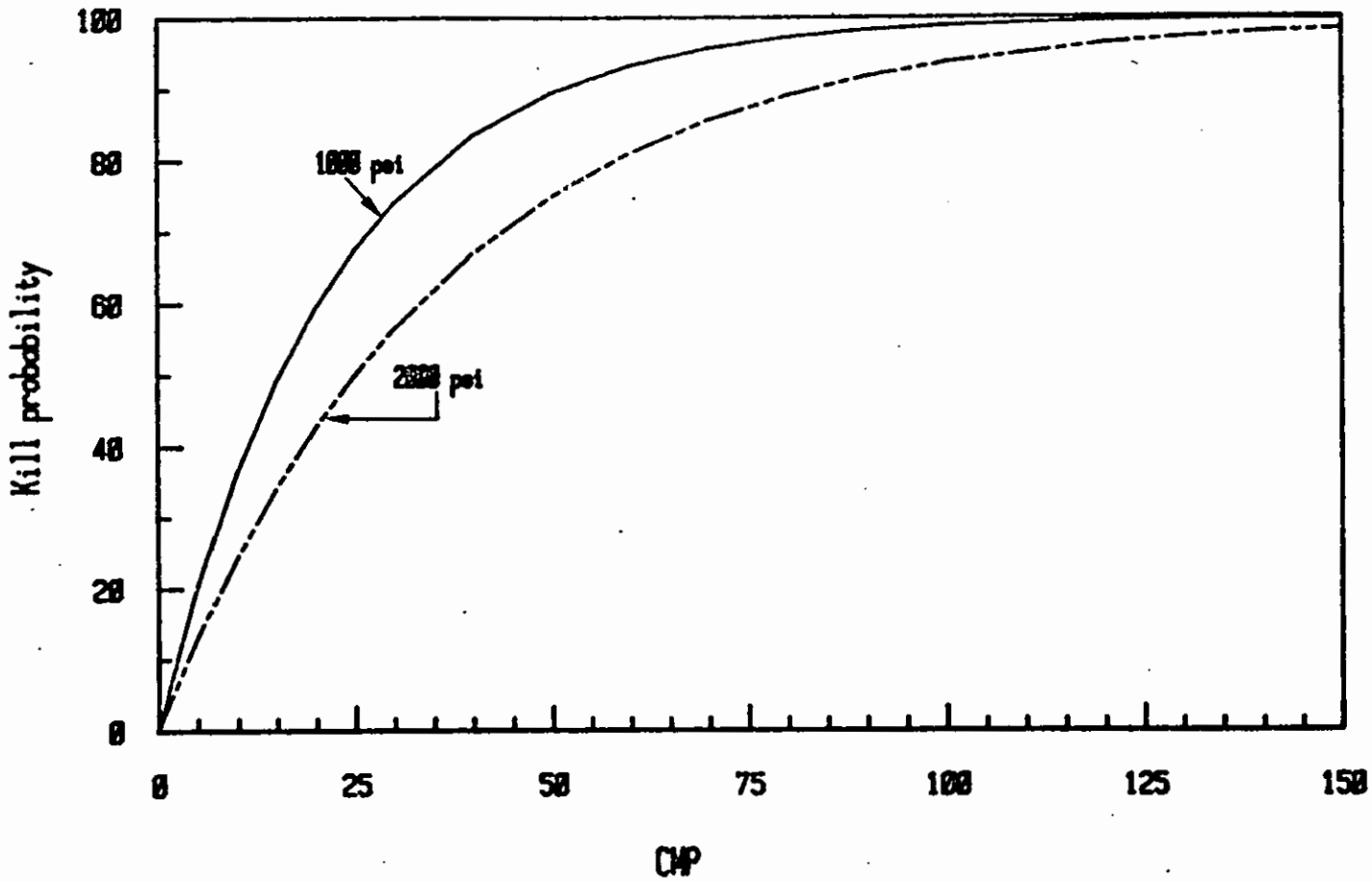

Fig. 8--Relationship between CMP and hard target destruction

percent. This observation suggests two central problems with the CMP measure: As warhead CEP becomes very small, CMP values become much larger than are really meaningful;[9] and relatively small CMP values can be associated with kill probabilities approaching 100 percent though the arrival probability of the weapon may be much less than 100 percent. For example, it is impossible for a weapon system to have a kill probability that is higher than its probability of arriving at the target, but CMP ignores that constraint.

Effective Countermilitary Potential

The author has developed a formulation that corrects CMP for arrival probability and, thereby, removes a major source of bias in that measure. The resulting measure is called effective countermilitary potential, or ECMP.[10] While many analysts have attempted to correct CMP by simply multiplying it by the arrival probability (r), that formulation does not properly account for arrival probability.[11] The difference between the results of that procedure and of ECMP is illustrated in Fig. 9.[12] For relatively poor missile accuracies, the two procedures produce about the same effect. But for missile CEPs better than about .15 n mi, the two procedures diverge dramatically, with ECMP at best equal to the CMP value that has a kill probability equal to warhead arrival probability. Because many new weapons are likely to have CEPs of .15 n mi or less, the use of CMP or some multiple thereof could be very misleading.

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[9]This is especially true since CMP ignores systematic bias, the other component of accuracy; therefore, even if the CEP were to approach zero, a non-zero systematic bias would keep the kill probability below 100 percent for smaller yield warheads.

[10]The formulation for ECMP is given in Appendix C. Note that this formulation requires that the target hardness be included, and thus ECMP is not as general a measure as CMP.

[11]Multiplying CMP by reliability is like multiplying the number of warheads assigned to a target by the reliability to get the survival probability. The problems with this procedure are discussed in the subsection on ICBM vulnerability above.

[12]In this figure, a 1 MT warhead with an 85 percent arrival probability is targeted against a target hardened to 2000 psi.

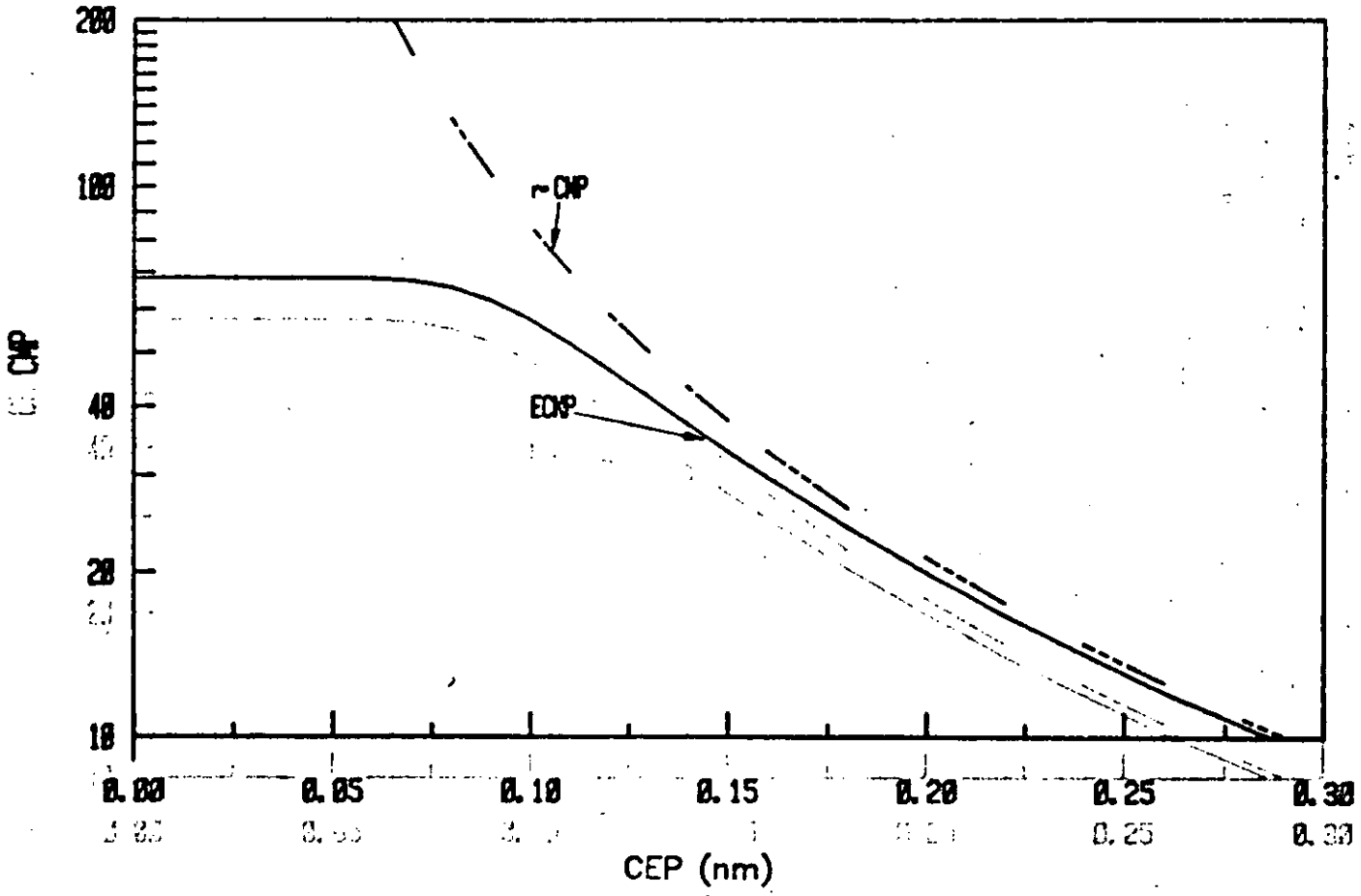

Fig. 9--Comparison of ECMP with CMP times arrival probability

These observations have some potentially important implications for the strategic debate. For example, CMP has been a favorite measure of those who oppose programs for improving U.S. counterforce capabilities. They argue that CMP shows the United States to have a very large and rapidly growing counterforce capability both in absolute terms and in comparison to the Soviet Union.[13] They attribute to U.S. strategic forces CEPs so small that they encounter the CMP bias problem. Also, some include bomber CMP in their aggregate estimates. Though bombers carry many large yield, accurate "warheads," bombers must penetrate Soviet air defenses, thus making their arrival probabilities lower than those of either ICBMs or SLBMs.[14] Since CMP does not account for this extra warhead attrition, it makes the bomber force appear to be very effective against silos. However, when arrival probability is properly taken into account, the bombers do not appear to be so effective. For example, assuming that a B-52 carries four bombs with CEPs of 1000 ft, and four SRAMs with CEPs of 1500 ft, and that the B-52 arrival probability is 60 percent, the CMP value (170) is more than twice as large as the ECMP value (83) for each B-52. (The calculation r times CMP gives a value of 102.)

Warheads

Many other military targets include at least some component which is relatively "soft" and small, and thus can be destroyed by a single warhead. This has induced some analysts to use the number of warheads as an aggregate measure of the capability to destroy other

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[13] A particularly strong advocate of this position is Kosta Tsipis. See, for example, Tsipis (1975). This argument has also been raised in the Congressional debate, with Congressman Leggett a strong advocate. See Leggett (1975).

[14] Because of the ABM Treaty which was part of SALT I, ABM destruction of ICBMs during penetration can be virtually ignored in most aggregate analyses. The same can not be said of bomber defenses in the Soviet Union. Also, bombers take much longer to get to their targets, increasing the probability of an ICBM launch on warning, which in turn would make a bomber strike on opposing ICBMs essentially worthless.

military targets.[15] Because some warheads will not arrive on target, analysts usually deflate the number of warheads by their arrival probability, referring to this measure as "deliverable warheads." Deliverable warheads is, therefore, a measure of the maximum number of targets liable to be hit.

For a variety of reasons discussed above, neither a count of warheads nor a count of deliverable warheads precisely measures the capability to destroy other military targets. While deliverable warheads tend to overestimate the number of other military targets destroyed, collocation of many targets may balance out much of this bias, at least for fixed installations. The net effect of the various flaws in this measure is not clear, though the measure is probably a fair indicator of a capability to destroy fixed installations.

AGGREGATE MEASURES OF COUNTERVALUE CAPABILITIES

Over time, a number of aggregate measures of urban-industrial damage potential have developed. Analysts have tended to employ them indiscriminately in general assessments of relative U.S. and Soviet capabilities. However, each of the principal measures used today attempts to specify the effects of nuclear attacks in terms of population fatalities or damage to industrial assets. Nitze (1976-77) has argued that aggregate measures of countervalue capabilities should be interpreted in the following manner: (1) megatonnage is the best indicator of fallout effects (and, therefore, of population fatalities from fallout), (2) equivalent megatons (EMT) is the best indicator of blast damage effects (and, therefore, of prompt damage to industrial facilities and urban population), and (3) throwweight is "the best overall measure of the countervalue potential of a

[15] Before MIRV warheads were introduced, the number of missiles was a measure of target coverage, and before that, when bombers carried only a single nuclear weapon, the number of bombers was also a measure of target coverage. Today, the number of delivery vehicles (missiles and bombers) cannot serve such a function, and thus this number is useless as a measure of strategic force capability despite its use in setting SALT force limits.

strategic force. Nitze's categorization provides a useful starting point for assessing these aggregate measures.

Megatonnage as a Measure of Fallout Effects

The megatonnage of a strategic force is calculated by simply summing the yield of each warhead. Nitze's use of megatonnage as an index of fallout effects has somewhat different implications,[16] reflecting in part his concern about the potential effectiveness of Soviet civil defense—especially city evacuations—in limiting civilian fatalities. Therefore, he relates megatonnage to the total geographic area subject to lethal fallout effects, the area being an index of the portion of the (evacuated) population at risk.[17] Without questioning the plausibility of major civil defense evacuation programs, a number of questions are raised by this use of megatonnage as an index of potential civilian fatalities.

In addition to the yield of a warhead, at least six factors determine the area covered by and the radiation intensity of the fallout pattern: (1) the fission fraction of the warhead yield;[18] (2) wind speed, dispersion, and direction; (3) the warhead height of burst; (4) the distribution of the population; (5) the degree of

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[16] Many authors incorrectly attempt to equate explosive yield with blast effects, in turn comparing the megatonnage in today's arsenals with the damage caused by conventional bombs in World War II, or dividing megatonnage by the earth's population to show an "overkill" of about 10 tons of TNT per person. As will be shown below, the area damaged by blast effects is a linear function of the yield of a weapon taken to the two-thirds power; thus, Brown has estimated that at least 500 1 MT bombs would be required to create the same amount of area damage as conventional bombs dropped on Germany in World War II. Further, calculations are meaningless unless they take account of accuracy considerations. Brown also notes that the United States alone made enough rifle and machine gun cartridges during World War II to kill the entire world's population five to ten times over. See Brown (1977).

[17] This assumption follows from the Boeing work on civil defense, in which it is assumed that all major urban areas are evacuated in a way that spreads the urban and rural population uniformly over the rural area surrounding cities. See Boeing (1977), pp. 35-72.

[18] The fission fraction of a warhead is the percentage of the warhead yield contributed by fission as opposed to fusion nuclear reactions. See the discussion of nuclear weapon effects in Appendix A.

population sheltering; and (6) the location of the warhead explosions relative to populated areas. Even if we ignore the issues of population distribution and vulnerability, as Mitre does, the warhead yield is only one of four factors affecting the magnitude of fallout effects. The lethal fallout area scales directly with warhead yield only if all weapons are groundburst and have a relatively constant fission fraction, and if the wind direction, dispersion, and speed are constant.[19]

These factors can make a significant difference in the area covered by a fallout pattern. In Figs. 5 and 6, we showed the effect of variations in wind speed and direction on the area covered by five fallout clouds in a row. Figure 10 shows the effect of variations in wind speed on a single fallout pattern for two different lethal dosages.[20] If any degree of shelter can be obtained,[21] the 1000r fatality criterion is probably closer to being correct; thus, the previous figures may have underestimated the effect of variations in the wind, as the change in wind speed from 10 to 60 km changes the pattern size only by over a factor of ten for 1000r dosage over the same interval. Similarly, changing the fission fraction from 50 percent to

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[19] Even this assumption depends upon the fallout model chosen. At least one model treats this assumption explicitly, finding that the lethal area (A, in square miles) and the warhead yield (Y, in megatons) of groundbursts (for a 15 km wind) are related by:

$$I = 6000 \cdot f \cdot 10^{-0.5\sqrt{A/Y}}$$

where I is the intensity of the radiation at h+1 hours, and f is the fission fraction of the warhead. See Thomas, (1976), pp. A-3 to A-4.

[20] The assumptions used above in evaluating the five overlapping fallout patterns are repeated here for a single pattern. In particular, this assessment is based upon the WSEG fallout model.

