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The Uncertainties of a Preemptive Nuclear Attack

It is said that the U.S. needs new land-based missiles because its present ones are vulnerable to attack. Analysis of uncertainties in such an attack suggests that the vulnerability is exaggerated

by Matthew Bunn and Kosta Tsipis

The deterrence of nuclear war requires that nuclear forces not be vulnerable to a preemptive attack. For decades strategic planners in both the U.S. and the U.S.S.R. have been concerned about the possibility of a disarming nuclear first strike, which would leave the victim of the strike unable to retaliate in kind. Each nation has expended large resources on efforts to maintain the survivability of its strategic nuclear forces.

Concerns over the vulnerability of land-based nuclear forces were heightened by the development of multiple independently targetable reentry vehicles (MIRV's) in the late 1960's. This technology, tested initially by the U.S., makes it possible for one missile to carry several warheads, each warhead capable of striking a separate target. Thus each MIRVed missile might be able to strike several of the opponent's missiles, each of which might itself contain several warheads, giving the attacker a double advantage.

As a result the evolution of Russian MIRV technology generated fears that once the U.S.S.R. had developed MIRV's with the appropriate combination of accuracy, yield and reliability it would have the ability to destroy most of the U.S. land-based missile force in a first strike, using a fraction of its available weapons. Although land-based missiles constitute only a fourth of the U.S. strategic nuclear forces, with the rest represented by submarine-launched ballistic missiles (SLBM's) and bombers, concern has arisen that the vulnerability of the ICBM component of the strategic "triad" alone would present the U.S. with a grave problem of national security.

In the fall of 1977 the worst fears of U.S. strategic planners were realized. The U.S.S.R. began a series of tests of a new guidance system with greatly improved accuracy. Simplified calculations indicated that once the U.S.S.R. had deployed an adequate number of these more accurate MIRV's it would indeed have the ability to destroy the bulk of the U.S. land-based missile force in a first strike. Thus was born what has come to be called "the window of vulnerability." This concept has dominated American strategic thinking for some years, providing the primary justification for the development of a new generation of U.S. strategic weapons, including the MX and Trident II missiles.

Simplified calculations do not, however, do justice to the substantial uncertainties inherent in any assessment of the results of a countersilo attack. Intelligence information is rarely absolute, and when strategic planners are confronted with uncertainty about the actual value of such parameters as the accuracy of the other side's ICBM's, they must make assumptions that are conservative from the defender's point of view. Unfortunately the process often obscures the fact that any attack would also involve substantial uncertainty from the attacker's point of view.

Because of the immense destructive power of modern nuclear arsenals, any nuclear first strike would represent a gamble on a scale absolutely unprecedented in human history; the future of entire civilizations would hang in the balance. As a result of the magnitude of the stakes any uncertainty about the outcome of such an attack will act as a powerful deterrent; such gambles are not taken without extremely high confidence in the outcome. The question for anyone considering how to plan the attack will always be not only "What is the expected outcome?" but also "What is the worst plausible outcome?" Therefore in assessing the possibility of an attack it is crucial to gauge quantitatively the uncertainties involved, in order to develop an assessment that is "attack-conservative." In U.S. assessments of the strategic balance this is rarely done. What is generally presented to Congress and the public are the results of an idealized, nearly flawless attack; the uncertainties inherent in the attack are often ignored. In this article we shall be offering a corrective.

The silos in which modern ICBM's are housed are underground concrete structures, "hardened" to withstand the effects of nuclear blasts. There is a wide range of nuclear effects that might damage an ICBM within such a silo, but spokesmen for the U.S. Air Force have indicated that U.S. ICBM silos are generally most vulnerable to the shock wave of the nuclear blast. Thus the hardness of a given silo is usually expressed in terms of the shock-wave overpressure required to destroy it, measured in pounds per square inch (p.s.i.).

The silos currently housing the 1,000 U.S. Minuteman ICBM's are generally estimated to be capable of withstanding overpressures of up to 2,000 p.s.i. The detonation of a half-megaton weapon, such as those carried by the most accu-

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rate Russian MIRV's, would create such overpressures at ranges of roughly 300 meters; therefore to destroy a Minuteman ICBM a half-megaton weapon would have to be detonated within 300 meters of the silo. Thus the accuracy with which the weapon is delivered, although it is not particularly important in an attack on a city, would be of decisive importance in any attack on hardened targets such as ICBM silos.