[21] Terrain roughness alone reduces the deposited dosage by about 25 percent, in reality making 600r the mean lethal dosage that must be deposited on the ground. Houses have protection factors of 1.5 to 3, increasing the mean lethal dosage that would have to be deposited to 900r to 1800r.

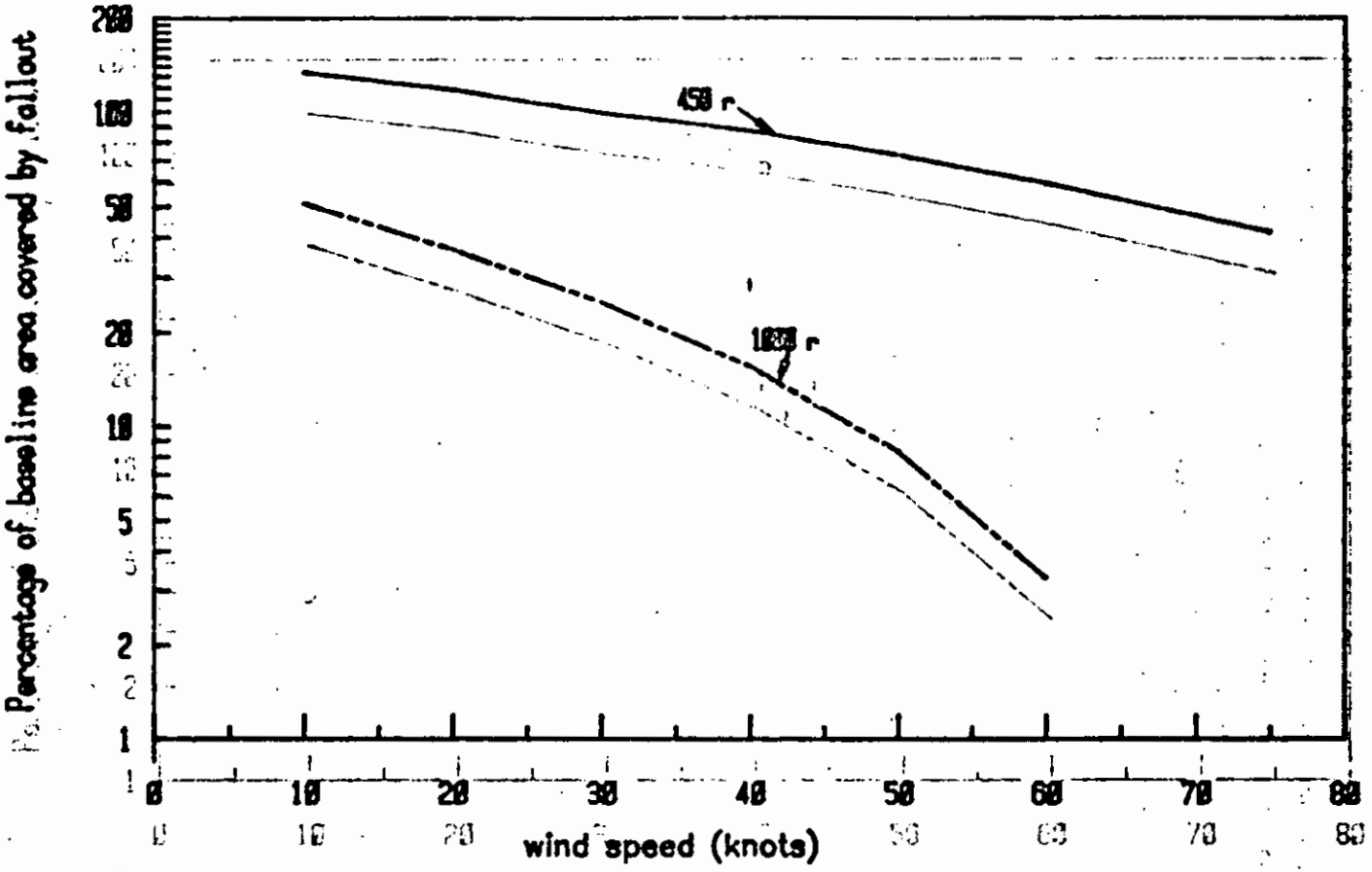

Fig. 10—Impact of wind speed on the lethal area covered by a single fallout pattern

Fig. 10—Impact of wind speed on the lethal area covered by a single fallout pattern

100 percent[22] increases the dosage received by a factor of two, roughly the difference between the 450r dosage and the 1000r dosage. Finally, if an airburst is used in the place of a groundburst, essentially no area receives lethal fallout. In short, while the lethal fallout area may be roughly proportional to the aggregate warhead megatonnage employed, there is certainly no close or consistent relationship between these factors.

For a variety of reasons, it is also true that no simple relationship interconnects lethal fallout area and fallout fatalities. That would occur only if the population were uniformly spread across the affected area. The rural population is, after all, not spread uniformly, and evacuated urban population will most likely be hosted in those areas. Some extremely high density rural population locations will exist even if an attempt is made to spread the evacuating population more evenly, and the density of evacuees around the very large cities would undoubtedly be higher than that around much smaller cities. If a uniform density could be obtained, the fallout patterns would probably not effectively cover these areas because of their size, shape, and uncertainty in placement. Thus, megatonnage is not a good measure of potential fallout fatalities.

If all of these other problems could be solved, megatonnage would adequately measure civilian fatalities only if fallout were their major cause. However, unless urban areas were evacuated, prompt weapon effects would probably cause most of the civilian fatalities in a countervalue attack. Indeed, fallout effects may be insignificant because airbursts would be used to maximize damage to industrial targets. Even if the cities were evacuated, prompt effects would still be the major cause of fatalities, depending upon the vulnerability and location of the evacuees. Thus, civilian fatalities are better estimated in terms of prompt effects damage.

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[22] Normally, a weapon in the 1 MT range has a fission fraction of roughly 50 percent, whereas much smaller weapons (about 100 Kt or less) are essentially pure fission. Thus, the contribution of yield to fallout depends on the weapon size. For more information on the mix of fission and fusion, see Appendix A.

Equivalent Megatons

Equivalent megatons (EMT) is used as a measure of urban-industrial damage because it is proportional to the amount of area that can be destroyed by blast effects from a given strategic force and because urban-industrial targets are considered to be area targets. Naturally, this formulation assumes that the resulting lethal area of a weapon matches (in size and shape) potential target areas, or else "excess" lethal area would be included in a direct calculation of EMT. All target areas are also assumed to be of essentially equal value, otherwise, EMT would not directly measure the damage to industry or population.[23] Neither assumption holds in reality, and thus EMT is actually a biased measure of countervalue damage potential.

EMT is normally formulated as the warhead yield (in megatons) taken to the 2/3 power ($Y^{2/3}$). This formulation reflects the fact that the lethal radius of a weapon is proportional to its yield to the 1/3 power, and also that the lethal area is proportional to the square of the lethal radius. The aggregate EMT is calculated by summing the EMT of each warhead. However, many analysts have recognized that the lethal radius of larger warheads exceeds the radius of some target areas, and thus some change the EMT formulation, expressing EMT as yield to the one-half power for yields above 1 MT. A related problem, though one not as easily solved, is that most target areas are not perfect circles, and thus, in attempting to cover them, much of the lethal effects would be "wasted." Similarly, complete coverage of target areas requiring more than one warhead could be obtained only by overlapping the lethal areas to some extent, also creating some "waste."

These target coverage problems can be addressed by modifying the EMT formulation. Normally, this is done by using exponential terms other than 2/3 to calculate EMT. For example, Downey (1976) has

[23] That is, warheads will normally be allocated to the most valuable targets first, and thus analysts will find decreasing marginal returns for further EMT allocations. For example, if 200 EMT could destroy 30 percent of MVA, 400 EMT would not destroy 60 percent of MVA, but rather some intermediate value.

suggested that EMT should be adjusted to reflect the size of U.S. and Soviet industrial targets, employing an exponent of .4 for Soviet weapons and .3 for U.S. weapons. Simple reformulations of this kind improve the accuracy of EMT but still do not correct the basic bias, since the power of yield required to make *equivalent* megatons varies with both the warhead yield and the level of damage to be done. This point is illustrated in Figs. 11 and 12.[24] The curves in these figures suggest that the 2/3 exponent is almost always too large, and that the larger the warhead, the smaller the size of the exponent that should be used. Also, as an increasing percentage of MVA is destroyed, ever smaller industrial facilities remain undamaged, and attacks again these "waste" more lethal effects, causing the appropriate exponent to continually decrease. Thus, a single, simple formulation of EMT fails to produce *equivalent* megatons, though using an exponent of perhaps .5 or less would certainly be more appropriate than the present EMT formulation that uses the 2/3 exponent.

A related problem for EMT is that not all warheads would arrive and detonate on target. To compensate for arrival probability, analysts often employ "delivered" EMT, which is simply the product of arrival probability times the EMT of each warhead, this value being summed across the entire strategic force. However, it is implicit in the concept of delivered EMT that all warheads do indeed arrive on the optimal targets, with no inefficiencies caused by warhead failures. In reality, some valuable targets could be left uncovered when the warheads assigned to them fail to arrive, and thus delivered EMT

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[24]These curves depict weapon laydowns against the MVA data base described earlier and against a U.S. population census data base. Because some of the target representations of both MVA and population have very large target radii, the lethal area of the warheads used here will usually not cover the targets. This difficulty introduces a bias because the standard evaluation procedure used here assumes that the target value is circular normally distributed across the target area, and that after one warhead is detonated on any target, the value destroyed is removed, but the value distribution is still circular normal. Naturally, reassuming a normal distribution after each warhead overestimates the damage that subsequent warheads can do; as a result, some anomalous results do occur.

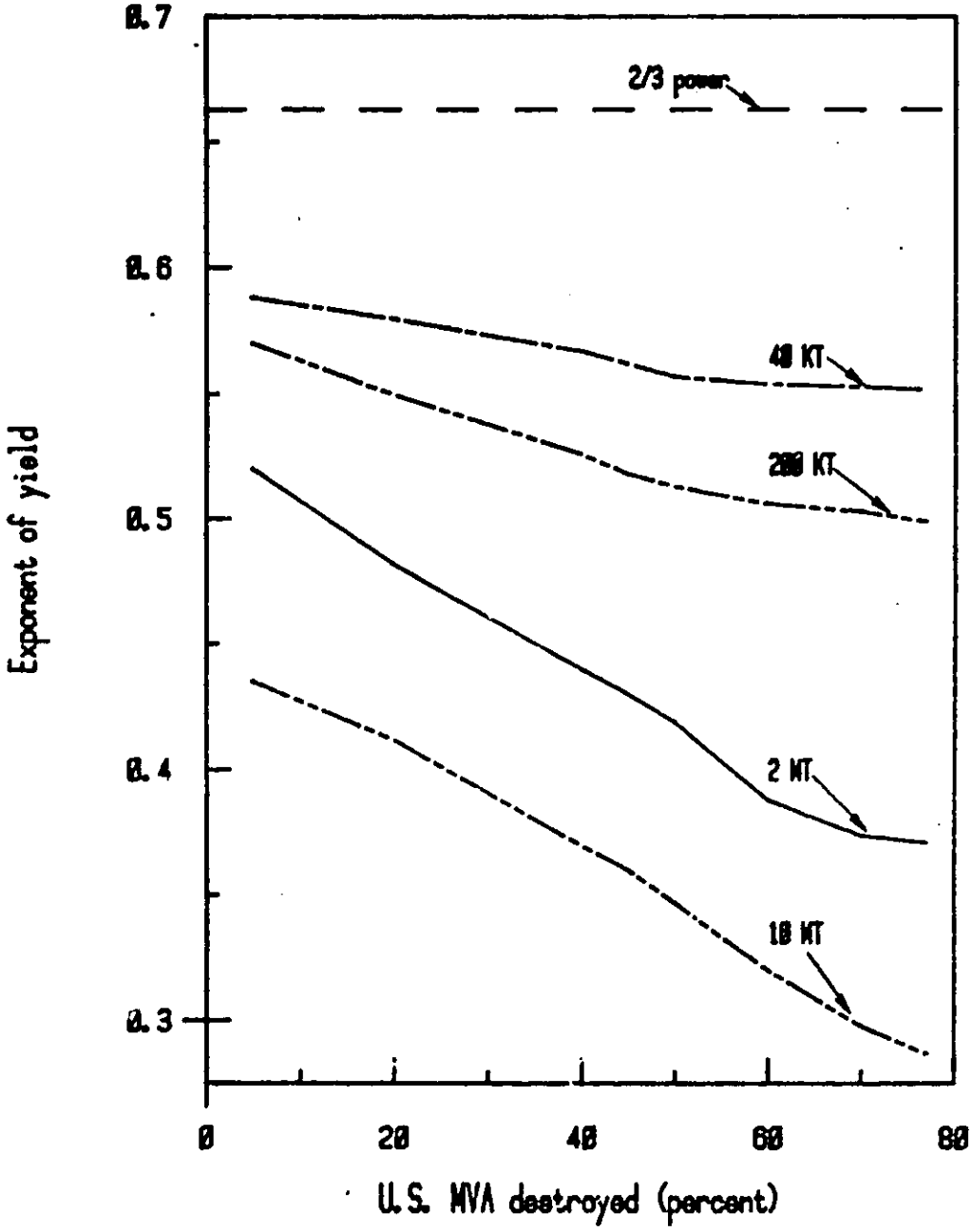

Fig. 11--Exponent of yield required to produce true "equivalent megatons" for various Soviet yields used to attack U.S. industry

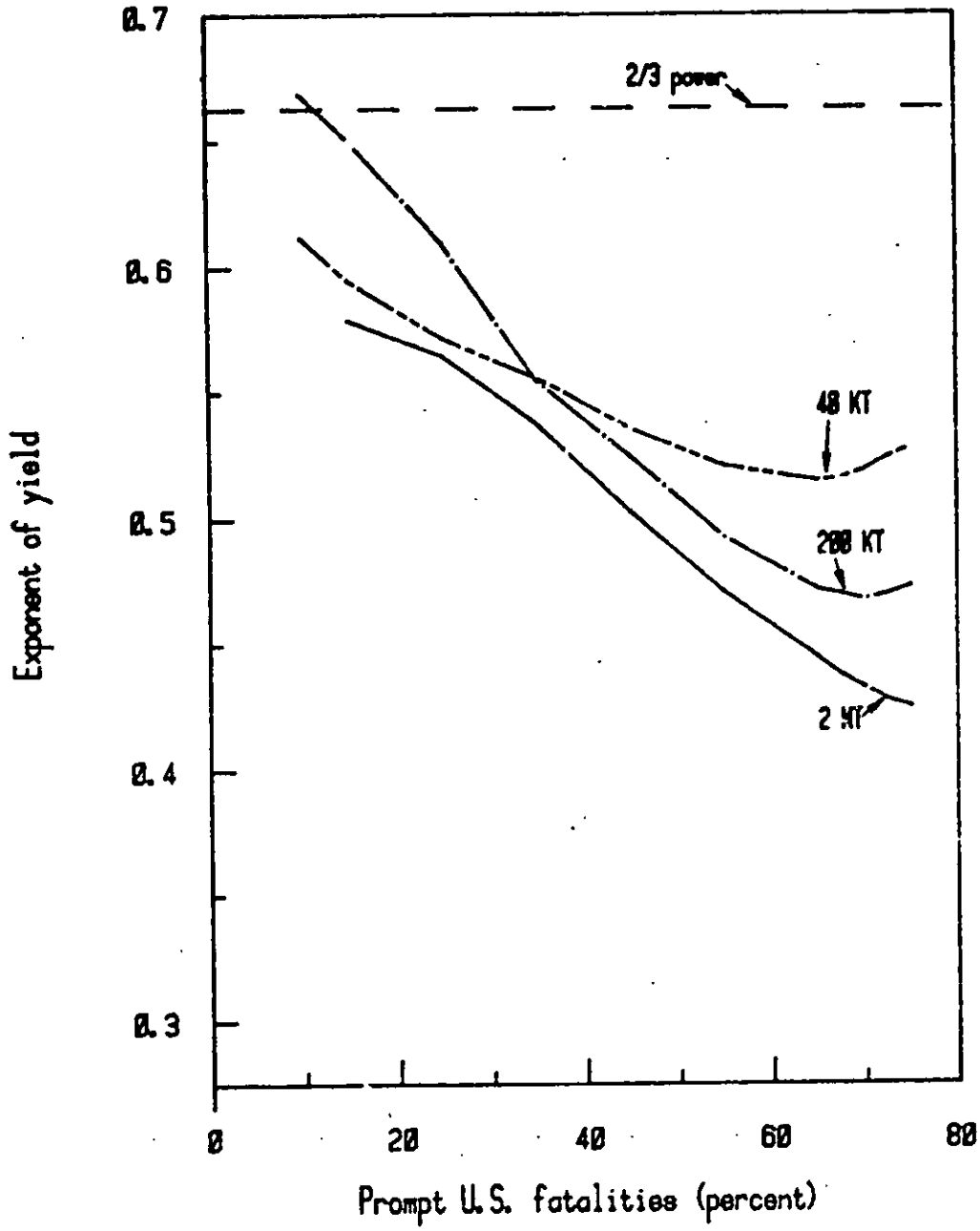

Fig. 12—Exponent of yield required to produce true "equivalent megatons" for various Soviet yields used to attack U.S. population

overestimates the amount of damage done.[25] This overestimate tends to be small if the arrival probability is high (i.e., only reliability is included in arrival probability), and large if the arrival probability is quite low (i.e., in a second strike with heavy damage). Unfortunately, the extent of the bias introduced by simply deflating EMT in this way can be determined only by detailed calculations of weapon laydowns on the target data base of interest; since such an exercise would complicate the use of EMT, this bias is almost never corrected or even acknowledged in strategic analysis.

The usefulness of EMT is reduced by these biases and because all industrial areas are not of the same value. Figure 13 shows the results of a normal, "delivered EMT" formulation[26] widely used by analysts today to define force requirements for assured destruction. This formulation is biased in a number of ways. First, the curves are apparently based upon allocations of 1 MT warheads, although the United States has relatively few warheads of that yield. Second, the curves are based on the assumption that delivered warheads will be optimally allocated. Third, the flattening of the MVA curve just above 75 percent destruction suggests that the data base employed contained only that much Soviet MVA (just as the U.S. MVA curve in Fig. 4 flattened in the same region). Finally, the data used in deriving these curves are at least ten to fifteen years old and thus fail to reflect recent changes in Soviet cities.

Fortunately, some of these biases offset each other. The use of 1 MT warheads instead of the more numerous smaller warheads causes an overestimation of the EMT required to do any given level of damage unless EMT is calculated with an exponent less than 2/3. Similarly, when some of the Soviet economic data are excluded, the amount of damage done at any given level of attack is underestimated. On the

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[25] Thus two 1 MT warheads with a 50 percent arrival probability, while nominally equal to one delivered EMT, do not have the same effect as one 1 MT warhead with a 100 percent arrival probability. This bias is increased if incorrect warhead arrival probabilities are used, which is normally the case, since most analyses use a 100 percent arrival probability to estimate the damage caused by delivered EMT.

[26] See Enthoven and Smith (1971).

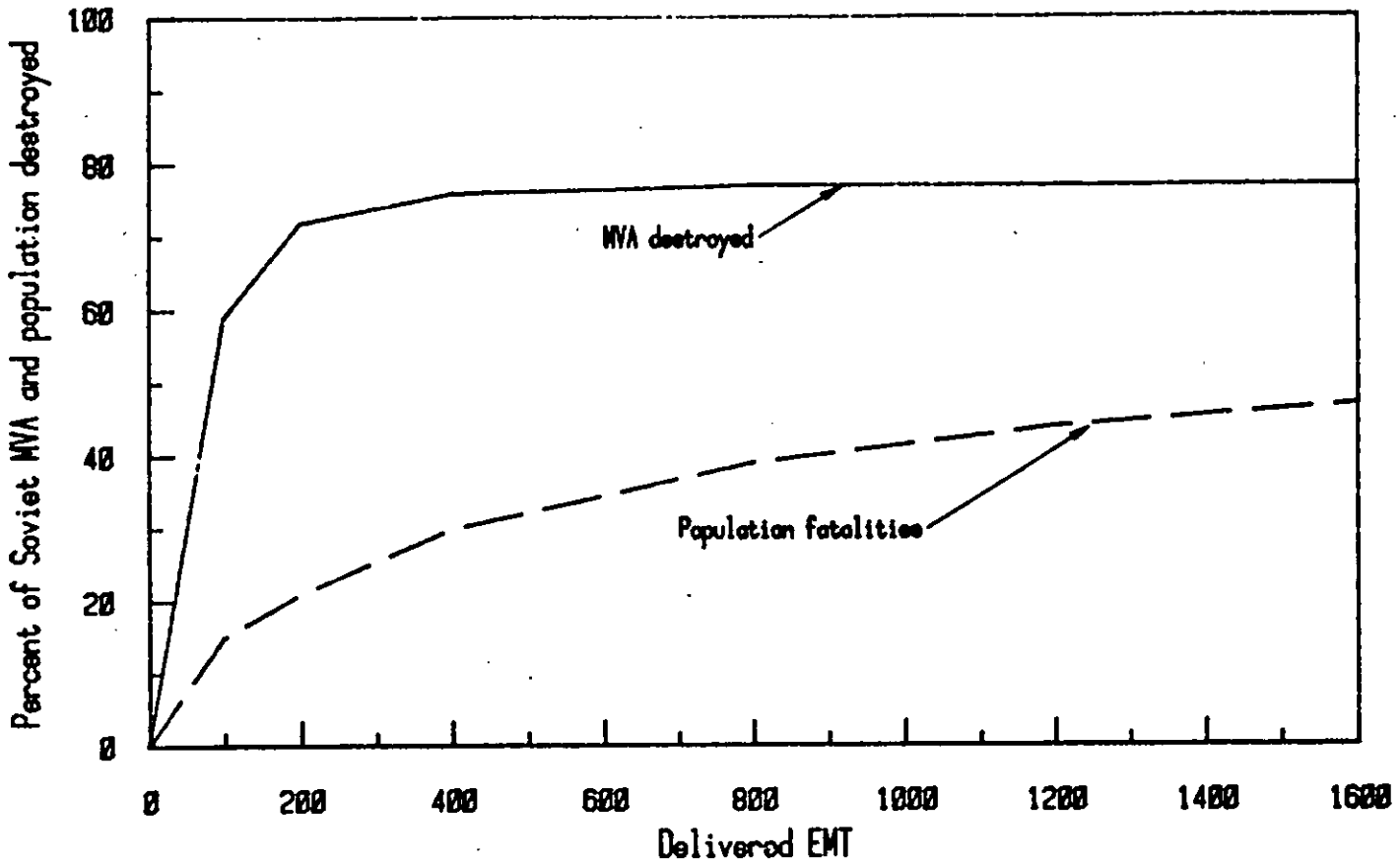

Fig. 13--Relating EMT to urban/industrial damage

other hand, use of an optimal laydown overestimates the damage done by a given level of attack. Finally, the consequences of using old data are unclear, though (in particular) they will probably cause population fatalities to be underestimated, since the relative proportion of the urban population has been growing in the Soviet Union over the last decade or so. The net effect of all of these biases is, of course, somewhat difficult to assess without performing a very detailed analysis of potential weapon laydowns.

Even if all of these biases were to offset each other, EMT would still be a biased metric of urban-industrial damage. As is clear from Fig. 13, EMT does not relate linearly to MVA destroyed. Rather, any percentage increase in EMT employed produces a smaller percentage increase in the damage done. Thus, twice as much EMT would not produce twice as much damage. While many analysts recognize this bias, they use EMT ratios as a relative measure of countervalue capability ignoring the bias. In short, ratios of EMT do not measure relative countervalue capabilities directly; analysts would be better advised to use ratios of MVA damage potential or some similar metric.

Throwweight as a Measure of Countervalue Potential

Throwweight relates less directly to specific countervalue capabilities than does either megatonnage or EMT. However, throwweight is roughly correlated with both megatonnage and EMT and therefore should be able to measure, more or less, the same attributes. Further, throwweight is more easily measured. Warhead yield is usually estimated by first determining the missile throwweight and the division of this weight among the warheads, and then calculating the approximate warhead yield using assumptions on the yield-to-weight ratio.

In the 1960s, throwweight was adopted as a measure of strategic capabilities primarily because of its correlation with the EMT of a missile.[27] However, that correlation appears to be valid only for single warhead missiles. Available data suggest that there is indeed a linear correlation between throwweight and the EMT of a single

[27] DDR&E (1964), pp. 193-195.

warhead missile, at least for a fixed warhead technology,[28] and a somewhat lower correlation between throwweight and megatonnage.

However, such a simple relationship does not exist with multiple warhead missiles. The difficulty is that the addition of extra warheads requires the addition of other weight as well, such as fuel to propel each warhead on the proper trajectory, thereby reducing the weight available for individual nuclear packages within a fixed total throwweight. The available data suggest that the addition of each warhead reduces the total megatonnage of a missile by 10 to 25 percent; therefore throwweight will not correlate well with megatonnage if various multiple and single warhead missiles are included in an assessment. Figure 14 shows the correlation between EMT (using the 2/3 exponent) and throwweight for two exemplary throwweights.[29] In general, the EMT tends to be greater for two warheads per missile than for a single warhead. However, as fractionation of the warheads proceeds, a peak value of EMT is quickly reached and further fractionation can dramatically decrease the EMT carried by the missile. Thus, the EMT and throwweight of MIRVed missiles are not linearly related both because EMT is not constant at each value of throwweight and because the ratio of EMT values at each warhead level is not constant.

For throwweight to be a good measure of countervalue potential, two conditions would have to hold: (1) It would have to correlate linearly with EMT and megatonnage, and (2) EMT and megatonnage would have to be good measures of countervalue potential. Clearly, throwweight does not correlate well with either megatonnage or EMT for today's forces of MIRVed missiles. Further, many analysts include bomber payload or bomb weight in throwweight; in such instances, the correlation between these measures will be tenuous. Finally, neither

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[28] See the formulation developed in Appendix D, which describes exactly such a relationship. The warhead technology (the warhead yield-to-weight ratio possible at any given weight) is unfortunately not very uniform even today. Thus, the Minuteman III Mk-12 warhead will soon be replaced by a Mk-12a warhead of roughly the same weight but twice the yield. See Pincus (1979).

[29] Yield estimates used in this figure are derived according to the methodology of Appendix D.

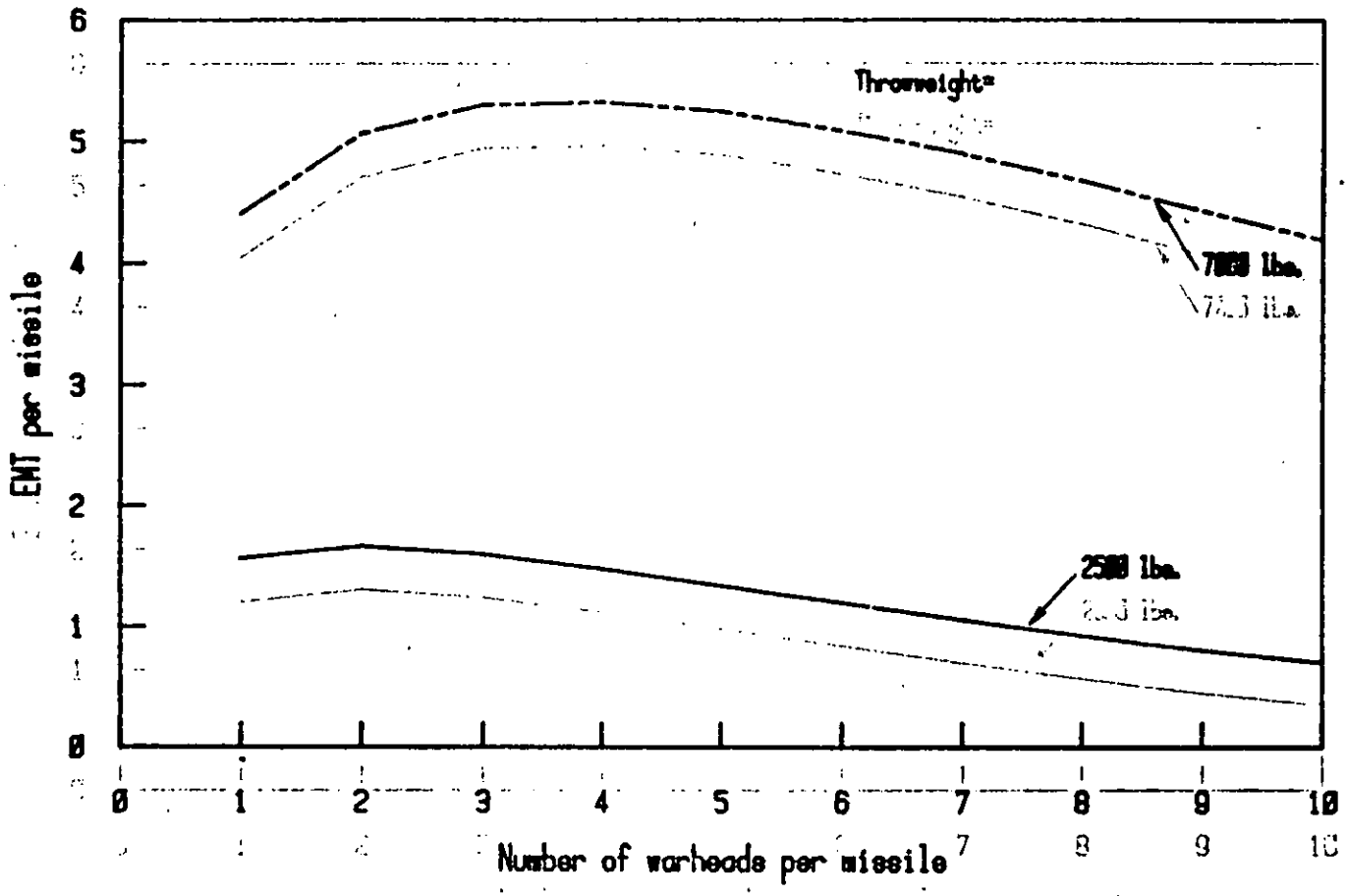

Fig. 14--Relationship of throwweight to EMT for multiple warhead missiles

EMT nor megatonnage is a good measure of countervalue potential. Therefore, the value of throwweight as a measure of countervalue potential is questionable. Rather, the throwweight of an individual missile tells us a great deal about the potential for MIRVing that missile, and it is in this context that throwweight has value for strategic analysis.

AGGREGATE MEASURES OF COMBINED OR MASSIVE ATTACK CAPABILITIES

Aggregate measures of massive attack capabilities are intended to combine the assessment of countermilitary and countervalue capabilities into simple indices. Because such a combination is not an easy task, only two aggregate measures are used today for this purpose: equivalent weapons and relative force size.[30] However, to compensate for this general lack, many analysts display a wide variety of other measures in a single table or figure, suggesting that if a single pattern emerges, it is a measure of massive attack capabilities. Each of these "measures" is examined below.

Equivalent Weapons

Equivalent weapons (EW) is a relatively new aggregate measure, introduced only recently by Fred Payne (1977). Because of its purported generality, though, it has already begun to receive fairly wide usage. Unfortunately, EW is misleading, biased, and inconsistent. In particular, it tends to systematically underestimate all capabilities, particularly those of a specialized or mixed force.

EW is formulated as:

$$EW = \frac{1}{\frac{a}{PK_a} + \frac{b}{PK_b} + \frac{c}{PK_c}}$$

[30] The Arms Control and Disarmament Agency has also developed a new strategic forces measure as yet unnamed and not widely known. This measure evaluates damage to a fixed set of 5000 soft (10 psi) point targets and 1500 hard (2000 psi) targets on each side. It thus ignores the area nature of urban targets and assumes a (nonexistent) symmetry in the target systems of each side. See ACDA (1978b).

where a, b, and c are the percentages of the opponent's soft point, soft area, and hard point targets, and PK_a, PK_b, and PK_c are the kill probabilities against each of these classes of targets, respectively.[31] Thus EW is assumed to proceed from a weighted harmonic average kill probability, with the weights being the percentages of each target type. Indeed, Payne describes EW as, ". . . the capability of a weapon to kill with equal probability each type of target . . . . ."[32]

However, EW is not a weighted average kill probability. By assumption, Payne sets the kill probability against soft area targets equal to the EMT of that warhead. Clearly, EMT is not a kill probability but rather a measure of lethal blast area irrespective of the impact point of the warhead. Also, EMT can be greater than one (when the warhead is larger than 1 MT), and thus EW itself can also be greater than one, which cannot be true of kill probabilities.

More important problems with EW arise from the implied weapon allocation scheme in the EW formulation. In this formulation, each warhead type must be allocated against each target type so that the percentage of total target kills associated with each target category is the same as the preattack percentage of total targets in each category. Payne suggests that these target percentages might be: 45 percent soft point targets (a=.45), 45 percent soft area targets (b=.45), and 10 percent hard point targets (c=.1). As a result, a weapon type intended to kill 100 total targets would have to kill 45 soft point targets, 45 soft area targets, and 10 hard point targets. Thus, a cruise missile with a small yield but good accuracy would be used primarily against soft area targets rather than hard point targets, and a Titan II with a high yield but poor accuracy would be used primarily against hard point targets rather than soft

[31] Payne specifies the kill probability against soft point targets as 100 percent and against soft area targets as the EMT of the warhead. He also specifies a formula, but not a hardness, for the hard point kill probability. A hardness of 2000 psi is assumed herein to retain consistency with the above calculations. These formulas all ignore arrival probability, which Payne factors in at a later point in developing a force EW measure.