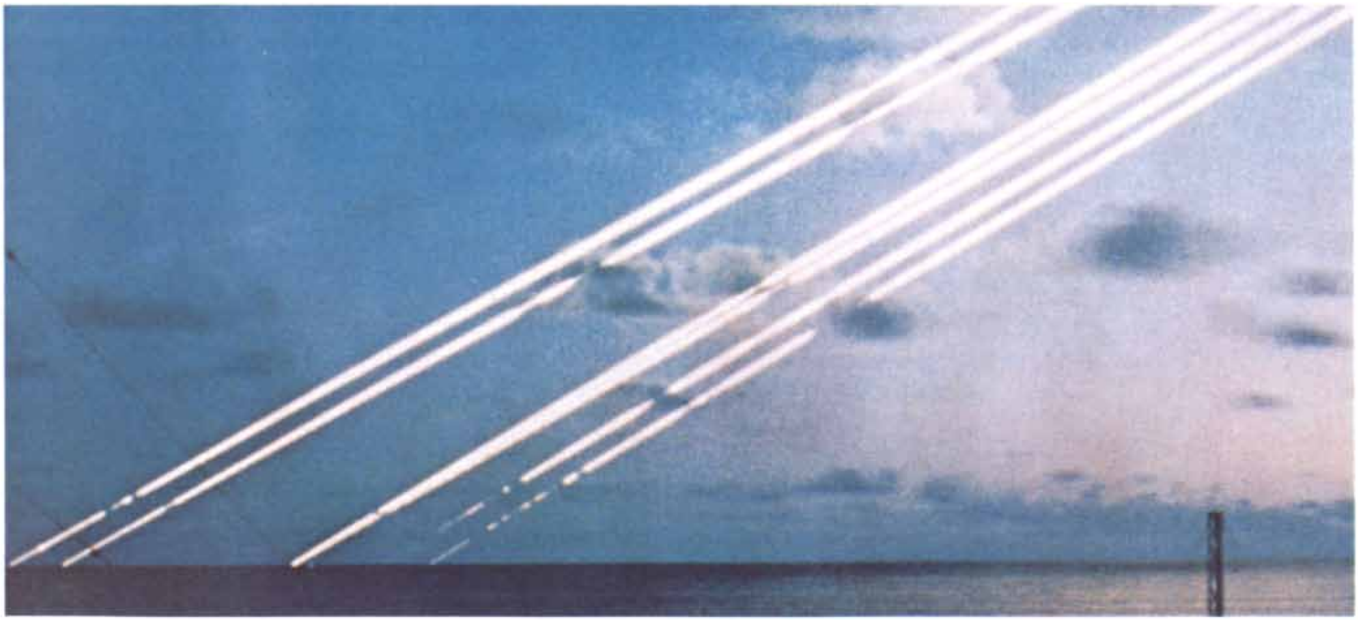
The ICBM's with which such weapons are delivered have three major parts: a rocket, which may have several separate stages; the payload, which consists of one or more reentry vehicles (RV's) armed with thermonuclear warheads, and the guidance system, which directs the rocket thrust in order to place each RV on the appropriate trajectory for it to reach its intended target. When such a missile is launched, the main rocket fires for only the first three to five minutes of the flight. Over the next few minutes a smaller rocket known as the postboost vehicle provides the final trajectory adjustments necessary to set each RV on the path to its intended target. The RV's are then released and fall freely in the earth's gravity field, unpowered and unguided. At the end of a half-hour flight the RV's reenter the atmosphere and detonate over their targets. The missile's flight can therefore be divided into three phases: the boost phase, free flight and reentry.

To deliver the RV's within several hundred meters of their targets over ranges of 10,000 kilometers calls for a highly sophisticated guidance system. Current strategic weapons rely on the technique known as inertial guidance, in which gyroscopes and accelerometers are used to measure the specific forces acting on the missile. These inertial instruments cannot, however, measure the force of gravity, because of the equivalence of gravitation and acceleration described by Albert Einstein: an accelerometer in a free-falling elevator would register zero, even though the elevator would be accelerating toward the ground under the influence of gravity. Therefore in order to account for the effects of the earth's gravitational pull on the motion of the missile a mathematical model of the gravity field as a function of position must be programmed into the missile's guidance system prior to launching. By combining the gravity model with the measurements of the specific forces made by the accelerometers, the guidance computer can use Newton's laws of inertia to calculate the motion of the missile in three dimensions and put it on the appropriate trajectory to its target.