[32] Payne (1977), p. 109.

area targets.[33] In other words, the use of EW encourages allocating specialized weapons to targets they are least suited to. Payne argues that this approach is rational because we can never be sure of the survivability and penetration of any weapon, and thus each weapon should be assigned essentially the same role in a massive attack. He ignores the correlation between the survivability and penetration of some very different weapons (e.g., Titan II and Minuteman III Mk-12a), since within correlated groups specialized tasks could still be performed by forces that do them well, ensuring the success of a comprehensive massive attack.

Payne also uses the percentages of targets as if each target class had an infinite (or very large) number of targets, and thus each target would receive only one warhead. Under that assumption, the EW measure avoids the problem of multiple warheads being assigned to the same target, changing the kill probability for each warhead after the first. Unfortunately, nothing in EW prevents the allocation of more warheads to a target type than there are targets. Indeed, with hard targets, the forced allocations would undoubtedly cause many more warheads to be allocated than there are targets, and thus the measure fails to record actual target kill capabilities.

The choice of the target ratio (soft point, soft area, and hard point) can also affect EW. In particular, few weapons are effective against hard targets, and so small changes in the preattack percentages of weapons allocated to these targets could cause large changes in the value of EW. Unfortunately, there is no easy way to set the appropriate percentages. For example, which are soft point targets and which are soft area targets? How are the number of 1 MT soft area targets determined? Are all possible targets considered, or only those above some minimum value?

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[33] For example, take the 5 MT yield and .4 n mi CEP of the US-C warhead in Table 2. To kill 100 targets, 45 US-C warheads would be assigned by EW to soft point targets, 15 to soft area targets, and 50 to hard point targets. These assignments destroy 45, 45, and 10 targets of each type, respectively.

Perhaps the most important aspect of EW is that it is biased in favor of relatively uniform weapon systems, even if these systems have only modest capabilities against some target types. This is demonstrated in Fig. 15, where 1000 targets divided into the above percentages are attacked by two different forces, each having 1000 warheads.[34] One force contains only 1000 US-A warheads, as defined in Table 2, whereas the other consists of 900 large, inaccurate warheads and 100 small, accurate warheads. The pure US-A force has only a modest capability against either soft area or hard point targets, giving it an EW rating of 518 (.518 per warhead). Alternatively, the large, inaccurate warheads do well against either type of soft target but very poorly against hard targets; in turn, the small, accurate warheads do very poorly against soft area targets but very well against hard point targets. Still, EW evaluates the mixed force as less than half as capable as the pure US-A force. In reality, the pure force could destroy about 665 targets if optimally spent, whereas the mixed force could destroy all 1000 targets. In other words, the mixed force, when used on the targets it is designed to cover, is the much better force despite the fact that EW rates it as only half as good. Since EW can be so misleading and biased a measure, it is of limited use in strategic analysis.

Relative Force Size

Over the past several years, the Secretary of Defense has used a measure of massive attack capabilities called "relative force size."[35] The formulation of this measure has never been published. However, it apparently allocates forces to both industrial and military targets, assuming some basic level of damage against each. The procedure stops once this level is reached, and then calculates the size of the total force as a percentage of the force required to obtain the basic damage levels. Thus, a relative force size of two

[34] The numbers of these weapons come from Table 2, except those for the cruise missile, which are simply provided to make the point in the text.

[35] See, for example, *1980 Defense Annual Report*, pp. 114-116.

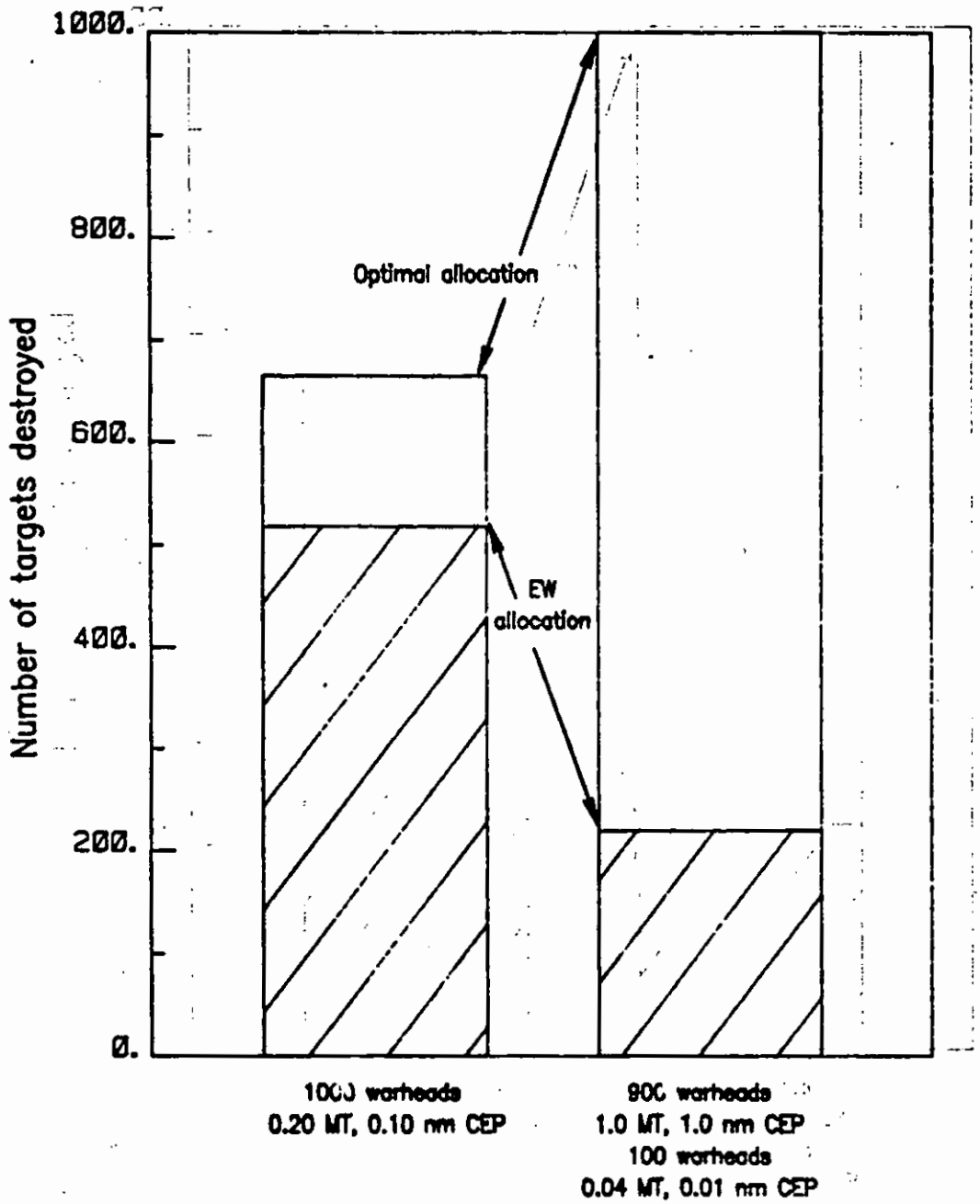

Fig. 15--Comparison of EW to optimal weapon allocations

implies that the force is twice as large as is necessary to obtain the basic damage levels.

This measure has several interesting aspects. First, strategic forces targets are apparently not counted among the military targets, as the measure is always applied both before and after a counterforce exchange to show how that exchange degrades the ability to damage the basic military-industrial target set. This exclusion implies that relative force size determines damage only against other military targets, and undoubtedly only against their fixed facilities, as discussed above. Second, it does not reflect the actual targeting of the strategic forces, raising questions about its validity in the first place. Further, relative force size may not include a large number of important targets, or may include some unimportant targets; by varying the number of targets included and the damage levels required, relative force size can be changed dramatically. Third, it is not clear how an analyst should determine the force required to obtain a fixed level of damage: Is the aggregate measure used in the division (to obtain relative force size) EMT, warheads, throwweight, or some other metric? Depending upon the procedure used, a variety of outcomes could be obtained. Fourth, relative force size has been calculated for both the United States and the Soviet Union using the same target base, rather than the target base that each faces,[36] ignoring the often significant differences in targets that characterize the two countries.

While many of these difficulties can be redressed, the basic concept of relative force size is so inappropriate that efforts to improve that measure are not likely to be worthwhile. That is, relative force size is a theoretical indicator of the capacity of strategic forces to destroy a set of targets; however, values in excess of one have generally been interpreted as an indicator of "overkill" in the strategic forces. Defense planners have always included excess forces in the overall strategic force as a hedge against uncertainties

[36] "Relative force size is a measure of capability to destroy a given set of military and economic targets." *1980 Defense Annual Report*, p. 15.

in force performance. Since such a hedge is the real justification for maintaining forces appreciably larger than mission assignments require, relative force size should be replaced by a measure of the confidence with which a set of targets could be destroyed.[37] Relative force size is not and cannot be that measure because it in no way accounts for the uncertainties in the performance of strategic forces.

Time Trends of Various Measure Comparisons

Recently, strategic force capabilities have often been assessed in terms of the time trends of various aggregate measures.[38] Often, these measures are evaluated in a relative sense, showing the ratio of U.S. to Soviet capabilities. These measures are assumed to reflect the balance of massive attack capabilities because measures of both countermilitary and countervalue capabilities are included, and because the inclusion of a variety of measures should help to compensate for biases in any single measure. Even skeptics will argue that the combined trends in aggregate measures are at least useful for showing trends in strategic capabilities, if not the absolute capabilities, since the trends in all of these measures tend to be correlated.

This type of capability assessment can only be as valid as the measures used in it. Since the measures used in it tend to be those critiqued above, analysts should not expect a strong correlation between relative capabilities and the ratios of these aggregate measures. On the other hand, the direction of change in both the aggregate measures and in force capabilities will exhibit a much higher correlation; thus assessment of trend data in the ratios of aggregate measures should at least tell us which way the balance is moving, though the pace of that movement or the actual value of the balance at any given time is much less reliably obtained through this process.

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[37] For example, from Fig. 7 we could determine the probability of successfully accomplishing an assured destruction mission, and from Fig. 3 we could determine the probability of a successful countersilo attack (once "successful" is defined as a specific damage requirement).

[38] See, for example, Rumsfeld (1977), pp. 20, 61, and Nitze (1976-77), pp. 201-203.

Naturally, even in reaching this conclusion, we must assume that other parameters relevant to capabilities, but not captured by the aggregate measures, do not change. For example, during the late 1960s, improvements in U.S. ICBM accuracy and the beginning of MIRVing may have suggested that countersilo capabilities were shifting in favor of the United States (judging by CMP ratios); however, the proliferation and hardening of Soviet ICBMs during that period may have invalidated that premise. Such changes in the target data cannot be captured by CMP ratios alone because they do not take account of target data, and therefore the trend in CMP alone would not necessarily reflect the trend in countersilo capabilities.

V. ASSESSING STRATEGIC FORCE CAPABILITIES IN OFF-DESIGN SCENARIOS

Almost all assessments of the strategic balance focus on the capabilities of the strategic forces in a few, standard scenarios. These scenarios involve very large counterforce or countervalue attacks, with escalation to the highest level of conflict occurring immediately at the nuclear threshold. After these attacks, the outcome of the war is assessed according to damage caused (or assets surviving) and forces remaining, assuming that any major form of hostilities ends at that point.[1] These scenarios also consider only two force postures from which the war could be initiated: day-to-day alert (corresponding to a surprise attack) and fully generated alert (after several days of force generation in a crisis). While there are no "rules" of strategic analysis prohibiting the use of other scenarios, these scenarios are employed because they describe relatively simple "wars," the nature of which is fairly easy to parameterize.

In the last several years, many analysts have come to recognize that these standard scenarios are fairly unlikely contexts for nuclear war. In particular, the Soviets are believed to view nuclear war as a likely prospect in a very prolonged crisis, or as an escalation from conventional levels of conflict. These analysts also perceive a Soviet interest in winning (or at least in not losing) the war, and therefore doubt that it will end cleanly after one or two nuclear exchanges. Finally, in a desire to control escalation but also to provide a hedge against conventional force inferiority in any given theater, these analysts have examined a variety of limited nuclear options which would precede, if not replace, the very large nuclear exchanges.

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[1]Some analysts will argue that the assessment of remaining forces serves as a proxy for the outcome of the war after some point in time. However, a variety of factors other than simply the residual force levels will influence the nature of conflict thereafter requiring a somewhat more systematic analysis of what could, indeed, happen.

Since most of this work has yet to be seriously evaluated in a strategic balance context, the conditions considered have been referred to as "off-design scenarios." In this section, we examine these scenarios and attempt to evaluate their effects on the balance frameworks established above (which correspond more closely to the traditional scenario approach). Specifically, we examine three phases of nuclear war in which variations could be expected from traditional scenarios: (1) preparation, (2) escalation, and (3) protracted war after a massive attack. In each of these phases, we discuss the scenario conditions that could alter the present procedures for evaluating the strategic balance.

PREPARATION

In past assessments of the strategic balance, very little attention has been paid to the preparatory phase of nuclear war. This has been primarily due to a traditional focus on surprise nuclear war, for which neither side is suitably prepared.[2] Over time, analysts have come to view surprise nuclear war improbable, recognizing that its outcome would be so devastating for both sides that no rational national leader would be likely to adopt such a strategy as an element of premeditated military aggression.[3] Rather, nuclear war is perceived as being more likely to result from a prolonged crisis that led one side to view that option as the least undesirable choice, somewhat as the Japanese viewed the initiation of war against the United States in 1941. In a crisis of such magnitude, both sides would presumably mobilize their military assets well before the conflict began; at the initiation of the conflict, the fully generated strategic forces of each side would confront one other. Many

[2]That is, the defender is surprised and thus makes no preparation other than that which tactical warning (about 20 minutes) allows him, while the attacker cannot extensively prepare for fear of signaling his intentions and losing the advantage of strategic surprise.

[3]The attacker must feel that he has much to gain and little to lose; otherwise, he can afford to avoid conflict, or to pursue his intentions through crisis actions. With nuclear war, it is extremely unlikely that any attacker would perceive that he had little to lose.

analysts have recognized that war could occur during mobilization, when strategic force levels were moving from a status of day-to-day alert to fully generated alert levels. Thus these are commonly treated as the extremes of the range of forces that could be employed.

Determining the availability of strategic forces is a much more complicated problem. Even in a crisis situation, there are many reasons for not generating strategic forces or for generating only part of them.[4] Yet if a crisis is sufficiently grave to make nuclear war a real possibility, one side or both may attempt to mobilize by (1) preparing surplus missiles for firing,[5] (2) placing nuclear weapons on aircraft other than existing bombers, and (3) producing more nuclear weapons or their delivery vehicles. (In a protracted crisis, weapons production could become a significant consideration.) Such actions would be designed to increase the availability of strategic forces above even the fully generated levels. But some actions intended to increase the availability of other military forces (e.g., moving troops or supplies into Europe) could actually degrade the capabilities of the strategic forces by drawing resources from them (e.g., by reassigning tankers from bomber support to support of airlift forces). Also, after a crisis had continued for days or weeks, the operational capabilities of weapon systems could degenerate; growing maintenance demands and diminishing crew endurance would cause force availability to fall below its maximum. If the crisis continued longer, further degradation would have to be accepted to sustain personnel training; some of the mobilized forces might also have to return to their normal activities. Actions to that end by one side would not necessarily be paralleled by

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[4]Force generation could be an escalatory act in a crisis and would have to be avoided to maintain the crisis at a relatively low level.

[5]In SALT, only the number of missile launchers (silos) and not the number of missiles is limited. Therefore, both sides have a variety of extra missiles available that are (1) obsolete systems, (2) test systems, and (3) spares and replacements. The Soviets also apparently plan to reload some silos and thus may well have a supply of extra missiles available for that purpose.

comparable actions by the other party and thus the balance of forces probably would be altered.

Somewhat less thought has gone into the potential defensive actions in a crisis period. Strategic defensive forces (air defense, ABM, and ASW) would undoubtedly be placed on higher levels of alert, much as their strategic offensive force counterparts. If exotic systems (lasers and particle beams) or systems banned by treaty (excess ABMs) were available, they would probably be deployed. During an intense crisis, either side might activate civil defense measures, disperse military forces, and take precautions to protect the national leadership. Once again, the specific timing or sequence of these activities would undoubtedly be different for each side, and such choices could have a significant influence on the balance of capabilities.[6]

As a crisis developed and forces were generated, each side might begin "testing" the other, posing threats to see what reaction was elicited. For example, the Soviets could move several SSBNs toward the U.S. coastline, increasing the vulnerability of U.S. bombers. If the United States failed to react, the Soviets would have a significant advantage should war start. Even if the United States responded defensively (e.g., further dispersing its bombers), the threatening Soviet action would still retain some advantage (e.g., shorter SLBM flight times to all bomber bases). Further, the United States might degrade its own real capabilities somewhat (e.g., decreasing bomber range by putting bombers on shorter dispersal airfields, which limit takeoff fuel loads). Were the United States to respond by taking a similar threatening action (e.g., moving SSBNs in close to Soviet shores), the Soviets would still be better off as long as they had

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[6]In general, defensive actions improve the balance of capabilities from the defender's point of view, though with some actions there is a transition period during which the opposite may be true. For example, in activating civil defense, there would be a period immediately after the order to evacuate or shelter people in which more fatalities would occur in an attack because some people would have moved outdoors where they were more vulnerable, and few or none would have yet reached protected locations.

chose some threat to which the United States was more susceptible.[7] If the United States backed down, the Soviets might "win" the entire crisis situation—their goal in the first place. In short, depending upon the action/reaction choices, such testing exercises can also significantly influence capabilities.

In a sufficiently heated crisis, conventional conflict could eventually result. Conventional conflict could begin either as a response to the "testing" dramas or as an escalatory step after one side decided it could gain an advantage. In either case, even though nuclear weapons were not used, conventional weapons probably would be used to attack this opponent's nuclear stockpiles. This would be particularly true of a war in Europe, though any nuclear weapons destroyed in that case would presumably be theater related systems. However, should conventional naval warfare develop, the destruction of SSBNs would certainly change strategic capabilities. Further, with B-52Ds now being assigned a theater role in Europe, many of these strategic delivery systems could be destroyed in a conventional conflict there (either by attacks on their airfields or by defensive action while they were attempting penetration of Soviet defenses while carrying conventional bomb loads).[8]

Notwithstanding the past history of warfare, strategic analysts almost completely ignore the possibility of paramilitary attacks against strategic forces in either the preparatory or later phases of a nuclear war. Properly equipped and motivated Soviet agents in this country conceivably could attack strategic force bases or en route weapon systems, perhaps destroying some of them. A successful sur-prise attack of this sort could detract from strategic force availability before the first nuclear warhead exploded.[9]

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[7] Since the aggressor can choose the threat to raise, he would be best served by choosing one which his opponent cannot respond well to. However, he should not choose one in which a moderate escalation could reverse the advantage. For example, the threat of moving SSBNs in close might be met by a conventional attack that sinks them. This would be very costly to the aggressor, and may be very hard to respond to without significantly escalating the conflict.

[8] See Robinson (1979), p. 14.

[9] Such actions would be best timed so that they did not provide strategic warning, perhaps barely preceding the arrival of nuclear weapons.

ESCALATION

As stated above, traditional analysis of likely scenarios usually assumes that there is no escalatory phase in a nuclear war. Analysts sensitive to the possibilities of such a phase sometimes justify this assumption by suggesting that the damage caused during such a phase would simply be part of the total damage caused by an eventual massive attack, and thus assessment of massive attack capabilities includes an assessment of this phase as well. However, the weapons used in limited nuclear options (LNOs) may be sent against different targets from those selected for those weapons in a massive attack. If the war failed to escalate above the LNO level, the strategic balance would be tied to the relative abilities of each side to carry out such options. Nevertheless, analysts should attempt to assess the effect that resorting to LNOs will have on the eventual execution of a massive attack in the event that the war did escalate.

The relative vulnerability of assets, including the capability of an opponent to destroy those assets without forcing escalation, is the basis of effective LNOs and thus of strategic capability during escalation. In determining the relative vulnerability of any type of asset, the key issues are: (1) the size of attack needed to destroy that asset, (2) the type and location of weapons that would be used, (3) the effect on other capabilities and assets if that asset were destroyed, (4) the geographic distinguishability of that asset (is it spread throughout the country or located in a small geographic area?), and (5) the collateral damage that would be caused in an attack.[10] If the size of the attack (in launchers or warheads) or its geographic extent is too great, the attack could prove to be highly

[10] In particular, analysts look for "choke-point" sectors in industry or extremely critical capabilities in other areas that can be destroyed with few weapons on the opponent's side but not on the attacker's side (or, at least, the same kind of target is not as critical to the attacker). While such attacks may have intense short term effects, few parts of an economy or of any other capability cannot be bypassed in the long term, especially if relatively small target systems are considered. Thus, the effectiveness of an LNO would tend to be of relatively short duration, and also to be a function of an opponent's ability to reconstitute the attacked capabilities.

escalatory. Similarly, the location and type of weapon used could also determine the level of escalation. For example, a weapon launched from a European battlefield may be less escalatory than one launched from the continental United States. The escalatory potential of the attack would also depend on how well the opponent perceived the objective of the attack, which presumably would depend on the geographic distinguishability of the attack and the collateral damage the attack caused. Finally, the effectiveness of the attack depends upon its ability to destroy the targeted assets and in turn upon the disruption of other capabilities ensuing from the destruction of this asset.

While assessments have been made of these relative vulnerabilities, the methods employed in these assessments do not provide a good basis for measuring the balance of LNO capabilities. Assessments tend not to consider all of the issues important to LNOs and are often more qualitative than quantitative.[11] Further, there is no obvious way to combine various issues in a single assessment or to express the tradeoffs among issues. Indeed, much of the effectiveness of an LNO attack would depend on an opponent's perception of how much escalation it represented and his decision on whether to reply in kind or to escalate. In short, it is not surprising that a balance of capabilities at this level is seldom included in strategic capability assessments, even though this kind of capability might be crucial to the outcome of a nuclear war.

LNOs would also affect the strategic capabilities by changing the ability of the force to carry out its other missions. In part, this effect would be limited if LNOs included only massive attack targets and the weapons assigned to them in massive attack plans.

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[11] While the basic approach to assessing attack effectiveness tends to be quantitative (e.g., examining an input/output table for LNOs against industry), there is usually no way to determine the precise effect of destroying some critical assets because too many leadership choices remain on bypassing the loss or changing the use of the residual capability. Thus, at least some qualitative judgments must be made, and once they are introduced, the uncertainty in the actual outcome becomes so large as to defy quantitative assessment.

However, in a crisis, unplanned contingencies would probably develop and some strategic weapons might have to be retargeted. Further, the desire to minimize most forms of collateral damage characterizes most escalatory options; that goal stands in contrast to the notion of maximizing collateral damage in a massive attack. As a result, even if warheads were aimed at the same targets for both limited and massive attacks, their aim points should be offset toward other targets in massive attacks and away from other targets in limited attacks.[12] As a result, each weapon launched in a limited attack would be intended to cause less damage than would the same or a comparable weapon in a massive attack.[13]

It is also possible that a protracted limited nuclear war might lessen the eventual capability of one side to engage in a subsequent massive nuclear exchange. Nuclear explosions could destroy communication links or degrade them to such an extent that the execution of particular options became temporarily impossible. Other command and control assets might also be diminished during an escalatory period,[14] making stepwise escalation increasingly difficult at higher levels of conflict. Many of these problems are similar to the problems incident to absorbing a massive first strike, except that an escalatory phase conceivably could last for days or even weeks, and it would be very difficult to maintain command and control capabilities at peak efficiencies over such a protracted period.[15]

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[12] Naturally, it may not be possible to switch the aim points of warheads in this fashion, and therefore some compromise may be reached, such as aiming directly at the target. This kind of compromise could degrade the performance of both LNOs and massive attack options.

[13] If only very few or very small LNOs are executed, this lessening of damage might be insignificant overall. If the limited attacks became larger, the massive attack outcomes would be affected somewhat more.

[14] For example, airborne command posts can stay airborne for only so long, and maintenance failures will accumulate during an escalatory phase.

[15] The performance of people, for example, tends to degrade under stress. Should attacks escalate to the massive strike level, the execution of forces could then well be "ragged" and incomplete.

PROTRACTED WAR

In the years just before World War I, most military opinion held that the next major European war would emphasize offense and be extremely brief. It was not. While the analogy may seem a bit strained, most Western analysts today also believe that a future nuclear war would be extremely brief, involving a quick spasm of nuclear exchanges. But, again, that might not be the case. Indeed, the Soviets do not expect a future nuclear war to be a spasm nuclear war; much of their nuclear force posture is geared toward enduring capability.[16] In particular, the outcome of a protracted war will undoubtedly depend on the size and competence of the strategic forces of each side, their ability to identify and strike targets, and each side's cohesiveness.

Following a massive attack, forces for follow-on strategic operations could come from three possible sources. First, some of the initial strategic forces might have been held in reserve. Second, some of the bombers might be recovered[17] and reconstituted, and some missile reloads might be exploited. Third, new production or product conversion could be used to create strategic forces. All of these sources and the facilities that support them would be prime targets of the opponent; therefore, the strategic forces in each area should be able to survive and function. Further, these systems might not be used for weeks or months or even longer, and therefore they should be able to maintain readiness for a long period of time.

No matter how many strategic systems survived after the execution of preplanned options, they would be of little use unless some means of identifying and striking targets were developed. Many of the standard sources of target intelligence and the facilities for processing such information may have been destroyed, making it essential to identify and exploit surviving assets. The leadership with nuclear

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[16] If the Soviets prepared for protracted warfare and the United States did not, the Soviets would obviously have an advantage should this type of warfare occur.

[17] Bombers may be recovered if they do not receive an execution message, or after they accomplish their primary missions and return to their homeland.

release authority must also be identified and given access to intelligence, evaluation, and option development. Finally, communications must be established with the strategic forces and procedures set for conducting continuing nuclear operations. In short, the command and control of strategic forces in a protracted war would undoubtedly be an ad hoc, boot strap operation, quite different from peacetime planning and implementation procedures. It is, therefore, very difficult to evaluate the effectiveness of strategic forces in such a world.

Other assets and capabilities would also contribute to the outcome of a protracted nuclear war. In particular, conventional military forces may have a major role in reestablishing national control, as well as in projecting power beyond national borders. Over time, agricultural and industrial production would also be important, affecting the survival potential of the population and the economic resources available to the nation. Some of these assets will probably have been damaged in the massive exchanges of a nuclear war and damage may continue during its protraction. Therefore, an advantage would accrue to the nation best able to reconstitute these capabilities in the shortest period of time and to protect them thereafter. Many factors would contribute to successful reconstitution of these assets, including national will, cohesiveness, self-sacrifice, self-control, substitution possibilities, and external aid. Because these factors and their effects are almost impossible to measure, their exclusion from consideration in standard capability assessments is hardly surprising.

VI. ASSESSING CAPABILITIES: AN EXAMPLE

This section provides a general assessment of hypothetical Soviet strategic force capabilities in order to give form to the methodological discussions of earlier sections. The purpose here is to display some of the difficulties of applying available methods of analysis and to show how some of them can be applied in particular situations. That process supports the assembly of some conclusions which, while not comprehensive, provide valuable insights into strategic force capabilities.

In this example, the hypothetical Soviet strategic force posture is first presented, and the capabilities of the different weapon systems are discussed in a general way. Aggregate measures are then used to assess the overall capabilities of the postulated Soviet forces. Next, the dynamic aspects of a nuclear exchange are developed, focusing on a massive Soviet attack. Finally, the potential of Soviet capabilities in off-design scenarios is assessed.

1985 STRATEGIC FORCES

Table 2 introduced some hypothetical strategic force parameters for U.S. and Soviet ICBMs. Table 6 extends that list by adding Soviet SLBM and bomber forces. These force levels were designed to be consistent with the arms limits proposed for SALT II. Table 6 also includes some aggregate measures of strategic capabilities, calculated for each delivery vehicle. Thus, an SS-A missile has an EMT of 5.8, a CMP of 401, and an ECMP of 256.[1]

While aggregate measures of strategic force capabilities generally are not very accurate, they do provide a basis for comparing individual weapons. The Soviet ICBM forces are particularly impressive. Not only do they carry large amounts of EMT for destruction of area targets, but they also have very high values of CMP and ECMP,

[1]This ECMP calculation assumes an 80 percent probability of arrival and a 2000 psi target.

Table 6

HYPOTHETICAL SOVIET FORCES

Weapon System	Delivery Vehicles	Warheads per Vehicle	Warhead Yield (MT)	Warhead CEP (n mi)	Aggregate Measure per Vehicle EMT	CMP	ECMP
ICBM-A	820	7	.75	.12	5.8	401	256
ICBM-C	400	1	12.00	.12	5.2	364	58
SLBM-A	380	7	.25	.36	2.8	21	17
SLBM-B	500	1	3.00	.36	2.1	16	12
Bomber	100	4	3.00	.24	8.3	144	102

making them effective in hard target attacks, as suggested in Sec. II, above. By comparison, the SLBMs have low values of CMP or ECMP, and thus negligible hard target capabilities. Their EMTs are less than half those of Soviet ICBMs. Indeed, if aggregate measures are considered, it is difficult to understand why the Soviets would choose to build SLBMs rather than ICBMs. The relative importance of SLBMs becomes clear only when one considers their relatively short flight times when positioned properly off an opponent's coastline and their relative invulnerability to attack, giving them a significant capability for endurance.

Soviet bombers have more EMT than other Soviet systems, making them good weapons for destroying very large area targets. Although they have fairly high CMP and ECMP values, bombers take much longer to reach their targets than do missiles, and thus generally cannot be used against relatively time-urgent targets, which make up a potentially high percentage of all hard targets.[2] Alternatively, if bombers can perform armed reconnaisance, they can be quite effective against a variety of mobile targets that could not otherwise be struck, and against any hard targets (such as withheld ICBMs) that escaped damage in an initial attack.

[2]Soviet (and American) bombers would require perhaps ten hours to reach their targets in another hemisphere, giving the opposing side time to disperse or shelter some assets.

AN AGGREGATE MEASURES ASSESSMENT

Most analysts ignore aggregate measures in discussing the kinds of systems tradeoffs related above, proceeding directly to a comparison either of segments of the Triad or of total strategic forces. Table 7 makes such a comparison for six aggregate measures discussed in Sec. IV.

Table 7

AGGREGATE MEASURES OF HYPOTHETICAL SOVIET FORCES

System	SNDVs	Warheads	Total EMT	CMP (100s)	ECMP (100s)
ICBM-A	820	5740	4756	3288	2099
ICBM-C	400	400	2080	1456	232
Total ICBM	1220	6140	6836	4744	2331
SLBM-A	380	2660	1064	80	65
SLBM-B	500	500	1050	80	60
Total SLBM	880	3160	2114	160	125
Bomber	100	400	830	144	102
Total force	2200	9700	9780	5048	2558

In examining these aggregate measures, it is important to remember the problems introduced in Sec. IV. In particular, the specific measures tend to be only loosely correlated with a strategic force capability, and some tend to be misleading even then. More caution still is required in interpreting data like those shown in Table 7, in that the tendency is to make direct comparisons of the forces on the basis of these measures. The limitations of aggregate measures suggest that in comparisons, small differences (of 10 to 20 percent) are probably not very significant. Only gross differences can be depended on to reflect potentially greater capability. Even then, such conclusions should be verified, where possible, by more detailed analysis.

The postulated Soviet forces show significant differences between the various force elements. Their ICBM force completely dominates,

containing more than half the value of each aggregate measure and ranging as high as 94 percent in CMP. The Soviet bomber force, on the other hand, appears to be quite insignificant by any of the measures, and if the measures are accurate, could indicate the lack of a central role for bombers in the Soviet concept of nuclear war. The Soviet SLBM forces are well equipped with SNDVs and warheads, and even EMT in an absolute sense, but lack any significant hard target capability. Interestingly, each leg of the Soviet Triad has more than twice the amount of EMT required by advocates of assured destruction.[3]

Most comparisons of aggregate measures are made against total strategic inventories, as is done in Table 7. However, it is most unlikely that the Soviet Union would ever be able to use its entire strategic weapons inventory in an attack, particularly if starting from an environment where day-by-day alert levels are deliberately held well below 100 percent for both bombers and SLBMs. Further, some strategic weapon systems would never arrive on target, though aggregate measures normally do not reflect these losses (except for ECMP in Table 7). The potential importance of these losses is illustrated in Table 8, where the measures have been adjusted to reflect a day-to-day alert posture of 50 percent availability in the Soviet SLBM and bomber force and an 80 percent reliability in all weapon systems.

A day-to-day alert posture further increases the advantage of the Soviet ICBM forces. Soviet ICBMs on day-to-day alert make up 70 to 97 percent of their aggregate force. By comparison, the Soviet bomber force now appears miniscule and their SLBMs appear to be relatively inconsequential.