The accuracy of such a weapon can be affected by errors from many sources. The two main sources are errors in the inertial-guidance system and errors associated with reentry into the atmosphere; in some current ICBM's the deviation from the target resulting from either of these sources is 100 meters or more. The errors in the guidance system originate with imperfections in the gyroscopes or the accelerometers; they can be either constant, accumulating with time, or random, arising from vibration, shock or changes in acceleration. The errors associated with reentry originate with unpredictable atmospheric variations over the target, such as winds and variations in atmospheric density, and with uncertainties in the ablation of the RV's nose cone. Because the RV from an ICBM reenters the atmosphere at a speed of some 7,000 meters per second, the nose cone will begin to burn away as the RV passes through the atmosphere; this ablation tends to occur in a rather unpredictable and asymmetric manner, giving rise to aerodynamic instabilities that degrade the accuracy of the RV. Moreover, severe weather effects, such as heavy rain or snow, can cause drastic increases in the rate of ablation, further reducing the accuracy of the RV.

Lesser sources of error include errors in the gravitational model relied on by the inertial-guidance system, errors in war head fusing and errors in the determination of the position of the target. Each type of error can contribute several tens of meters to the system's overall "error budget." The determination of the initial position and velocity of the launcher is extremely important in systems fired from mobile platforms, such as SLBM's, but is negligible for silo-based ICBM's; indeed, this type of error is one of the reasons current SLBM's are considered to be too inaccurate to strike at hardened missile silos.

The bulk of the error sources of a ballistic missile will be random from one missile to the next. As a result if a large number of such weapons were fired at a single target, they would tend to fall in a random scatter around the target. The spread of the scatter is measured by the parameter known as the cir-



COUNTERFORCE TARGETING PATTERN is suggested by this photograph of six unarmed Mark 12 reentry vehicles streaking toward their targets on Kwajalein atoll in the western Pacific. The reentry vehicles were originally mounted on two Minuteman III intercontinental ballistic missiles (ICBM's), launched in an operational test from Vandenberg Air Force Base in California. The reentry pattern is typical of a countersilo attack in which two thermonuclear warheads from different missiles are directed toward each hardened target.

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cular error probable (CEP): the radius of a circle centered on the average point of impact within which 50 percent of the RV's would fall. Thus the CEP is a measure of the precision with which a given missile delivers its payload.

With estimates of the CEP, the explosive yield and the reliability of a given weapon it is possible to calculate the probability of the weapon's destroying a target of a given hardness. As an example, the Russian missile designated SS-19 Mod (for modification) 3 is estimated to have a CEP of 250 meters, and each of its six warheads has a yield of approximately 550 kilotons. The SS-18 Mod 4 has a similar accuracy and warheads with a similar yield, but it carries 10 independently targetable warheads. Assuming perfect reliability, warheads of this type would have a 63 percent probability of destroying a Minuteman silo hardened to 2,000 p.s.i. Assuming statistical independence, two such weapons would have an 86 percent probability of destroying the same silo. This calculation would indicate that with 2,000 warheads the U.S.S.R. could destroy nearly 90 percent of the 1,000 U.S. Minuteman missiles in their silos. This is the kind of alarming theoretical result that has been given wide circulation.