MEASURING SOVIET CAPABILITIES: THE STANDARD SCENARIO

While aggregate measures give a rough estimate of the Soviets' gross destructive potential, a more important measure is their ability to perform against potential U.S. targets. In this subsection, Soviet

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[3]It is important to remember that these EMT estimates ignore arrival probability; if arrival probability is 80 percent, then each Triad leg has at least 600 deliverable EMT, still well above the nominal assured destruction requirement of 200 to 400 deliverable EMT.

Table 8

AGGREGATE MEASURES OF DELIVERABLE DAY-TO-DAY FORCES

System	SNDVs	Warheads	EMT	CMP (100s)	ECMP (100s)
ICBM-A	656	4592	3805	2630	2099
ICBM-C	320	320	1664	1165	232
Total ICBM	976	4912	5469	3795	2331
SLBM-A	152	1064	426	32	32
SLBM-B	200	200	420	32	30
Total SLBM	352	1264	846	64	62
Bomber	40	160	332	58	51
Total force	1368	6336	6647	3917	2444

capabilities are estimated in a standard scenario involving a massive Soviet attack on the United States. The nature of possible U.S. targets is first developed, including their numbers, vulnerability, and time urgency. Then potential Soviet weapon allocations are addressed, showing some of the tradeoffs possible. Finally, the possible effectiveness of a Soviet attack is assessed as a direct measure of Soviet capabilities.

U.S. Targets

Sections II and III developed methodologies for assessing damage to military and urban-industrial targets and discussed the nature of some of these targets. Specifically, the military targets were divided into strategic force, command and control, and "other" military targets. Urban-industrial targets were classified as industrial-economic or population. A general description of each of these target types within the United States will now be developed.

Several sources describe the major military installations within the United States according to both branch of service and general

function.[4] Table 9 provides some rough estimates of the aggregate number of installations by type. While the functions indicated are somewhat arbitrary and do vary by service (with "Other Bases" including air stations for the Navy, Marine Corps, and Coast Guard), they provide a general notion of the importance of each type of installation.

Table 9

MAJOR U.S. MILITARY INSTALLATIONS

Service	Main Bases	Other Bases	Supply/ Support	Other	Total
Air Force	90	20	0	10	120
Army	45	20	30	40	135
Navy	10	30	25	30	95
Marine Corps	5	10	5	5	25
Coast Guard	20	5	0	0	25
Total	170	85	60	85	400

Many of the installations in Table 9 are not single targets or aim points. For example, Whiteman Air Force Base is carried as a single Air Force installation in Table 9, even though it includes almost 200 Minuteman silos and LCFs, an airfield, and other activities, most of which should be treated as separate targets. As the strategic forces (especially the ICBMs) are the main source of complication, Table 10 separately lists the primary strategic force targets. This table does not include command and control assets other than the Minuteman LCCs, as they tend to be much more highly concentrated with the main facilities at the installations in Table 9.

To categorize targets, two characteristics must be considered. The first is the target's size and vulnerability, which determine whether or not a single delivered weapon will be sufficient to destroy it. The second is the time urgency of the target. Command and control assets and bomber bases can be very time-urgent targets in the sense that they must be destroyed within minutes of tactical warning

[4] DMA (1976) and Rand McNally (1980), pp. 34-35.

Table 10

U.S. STRATEGIC FORCE TARGETS

Force Element	Approximate No. of Targets
ICBMs	1050
Minuteman LCCs	100
Bomber bases	35
SLBM ports	5

to prevent them from performing their functions. Since SLBMs can arrive on target within 10 to 15 min, whereas ICBMs require about 30 min to arrive, the most time-urgent targets in the United States must be struck by Soviet SSBNs close to the U.S. coast; these targets are shown in Table 11, including the number of SLBM warheads that would be required to destroy each in a time-urgent attack. Included in these targets are the main operating bases of the bomber force, which would probably be struck with a pattern attack of two to four weapons to destroy both bombers on the ground and some of those that had become airborne as well. Other weapons may be placed on the Air National Guard and Air Force Reserve tanker bases to stop the launching of tankers to support the bomber forces. The SSBN ports are not quite as time urgent, as SSBNs take somewhat longer to sortie from port, and yet they would probably also be struck by SSBN weapons just to guarantee that none escaped before Soviet ICBM warheads arrived. Also included in this list are an arbitrarily chosen, small number of political and military command and control assets, the destruction of which would stop or slow the execution of a U.S. counter strike.

Targets that are not quite so time urgent, or that are too numerous to be stuck effectively by SLBMs alone can be attacked by a combination of Soviet ICBMs and SLBMs. Included in this group are the U.S. ICBMs and LCCs and the other U.S. military targets. It is likely that Soviet ICBMs would also be allocated to the targets described in Table 11, to ensure their destruction. Thus, apart from the ICBM silos and LCCs, each of the roughly 400 targets in Table 4 would

Table 11

TIME-URGENT U.S. TARGET TYPES

Target Type	No. Targets	Minimum Allocation		Maximum Allocation	
		Warheads/ Target	Total Warheads	Warheads/ Target	Total Warheads
Bomber bases:					
Main bases	25	2	50	4	100
Other bases[a]	10	0	0	2	20
SSBN ports	5	1	5	3	15
Command/Control	20	1	20	2	40
Total			75		175

[a]Air Force Reserve/Air National Guard tanker bases.

receive weapons as part of an ICBM or SLBM attack on "other military targets." Since many of these targets are too large (in area) to be destroyed by a single weapon, and others are so hard that they would be likely to survive hits by single warheads, these targets would receive from two to four Soviet warheads, on the average.

Soviet doctrine relating to urban-industrial targets emphasizes the destruction of industry, focusing particularly on war-supporting industry. Apparently, population is not a deliberate target for the Soviets, though there is no reason to believe that they would attempt to minimize population casualties in attacking their targets. Thus, Soviet capabilities against urban-industrial areas may best be summarized by the curve in Fig. 4, which shows how much MVA the Soviets can destroy for a given allocation of warheads. Table 12 repeats these data for specific damage levels of interest, showing the number of 1 MT warheads (with an 80 percent arrival probability) required to achieve the given damage level. While it is difficult to anticipate how much damage the Soviets might want to cause, it is not unreasonable to assume that they would attempt to destroy at least 50 percent, but probably not more than 75 percent, of U.S. industry.

Table 12

SOVIET WARHEADS REQUIRED TO DESTROY THE U.S. MVA

Warheads Required	Warheads Deployed	MVA (%)	MVA (%)
30	30	10	10
90	90	20	20
190	190	30	30
340	340	40	40
550	550	50	50
690	690	55	55
870	870	60	60
1100	1100	65	65
1440	1440	70	70
2070	2070	75	75

Table 13 summarizes the U.S. target systems and the approximate number of warheads required to cover each. The hypothetical Soviet total force are more than sufficient to satisfy the maximum requirement; the day-to-day alert force (of 7920 warheads, 6336 of which are deliverable) can almost satisfy the requirement.

Table 13

APPROXIMATE SOVIET WARHEAD REQUIREMENTS

Target Type	Minimum	Maximum
ICBMs	2000	4000
LCCs	200	400
Time-urgent	75	175
Other military	800	1600
Industry	550	2070
Total	3625	8249

However, whether the Soviet have the right size and type of war-heads and whether they would be willing to expend so many warheads in that manner must be considered in more detail.

Soviet Warhead Allocations

To determine the effectiveness of potential Soviet attacks on the United States, one must consider the ways in which the Soviets could allocate their nuclear weapons. That requires some understanding of general Soviet force employment doctrine and individual weapon capabilities. Soviet doctrine suggests that an attack would be carried out against the targets outlined above, employing the maximum number of weapons where possible, to effectively destroy U.S. military capabilities. However, the Soviets would withhold some weapons in reserve[5] and other strategic weapons might be allocated to theater targets.

Using these general guidelines and considering the comparative advantages of individual force elements, an allocation scheme for Soviet weapons can be devised, and shown in Table 4. The allocations in this table are for Soviet forces on day-to-day alert, and this alert level reflects at least the maximum availability of Soviet forces and yet is a posture in which the Soviets presumably would be able to cover all critical U.S. targets. It is assumed here that the entire Soviet bomber force is held in reserve, since it represents a small fraction of all Soviet force capabilities. Of the Soviet SLBM assets, the SLBM-B missiles are partially committed against time-urgent targets, because they can be brought in close to U.S. shores. The remaining submarine-launched missiles are committed to theater targets. The MIRVed SLBM-A's are used to cover small other military targets and some of the industrial targets, but many such missiles are also held in reserve. Of the Soviet ICBMs, the large ICBM-C's are used against LCCs and other military targets associated with force command and control. The ICBM-A's are partially committed to the strategic reserve, and partially to other military targets. The remainder of the ICBM-A's

[5] The Soviets must be much more concerned about holding an large strategic reserve than is the United States, given the number of hostile neighbors they face and the potentially hostile powers of a post-nuclear-war world. Presumably, much of the Soviet reserve would be constituted from ICBM's and other reloads, although the Soviets would undoubtedly hold some of their initial forces in reserve until reloading could be assured.

Table 14

POSSIBLE ALLOCATION OF SOVIET DAY-TO-DAY FORCES

System	ICBMs	LCCs	Time-Urgent Targets	Other Military Targets	Industry	Theater Targets	Reserve
ICBM-A	?	0	0	700	?	0	800
ICBM-C	0	200	0	200	0	0	0
SLBM-A	0	0	0	700	330	0	300
SLBM-B	0	0	175	0	0	75	0
Bomber	0	0	0	0	0	0	200

force is available for use against U.S. ICBMs and industrial targets, as indicated in Table 14.

While Table 14 portrays the principal Soviet weapons allocations, it does not describe the tradeoffs involved in committing weapons to one type of target rather than another. Table 14 does not show specific allocations of ICBM-A missiles to ICBM and industrial targets, where some clear tradeoffs exist. These tradeoffs are shown in Fig. 16,[6] where the 4240 ICBM-A warheads not specifically committed in Table 14 are used in various combinations against these two target sets. The dashed line indicates that because SLBM-A warheads are allocated to industrial targets, about 25 percent of U.S. industry would be destroyed thereby even if no ICBM warheads were similarly committed.[7] Beyond that point, the attacker is free to choose his allocation. If, for example, he wished to maximize the damage to both target sets, he would allocate roughly 2500 warheads against the U.S. ICBMs, obtaining about 90 percent damage, while allocating roughly 1750 warheads against U.S. industry, raising the industrial damage

[6] This figure uses the EMT versus MVA destroyed curve of Fig. 4, assumes that the U.S. ICBMs are hardened to 2000 psi, and also assumes that no more than two warheads detonate on each silo (though many more could be assigned to guarantee that at least two arrived).

[7] That is, if the SLBM-A warheads were optimally targeted against the highest value U.S. industrial targets, they should be able to destroy 25 percent of U.S. MVA. If, instead, these warheads were placed on less valuable industrial assets, they naturally would cause less than 25 percent damage (and thus the dashed line in Fig. 16).

level to nearly 72 percent. Indeed, the tradeoffs of Fig. 16 are so clear that it is hard to imagine the Soviets choosing anything but this mixed allocation. Still, if they wished primarily to destroy the U.S. ICBM force, they could achieve nearly a 96 percent damage level against it, though significantly lessening urban-industrial damage. In actually making allocations, these kinds of tradeoffs must be considered for all target types. Table 14 simply postulates what allocations could occur without suggesting that Soviet allocations would indeed follow such patterns.[8]

In a fully generated force posture, the Soviets could gain up to 1800 warheads additional to those allocated in Table 14 and could increase the damage levels achieved by the day-to-day forces. But day-to-day forces were covering most U.S. targets of interest and modest increases in damage levels would not necessarily warrant the allocation of all 1800 additional warheads to the same sets of targets. Further, because of the operational difficulties involved in changing allocations of weapons already available, it is likely that some of the 1800 "new" warheads would be used to supplement the allocations of Table 14, but that many would be committed to the strategic reserve. Thus, going from day-to-day to a fully generated alert primarily would increase the Soviet strategic reserve and create a larger hedge against uncertainties.[9]

Attack Effectiveness

The warhead allocations suggested in Table 14 lead to very high levels of attack effectiveness. For example, a allocation of 1600 warheads against other military targets should lead to an overall damage level of about 95 percent or more. Similarly, more than 70 percent of U.S. MVA could be destroyed and 90 percent or more of the

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[8] However, some aspects of these allocations (such as the use of SLBM-b warheads on time-urgent targets) are almost required by operational considerations, and thus should not be viewed as arbitrary.

[9] If the Soviets chose to concentrate their ICBM-A forces on the U.S. ICBM silos, rather than balancing the counterforce and counter-value attacks, then the extra forces gained by moving to a fully generated alert could largely be allocated to U.S. industrial assets.

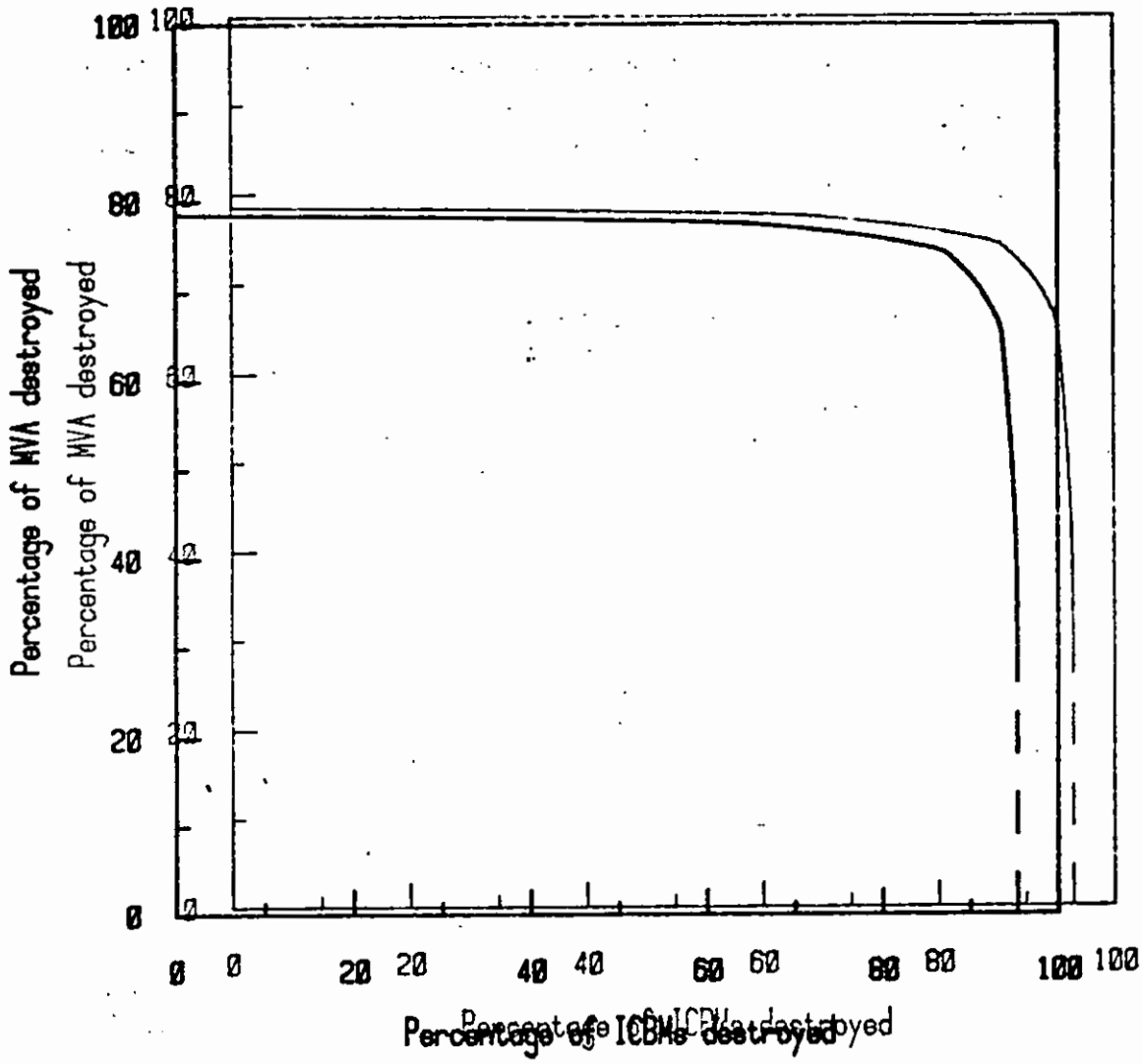

Fig. 16--Exemplary tradeoff between counterforce and countervalue damage

ICBM forces. Although these damage levels are high in terms of the expected (but uncertain) percentage of targets destroyed, the important question is the extent to which such a Soviet attack would degrade U.S. capabilities.

Even when expected damage levels were quite high, the actual damage level might be quite uncertain. For example, Sec. II considered the uncertainty in estimating the percentage of the U.S. ICBM force killed by any given Soviet attack. The Soviets could do two things to lessen those uncertainties. First, they could improve one attribute of a weapon's performance as a hedge against uncertainty in other attributes. For example, in the ICBM-C, the Soviets have increased the warhead yield to such an extent that uncertainty in accuracy may no longer be of importance; the lethal radius is so great that a 2000 psi target will be destroyed (as long as the warhead arrives and detonates) even if accuracy is degraded by 50 percent. Second, the Soviets could increase the size of the attack against any given target type to ensure that enough warheads do indeed arrive to perform the desired function (even if the arrival probability is reduced), and to increase the probability of getting two reinforcing detonations against any given target in lieu of one. As the Soviet forces and allocations indicate, they would be able to make many such adjustments, but they could not completely hedge against uncertainty. For example, they have too few ICBM-C missiles to use against all of the U.S. ICBMs.

The 200 ICBM-C missiles allocated against ICBM LCCs should be able to achieve a kill probability against the LCCs of about 98 percent.[10] As suggested in Table 5, such a kill probability would leave roughly 16 of 20 Minuteman squadrons without any LCCs and four squadrons with only one. Such a Soviet attack would clearly degrade U.S. capabilities in 80 percent of the Minuteman squadrons and would partially degrade those capabilities in the other squadrons.

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[10] For an LCC of 2000 psi, this missile should have a single shot kill probability (SSPK) of essentially 100 percent (80 percent when delivery probability is included).

The damage to time-urgent targets and to the U.S. ICBMs caused by a Soviet attack would depend largely on the action the United States took upon receipt of tactical warning of the attack. If the United States chose to launch some or all of its ICBMs on warning, the Soviet attack might do little in the short term to degrade the U.S. capabilities, though it would lessen the ability of the United States to retain a reserve ICBM force. Attacks on the U.S. bomber bases and SSBN ports would destroy the maintenance and support capabilities of those facilities (unless they had previously been dispersed), and might also destroy some of the bombers or SSBNs. However, much of the U.S. SSBN force is at sea at all times, and thus the damage to the U.S. SSBN force (in a short war) might not be great. On the other hand, the alert force of the U.S. bombers is prepared to sortie on warning, and thus it, too, should be able to survive most Soviet attacks. Therefore, while the Soviets could certainly reduce the number and endurance of strategic forces available to the United States, it is not at all clear that they could prevent U.S. forces from performing many of their preplanned missions.

The projected damage to U.S. industry from such a hypothetical Soviet attack is as high as 70 to 75 percent of U.S. MVA. Because a modern economy is fragile in many respects, some surviving assets would probably fail as a consequence of massive damage to U.S. industry. But the MVA destruction so postulated would include only the capital assets; labor and other inputs required in an industry might be little damaged (especially if an effective civil defense program were implemented). If surviving labor and other inputs could be substituted for some of the lost capital, production levels might exceed the residual 25 to 30 percent of MVA suggested by the simple damage figures. They would decline if relatively more skilled workers were killed or disabled. Further, some types of substitution among capital stock and inputs (including energy sources) might be possible after an attack. Thus, without a detailed model of an industrialized economy (including consideration of production technologies and their alternatives), it is extremely difficult to predict how much damage might be done. However, the chaos of nuclear war would almost surely

prevent any concerted economic activity for a long period; gradual reorganization and growth would presumably follow in time.

In summary, the Soviet attack hypothesized here could cause a high level of damage, suggesting significant Soviet capabilities to carry out all assumed missions. However, the damage levels are uncertain, even though the postulated Soviet force posture allows the USSR to partially offset those uncertainties in some areas, increasing Soviet confidence of achieving specific damage levels. Further, it is difficult to determine if the damage levels indicated here would degrade U.S. capabilities and assets to the same extent that targets were destroyed. Thus, the uncertainties in target damage are significantly compounded by the uncertainties in asset viability. Nevertheless, the postulated Soviet forces would be likely to destroy significant portions of U.S. capabilities.

OFF-DESIGN SCENARIOS

The Soviet attack described above assumes a single, massive first strike. However, no nuclear war is likely to be as uncomplicated as such a simple attack model suggests. Each of the three phases of a war examined in Sec. V could significantly alter the assessments made above.

Even if a nuclear war were spasmodic, actions preceding the spasm could significantly affect the outcomes of the war. For example, if the Soviets could generate forces larger than those maintained at day-to-day alert levels, they would be able to increase the levels of damage that would result from the allocations of Table 14, or (alternatively) to increase their strategic reserve forces. An increase in their strategic reserves would allow them to send additional warheads against preselected targets that somehow survived the spasm, thus reducing the uncertainty of outcome and raising the resulting levels of damage.[11] Damage levels could also be increased, and U.S. capabilities reduced, by virtue of effective actions by Soviet agents or

[11] This assumes, of course, that the Soviets could learn which of their initially launched warheads had not completed their assignments.

conventional forces before the nuclear attack. However, if such actions led to conventional conflict, the Soviets could stand to lose more than they gained, especially if the United States began an anti-submarine warfare (ASW) campaign. Given the small number of Soviet SSBNs programmed to strike time-urgent U.S. targets in the postulated allocations, U.S. ASW could overcome the Soviet capability to eliminate these targets, allowing at least some U.S. bomber bases and command and control nodes to survive until Soviet ICBMs arrived. Even if only half of the Soviet SSBNs assigned to these targets were destroyed, U.S. command and control wuld probably remain intact until the Soviet ICBMs arrived later. The United States would thus improve its opportunity to respond effectively to the Soviet attack. Given Soviet sensitivities about command and control effectiveness, it is likely that the Soviets would do all that they could to avoid the initiation of U.S. ASW.

If nuclear war developed through escalation, many of the massive attack capabilities discussed above would become irrelevant. That is, the essence of an escalatory phase would be limited attacks designed to achieve limited objectives in a way that clearly signaled those objectives to the opponent. While the specific objective at first might be no more than to demonstrate resolve (which could be done with a high altitude burst of almost any weapon), the general objectives would more likely extend to the systematic elimination of high-value opposing capabilities represented by a small number of targets. To carry out such attacks, weapons with very high effectiveness (to limit the numbers required to performed the selected task) would be required. They should cause little collateral or indiscriminate damage, which could confuse the opponent as to the objective or enrage him. Optimally, such weapons would have high accuracies, low yields, and high probabilities of arrival. While a few measures have been proposed to evaluate weapons using these parameters, it is not clear how meaningful such evaluations would be without a specific knowledge of potential target sets and surrounding assets.

On the other hand, a preliminary escalatory phase could well modify the effectiveness of a massive attack. If targets related to

the capabilities of strategic forces in a nuclear war. Thus, while conventional measures assign very high capabilities to the hypothesized Soviet strategic forces, neither the United States nor the Soviet Union can have high confidence in such assessments.

the strategic forces or their command and control were damaged in the escalatory phase, they might be incapable of performing their assigned roles at some later time. Given the value and relative isolation (from other assets) of such targets, it is likely that some would be struck in an escalatory phase, especially if limiting collateral damage were considered important.

In a protracted war, some potentially large portion of the strategic forces must be withheld in order to preserve an intrawar deterrence capability. One who has kept a strategic reserve could be in a position to dictate surrender terms to an opponent who has not. Holding back preassigned forces has the disadvantage of allowing those forces to be subject to enemy attack while they are withheld, thus reducing their arrival probability and their effectiveness. To use such systems most effectively, a retargeting capability is essential—in part to offset attrition, and in part to take advantage of late information about the surviving assets and capabilities of the opponent. Such a retargeting capability is also central to the effective use of forces committed to a general strategic reserve (including reloads and forces recovered or reconstituted). These forces are worthless unless specific targets can be identified for them. Thus, Soviet force capabilities in a protracted war would depend as much on retargeting and reconstitution capabilities as on the raw damage potential of individual weapons. Unfortunately, these capabilities are not easily taken into account using existing methods for assessing strategic force capabilities.

SUMMARY

The hypothesized Soviet forces would give the Soviet Union sufficient strategic capability, even on day-to-day alert, to cause high levels of damage to almost all probable of U.S. targets. However, estimates of the probable levels of damage contain a large element of uncertainty, as do assessments of how much such damage would degrade U.S. assets and capabilities. Moreover, given the broad range of nuclear war scenarios, it is unlikely that assessments concerned solely with massive attack capabilities would appropriately reflect

Appendix A
NUCLEAR WEAPON EFFECTS[1]

SOURCES OF NUCLEAR WEAPON EFFECTS

The detonation of a nuclear weapon is accompanied by a wide variety of "weapon effects," or destructive mechanisms. These effects vary with weapon type, size, and place of detonation. When a nuclear weapon detonates, it releases energy in different forms. These forms of energy can themselves become the weapon effects, or they can be transformed into weapon effects by interacting with the environment.

The destructiveness of a nuclear weapon is usually measured in terms of the total energy produced by the weapon (the yield). Normally, the yield is measured in terms of the amount of TNT that would cause the same energy release. Since nuclear explosions are generally much larger than conventional explosions, their yield is measured in kilotons (thousands of tons of TNT equivalent) or megatons (millions of tons of TNT equivalent).

Nuclear explosions derive their energy from two types of nuclear reactions. One, fission, involves the splitting of one large atom into several smaller atoms and particles of a lower total weight. The other, fusion, involves the combination of two small atoms into one larger atom and some other particles of a lower combined weight. In either case, the lost weight is transformed into energy according to Einstein's well-known formula: $E = m \cdot c^2$, where E is the energy produced, m is the mass lost, and c is a constant representing the speed of light. Most strategic nuclear weapons today employ some combination of these two types of reactions, as the two tend to be synergistic in effect.[2]

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[1]The effects of nuclear weapons are explained in much more detail in Glasstone and Dolan (1977).

[2]Specifically, a fission explosion is usually required to set off a fusion explosion, and in turn a fusion explosion produces neutrons of higher energy, which causes fission to increase its efficiency and also can lead relatively stable isotopes of uranium to fission. This latter effect is referred to as the "booster" principle. See York (1976), pp. 22-23.

While the energy released by a nuclear explosion may have its form changed several times, about 85 percent is carried as air blast or shock, thermal radiation, and heat. The remainder is released as either "prompt" or fallout radiation. The mixture of prompt and fallout radiation varies dramatically between the two types of nuclear reactions: Fission produces about one-third prompt and two-thirds fallout radiation, while fusion produces almost all prompt and almost no fallout radiation.[3] Most smaller strategic nuclear weapons are nearly pure fission in their reactions, whereas larger (megaton range) weapons tend to be about half fission and half fusion. Thus, these weapons release energy as some combination of prompt and fallout radiation. Since most of the energy associated with fallout radiation is not released until after the explosion, it is usually not included in standard estimates of warhead yield. Rather, warhead yield normally only includes the "explosive energy" of a nuclear weapon, or the energy released within the first minute or so after the detonation. Given the fission/fusion ratio for strategic weapons, this explosive yield should be about five to ten percent less than the total energy released by the weapon.[4] This convention is followed herein in discussing weapon yields.

Many factors determine the amount of energy that goes into each weapon effect. For typical nuclear bursts above the ground but below about 40,000 ft altitude, about 50 percent of the total yield goes into air blast effects. Thus, a 200 Kt weapon would produce an air blast roughly equivalent to 100 Kt of TNT. In this same range, about 35 percent of the total energy is emitted as thermal radiation and heat. For detonations at higher altitudes, the less dense atmosphere reduces the air blast effects and proportionately increases the thermal radiation effects.[5] The weapon type can also change the distribution of energy. In particular, "enhanced radiation" weapons (neutron bombs) increase the percentage of energy that goes into prompt radiation at the expense of blast effects.[6]

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[3]Glasstone and Dolan (1977), pp. 7-8.
[4]Glasstone and Dolan (1977), pp. 7-8.
[5]Glasstone and Dolan (1977), pp. 9-10.
[6]Snow (1979), pp. 3-5.

BLAST EFFECTS

The explosion of a nuclear weapon near sea level produces a fireball in which the maximum temperature is tens of millions of degrees. This intense heat raises the surrounding air to extremely high pressures, and in turn the air expands outward into lower pressure areas.[7] This expansion is so rapid as to create a shock or blast wave, which destroys targets in two ways. First, the air pressure within the shock front can literally crush objects because it is much higher than the air pressure within the object (14.7 psi at standard sea level conditions). This excess pressure is referred to as overpressure; the maximum overpressure associated with the shock wave at any given distance is called the peak overpressure. Second, the wind velocity and air density of the shock wave cause a "slapping" effect against structures. This slapping effect is referred to as dynamic pressure. The principal source of blast damage is determined by whether an object is damaged more by the crushing effect of overpressure or the slapping effect of dynamic pressure.[8]

The distance at which a target of fixed vulnerability will be damaged by the blast wave depends on several factors: (1) target vulnerability, (2) warhead yield, (3) height of burst, (4) duration of the overpressure pulse, and (5) atmospheric and terrain conditions. Target vulnerability is measured by either the overpressure or dynamic pressure required to damage it. The relationship between target "hardness" and the distance from the explosion at which that overpressure will be delivered is captured in fairly well defined curves available in a variety of sources.[9] The lethal radius of a weapon

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[7]The increased temperature affects the air pressure through the perfect-gas equation derived from Boyles' Law: $PV=nRT$, where P is the pressure, V the volume, n the amount of air, R a constant, and T the temperature. Thus the increased temperature first increases the pressure and then causes the volume to increase (and the pressure to correspondingly decrease) as well.

[8]However, many analysts ignore dynamic pressure, evaluating the vulnerability of structures susceptible to it in terms of the overpressure that would occur at the same distance as the lethal dynamic pressure. As a result, the analyst then need only evaluate one lethal radius function (for overpressure).

[9]See, for example, Glasstone and Dolan (1977), pp. 108-119.

increases with the warhead yield taken to the one-third power. The lethal radius also increases if the warhead is detonated just high enough above the ground such that the blast wave interacts with its reflection off the ground, causing a mach stem in which the net overpressure and dynamic pressure can be as much as doubled.[10] Also, the larger the warhead, the longer the shock wave lasts at any given pressure; this increased "pulse duration" can weaken a target, damaging it at a lower value of either overpressure or dynamic pressure. Finally, the initial air density (before the explosion), the terrain surrounding the explosion, and a variety of other factors can reinforce or degrade the blast effects delivered to any given distance.

Within the last decade or so, a modified system of measuring blast vulnerability has become quite popular. It is called the vulnerability number system. It expresses blast vulnerability in the form "VNTKV," where the VN is a logarithmic function of the lethal pressure, "T" is an indication of overpressure ("P") or dynamic pressure ("Q") susceptibility, and "K" is a measure of pulse duration sensitivity. This system is described in detail in several sources.[11]

Blast effects tend to be one of the predominant sources of damage to almost any type of target. Also, blast is perhaps the best understood of all nuclear effects. Therefore, almost all target vulnerability is given in terms of blast damage, and almost all damage assessment procedures focus on blast damage to the exclusion of all other nuclear effects.[12]

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[10] Even a groundburst receives some reinforcement from the reflected blast wave. Thus the lethal radius of a groundburst is larger than the corresponding lethal radius of a "free airburst," which is a distance to which the blast wave delivers a given amount of pressure through a uniform atmosphere.

[11] See, for example, DIA (1974).

[12] If other prompt effects may be lethal, many analysts base their damage calculations on the overpressure that would occur at the same distance where the other effect is lethal. Unfortunately, other weapon effects do not scale with warhead yield in the same way that blast does; therefore, this procedure is approximate at best. Most damage assessment procedures do calculate fallout damage separately from blast, primarily because fallout patterns are very different from prompt effects damage patterns. However, fallout affects only people, and so blast is used to evaluate damage for most other target types.

CRATERING

A nuclear weapon detonated on or near the surface of the earth creates a crater. The nuclear fireball produces part of the crater by melting the soil and rock, sending the resulting gaseous materials into the nuclear cloud. The vaporized particles eventually solidify as the temperature around them cools and fall back to the earth's surface (usually some distance from the original crater). Air blast also adds to the size of the crater by literally blasting away at the ground, causing debris to be thrown into the air. Other loose materials around the explosion are sucked up by the winds accompanying the air blast. All of this debris eventually falls back to the earth, the heavier pieces falling in or around the crater. Shallow underground bursts produce the largest craters because they subject the ground to the greatest fireball and blast effects. Deep underground bursts produce no crater,[13] nor do high airbursts. Airbursts form a crater if some part of the fireball touches the ground.[14]

The lethal effects that produce the crater vaporize or blow away almost anything located in the area the crater covers. Other assets beyond the lip of the crater are damaged by the impact of debris from the crater out to about twice the crater radius, though most of the large pieces of debris fall fairly close to the crater's lip. The crater radius from a 1 MT groundburst would be about 500 ft and its maximum depth about 225 ft. Note that this radius is considerably smaller than the lethal radius for even 2000 psi blast effects, and thus while cratering may be a lethal effect, it will normally not be the one to determine the lethal radius except against extremely superhardened targets.

GROUND SHOCK

When either the fireball or the blast wave touches the earth, it causes a shock wave in the ground. This ground shock propagates down

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[13] Today's nuclear tests are performed deep underground without cratering or venting of gases into the atmosphere.

[14] A crater will not form from a 1 MT warhead detonated above about 1800 ft.

and outward from the nuclear explosion, is severely damaging underground facilities up to three miles away from the explosion. Ground shock causes sudden acceleration, in short movement and displacement. Thus, underground objects not firmly mounted and cushioned are damaged by being thrown into each other or into the walls surrounding them. Also, since the ground is often not a uniform medium, the shock may travel faster in some areas than others, causing shearing effect along the boundary of materials that could break objects (like pipes) not otherwise damaged by the other ground shock effects.

Although most superhardened targets are buried and thus protected from blast effects, ground shock can damage them severely. In particular, all assets associated with the ICBM force, including the missile and machinery, must be firmly mounted and cushioned to avoid ground shock damage. If this is not done, ground shock can become the determinant of the lethal radius of a warhead against superhardened or other buried targets.

THERMAL RADIATION

Thermal radiation is electromagnetic radiation (ultraviolet, visible, and infrared) produced by the fireball of a nuclear explosion. This radiation can burn skin and ignite fires. Thermal radiation from larger nuclear weapons causes substantial injury to people outside of buildings, causing burns and eye injuries (to people looking directly at the fireball). But thermal radiation does not injure people sheltered by nontransparent materials. If such shelters are not fireproof, though, thermal radiation causes fires that destroy the structures and the people in them. The most such fires occur in large, built-up areas or in forests where fuel is plentiful. As found with conventional bombing-induced firestorms during World War II in Dresden, Hamburg, and Tokyo, fires can cause more casualties and destroy more facilities than any other bomb effect.

PROMPT NUCLEAR RADIATION

One of the products of nuclear explosions is prompt nuclear radiation, including gamma rays, neutrons, beta particles, and alpha

particles. Because beta and alpha particles have very short ranges (quickly interacting with air), they are not a significant source of prompt radiation dosages. Gamma rays and neutrons have much longer ranges and can cause significant casualties and damage to electronic equipment.

While thermal radiation can be blocked by any nontransparent material, prompt nuclear radiation is not so easily blocked. In general, different types of materials offer different degrees of protection by absorbing some prompt radiation, and this absorption increases with the thickness of the material. Even air absorbs some prompt radiation, and thus the dosage delivered to any given location depends on the distance from the detonation and the air density through which the radiation travels. But materials such as steel, concrete, and earth absorb prompt radiation more effectively, providing a fair amount of shelter. To evaluate the protection offered against prompt radiation by various types of structures, a transmission factor is estimated. For example, a transmission factor of .5 indicates that only half of the prompt radiation dosage outside of the shelter is transmitted through the walls of the shelter. Each type of shelter usually has a different transmission factor for gamma radiation and neutrons, and may have a different transmission factor for different types of gamma radiation as well.

To determine the damage radiation does to people, a total radiation dosage must first be determined,[15] and then this dosage must be adjusted downward to account for the biological recovery possible. Radiation dosages are usually measured in roentgens (r), and the dosage absorbed by a person is measured in rads. Exposure to one roentgen of gamma rays usually results in an absorption of about 1 rad; neutron dosages are normally given in rads only. A dosage in rads is in turn converted to an effective biological dosage, "rem" (roentgen effective man), by applying a factor usually close to one for gamma rays, and also close to one for neutrons except for some

[15] To determine the total radiation dosage, the dosage for fallout effects must be added to the prompt radiation dosage. The fallout effects are described below.

biological effects (where the factor can be as high as four to ten). Finally, prompt radiation dosages are delivered so quickly that the body has essentially no time to recover.

Once the biological dose (in rems) has been calculated, the damage to the individual can be determined. For dosages up to 100 rem, radiation sickness normally does not occur. Dosages of 100 rem to 200 rem commonly produce radiation sickness, but death is highly improbable. From 200 rem to 600 rem, almost all of the population exhibits radiation sickness, and many may die, especially in the higher dosage ranges. Almost everyone dies from dosages between 600 rem and 1000 rem, unless extensive therapy is immediately applied. Even then, recuperation is prolonged. Death is almost certain for dosages above 1000 rem.

Prompt radiation can cause transient radiation effects on electronics (TREE, for short). While the radiation itself is transient (occurring within about one minute of a nuclear explosion), the effects can be temporary or permanent. Temporary TREE usually causes false signals to be induced on electric circuits. Permanent TREE causes some change to the electronic materials themselves, altering their characteristics. The magnitude of either effect varies with the type of electronics involved and the prompt radiation dosages absorbed.

FALLOUT RADIATION

All nuclear explosions produce radioactive elements that emit radiation long after a nuclear explosion. When explosions occur on or near the earth's surface, these elements become mixed with a variety of debris particles drawn into a nuclear cloud. After the cloud forms, the debris particles begin to fall back to the earth, carrying with them some of the radioactive elements. This mixture of debris and radioactive particles is referred to as close-in or early fallout, because it falls in a continuous pattern that begins close to the site of the explosion. Other radioactive particles fail to mix very much with debris, and thus do not soon become heavy enough to fall to earth. These particles instead are often suspended in the stratosphere and lose most of their radioactivity to decay before falling to

earth, forming what is called delayed fallout.[16] The percentage of radioactive particles deposited early decreases dramatically as the height of burst increases (since very little crater is formed, and thus very little debris is pulled into the cloud); a 1 MT weapon air burst above about 1800 ft creates very little early fallout.

Fallout radiation is different from prompt radiation in many ways. Prompt radiation, which is produced within about one minute of the nuclear explosion, causes its damage very quickly; fallout radiation does not even begin to cause any significant damage until the debris falls back to earth, from minutes to hours after the burst. However, since fallout involves the radioactive decay of various elements, fallout radiation is produced for weeks and months after an explosion, though its intensity decreases over time. Thus, with fallout, the dosage received must be summed over time. Further, biological recovery must be considered in determining the net effect of new dosages received. Also, prompt radiation causes damage in a roughly radial, line-of-sight pattern around the explosion, whereas fallout is carried by the wind and thus may cause very little damage in areas very close to an explosion, while causing great damage in areas very far away (potentially hundreds or thousands of miles).

The total damage done by radiation to people comes from the sum of both prompt and fallout radiation. In calculating the radiation dosage from fallout, the same procedures as discussed for prompt radiation are applied. However, in determining the amount of protection provided by any form of shelter, a single fallout protection factor is used (for all types of radiation) instead of a transmission factor. The protection factor is the inverse of a transmission factor and indicates the factor by which the outside radiation dosage must be adjusted to calculate the dosage inside the shelter or building. Thus, if the protection factor is 25 and the out-of-doors dosage

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[16] Delayed fallout can have a variety of effects. In the atmosphere, for example, it can affect the ozone layer. Once it falls to the ground, some of the longer life particles (such as strontium) can still cause damage through radiation. These effects were summarized (and found largely insignificant in comparison to other effects) in National Academy of Sciences (1975).

1000r, the dosage in the protected location is 40r.[17] Any given building provides better shelter against fallout radiation than against prompt radiation. Thus a typical building may have a transmission factor of 0.8 for many types of prompt radiation, while having a protection factor of 3.0 for fallout.

OTHER NUCLEAR EFFECTS

A variety of other nuclear effects accompany most nuclear explosions. The most important of these are radio effects and EMP, which can impede communications and destroy electronic equipment. Radio effects occur because the propagation of radio waves is dependent upon the ionization of the atmosphere, and a nuclear explosion can significantly modify that ionization. As a result, communications can be "blacked out," and the background noise associated with communications can also be significantly increased. EMP involves the transmission of electromagnetic waves from a nuclear explosion. These waves are received by electronic equipment just as are radio waves; however, they are much stronger and can cause currents strong enough to damage most types of electronic equipment.

While other effects do exist, they are less important than those described above. It is hard to predict which of the effects described above will become the primary sources of damage for any given weapon and target combination. Indeed, many effects may cause damage at the same time, and subcritical damage by two or more effects can become critical when they are combined. Thus nuclear weapons effects are complicated, and are also very uncertain.

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[17] If people leave the shelter they forfeit the protection it affords and receive an unshielded dosage at the appropriate rate for that period of time. Since fallout does decay, within about one month or less people can normally escape from shelters to uncontaminated areas.

Appendix B

LETHAL RADIUS DERIVATION

The lethal radius (LR, in thousands of feet) of a 1 Kt warhead (groundburst) is related to the target hardness (h, in psi) by the equation:[1]

$$h = 3.3 \cdot LR^{-3} + 6.96 \cdot LR^{-3/2}$$

Multiplying through by the cube of the lethal radius and putting all terms on the same side of the equality sign yields:

$$h \cdot LR^{3} - 6.96 \cdot LR^{3/2} - 3.3 = 0$$

Solving the quadratic equation for $LR^{3/2}$ yields:

$$LR^{3/2} = \frac{6.96 \pm \sqrt{48.44 + 13.2 \cdot h}}{2 \cdot h}$$

Since the lethal radius cannot be negative, this equation simplifies to:

$$LR^{3/2} = \frac{3.48 + \sqrt{12.1 + 3.3 \cdot h}}{h}$$

Solving for the lethal radius produces:

$$LR = \left(\frac{3.48 + \sqrt{12.1 + 3.3 \cdot h}}{h} \right)^{2/3}$$

Or, for lethal radius in feet,

$$LR = 1000 \cdot \left(\frac{3.48 + \sqrt{12.1 + 3.3 \cdot h}}{h} \right)^{2/3}$$

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[1]Bennett (1980b), pp. 11-14. Note that the footnote on pp. 12-13 concludes with the statement that the initial coefficient of the second term should be about 220, not 192; thus, in the form used here, 6.07 is replaced by 6.96.

Table B-1 shows some typical values for hardness and lethal radius.

Table B-1

RELATIONSHIP BETWEEN TARGET HARDNESS AND LETHAL RADIUS FOR A 1 KT GROUNDBURST

Hardness (psi)	Lethal Radius (ft)
2000	122
1000	155
500	199
100	364
50	483
30	602
10	1013
5	1461

Appendix C

DERIVATION OF ECMP

Countermilitary potential is formulated as:

$$Y^{2/3}/CEP^2 \qquad (1)$$

with Y in megatons and CEP in nautical miles. From the text, CMP relates to the survival probability (PS) according to the formula:

$$PS = .5^{CMP \cdot LR^2} \qquad (2)$$

where LR is the lethal radius for 1 MT warheads, or ten times the lethal radius for 1 Kt warheads developed in Appendix B (since the total lethal radius scales with yield to the one-third power).

To account for arrival probability, PS must be modified to an adjusted survival probability (PS'):

$$PS' = (1 - r) + r \cdot PS \qquad (3)$$

In other words, the adjusted survivability equals the probability the warhead does not arrive (1 - r) plus the probability that the target survives if it does arrive (r · PS). However, this formulation of PS' lacks the analytic attractiveness that PS has of relating CMP directly to PS through the exponential term.[1] Thus, we define a new measure, effective countermilitary potential, which returns PS' to the simplicity of PS:

[1]That is, with PS, two warheads of the same type have the same impact as a single warhead with twice as much CMP, since the use of two warheads on the same target simply causes PS to be squared. But squaring PS' leads to a very messy expression, which generally does not equate the impact of two warheads to the impact of one warhead with twice the CMP.

$$PS' = .5^{ECMP \cdot LR^2} \tag{4}$$

Since both Eqs. (3) and (4) must produce the same value of PS', we conclude that:

$$(1 - r) + r \cdot .5^{CMP \cdot LR^2} = .5^{ECMP \cdot LR^2} \tag{5}$$

Taking the natural logarithm of each side gives:

$$Ln(1 - r + r \cdot .5^{CMP \cdot LR^2}) = ECMP \cdot Ln(.5) \cdot LR^2 \tag{6}$$

Solving then for ECMP gives:

$$ECMP = \frac{Ln(1 - r + r \cdot .5^{CMP \cdot LR^2})}{Ln(.5) \cdot LR^2} \tag{7}$$

Note that, from Appendix B, the basic lethal radius is a function of target hardness (h). We can therefore define a function of hardness:

$$f(h) = Ln(.5) \cdot LR^2 \tag{8}$$

such that ECMP becomes:

$$ECMP = \frac{Ln(1 - r + r \cdot e^{f(h) \cdot CMP})}{f(h)} \tag{9}$$

In short, ECMP will vary with the hardness of the target, and thus is not as general (in this sense) as CMP is.

Appendix D
A MIRV PAYLOAD MODEL

To estimate the impact of MIRVing on warhead yield for the SS-18, Bennett (1980a)[1] has used the equation:

$$TY = 25 \cdot (.9)^{m-1}$$

where TY is the total yield (megatonnage) carried by the SS-18, and m is the number of warheads deployed. This equation indicates that the addition of a warhead decreases total yield by 10 percent, presumably by increasing the required weight in the warhead bus, in fuel to deploy the warheads, and in fuzes and other essentials associated with each warhead. More generally, this equation can be expressed as:

$$TY = TY_1 \cdot b^{m-1}$$

where TY_1 is the warhead yield for one warhead, and b is the percentage of retained weight on the margin. To develop a relationship between throwweight and MIRV warhead yield, then, it is only necessary to estimate TY_1 and b in terms of throwweight.

While there is relatively little information available to help make such an estimate, Foster (1978) does contain two relatively complete MIRV tradeoff curves, including the throwweight of each missile. These data are first used to estimate TY_1 and then b. With only two points it is impossible to determine the best functional form for TY_1 in terms of throwweight. However, as indicated in the text, there is evidence that EMT and throwweight (TW, in thousands of

[1]Footnote, p. 69. This equation was derived by noting that in the 1980s an SS-18 with 1 warhead would have a 25 MT yield, whereas an SS-18 with 8 warheads of 1.5 MT each would have only a 12 MT total yield.

Table 5

MINUTEMAN SQUADRON COMMAND AND CONTROL NETWORK SURVIVABILITY

Individual LCC Survival Probability (%)	Probability of the Survival of:		
	No LCCs	1 LCC	2 or More LCCs
1.0	95.1	4.8	0.1
2.0	90.4	9.2	0.4
5.0	77.4	20.4	2.2
10.0	59.0	32.8	8.2
13.1	49.6	37.3	13.1
20.0	32.8	41.0	26.2
30.0	16.8	36.0	47.2
50.0	3.1	15.6	81.3

OTHER MILITARY TARGETS

There are various other military targets, the vulnerability of which depends on their size, mobility, and "hardness." In general, many of these targets are associated with "soft," relatively small, and immobile military bases that can be destroyed by a single nuclear warhead. Damage to these targets is determined by the number of warheads that can be delivered against them.

This type of formulation has some obvious difficulties. If the military capabilities themselves are either mobile or capable of dispersing on warning, destruction of the fixed facilities associated with a military capability may have very little effect on the capability itself (at least in the short run). Further, many military facilities are quite large and more than a single warhead might be required to cover the entire target. If these facilities are hardened, damage must be assessed as for ICBM silos, above. Also, because the attacker will not know which warheads will arrive, he may be forced to assign more than one warhead to each target to ensure that at least one arrives. Some other military targets may be so close to each other that more than one can be destroyed by a single warhead.

$$Y = \frac{TY}{n}$$

Table D-1 illustrates these values for the two throwweights given in Foster.

Table D-1

EXEMPLARY RELATIONSHIP OF WARHEAD YIELD TO MIRV LEVEL AND THROWWEIGHT

Number of MIRVs	TW = 2500 lb		TW = 7000 lb	
	TY	Warhead Yield (MT)	TY	Warhead Yield (MT)
1	2.0	2.0	9.3	9.3
2	1.52	.76	8.1	4.0
3	1.17	.39	7.1	2.4
4	.90	.23	6.2	1.5
5	.69	.14	5.4	1.1
6	.53	.09	4.7	.78
7	.41	.06	4.1	.59
8	.32	.04	3.6	.45
9	.24	.027	3.1	.35
10	.19	.019	2.7	.27

Naturally, the values developed in this model are at best approximate and reflect the level of warhead technology and other MIRV data given in Foster. However, the model does fit those data relatively well, and could probably be modified somewhat to reflect other levels of technology or other factors.

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