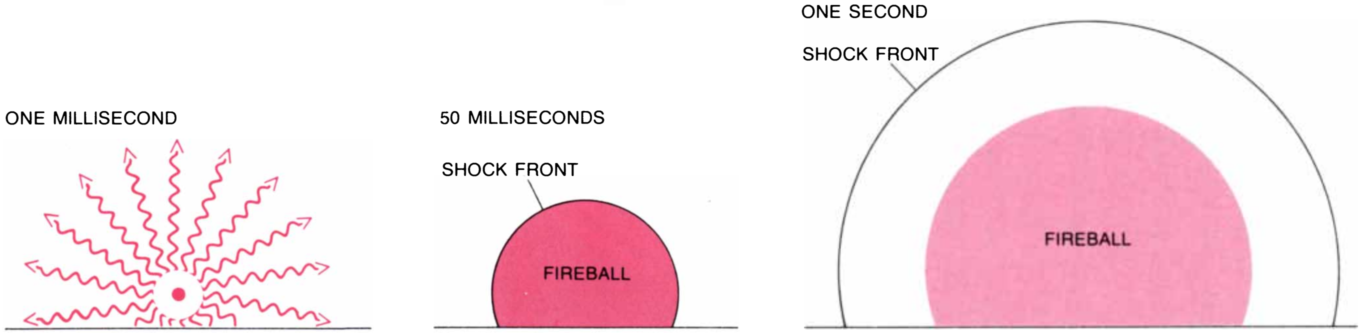
It is unreasonable to expect, however, that a system as complex as a modern ICBM will have a reliability close to 100 percent; a more plausible estimate for the reliability of current Russian ICBM's is 75 percent. Such a reliability would reduce the two-warhead kill probability to 72 percent, which agrees well with the 70-to-75 percent figure currently cited by the U.S. Joint Chiefs of Staff.

Even this figure does not take into account the broad range of uncertainties that must be considered in calculating the possible outcomes of any counter-silo attack. The planner of any such attack will always face further uncertainty about the actual accuracy, reliability and yield of his weapons under operational conditions, and about the hardness of his opponent's silos as well. Several less well known factors, such as interference among the weapons used in the attack, known as "fratricide," will also have significant effects on the outcome. As we shall show, these uncertainties would make it impossible for Russian leaders to have reasonable confidence in destroying significantly more than half of the U.S. land-based missile force, given the current capabilities of Russian ICBM's.

Let us first return to the leading source of uncertainty: the accuracy of the attacking weapons. As we mentioned in passing, the bulk of the errors in an ICBM system will be statistically uncorrelated from one missile to another, contributing to the random distribution described by the CEP. As with most other complex electromechanical systems, however, ICBM's show not only random errors but also systematic ones. Therefore whereas the standard calculations of ICBM vulnerability assume that the center of the impact distribution will be directly on the target, the actual distribution will often be offset somewhat. This distance between the target and the average point of impact is referred to as the bias. For example, if the estimated position of a given target is 20 meters south of its actual position, it is likely that the position of other targets in the same general area, such as other silos in the same missile field, will be similarly misestimated; thus on the average the RV's attacking that field will land 20 meters south of their intended targets. Similarly, the gravitational errors for ICBM's launched from silos close together in the attacker's territory will be strongly correlated, as will the errors due to prevailing winds and atmospheric density variations encountered by RV's reentering the atmosphere over the same area in the defender's territory. On the other hand, it should be possible to remove the most significant biases in the guidance system itself through peacetime testing and analysis.

Any bias smaller than roughly 100 meters has essentially no effect on the success of an attack against silos hardened to 2,000 p.s.i. The reason is that any weapon falling within three times that distance of the target will destroy it. Because of the nature of the bias, however, it will be difficult to place limits on the magnitudes of the bias that might be encountered in an actual attack, owing to the statistical properties of large numbers. If an error is simply random from one warhead to the next, then an attack involving 2,000 warheads would provide 2,000 independent trials for that variable; as with 2,000 rolls of a die, the probability of any significant variation from the average outcome is quite small. On the other hand, if an error is completely correlated over some fraction of the force, then for that fraction the attack provides only a single trial. Just as a roll of two dice might well turn up a two or a 12, rather than the more likely value of seven, so biases significantly larger than 100 meters in a single missile attack cannot realistically be discounted.

There is also some uncertainty about the estimate of the CEP for any given ICBM. A variety of sources of information are available on the accuracy of a given weapon. For example, nondestructive tests on the ground can provide



EARLY EFFECTS of the low-level atmospheric explosion of a 550-kiloton nuclear weapon are represented in the sequence of drawings on these two pages. Both the size of the explosive device and the height of its detonation are assumed to be appropriate for an ICBM attack on U.S. Minuteman silos. In the first millisecond after the warhead is detonated the temperature of the nascent fireball is approximately 400,000 degrees Celsius and the overpressure (the increment above ambient air pressure) is on the order of 100,000 pounds per square inch. Radiation (primarily neutrons and gamma rays) that can destroy a nuclear warhead extends outward to a distance of 800 meters from the point of detonation. After 50 milliseconds the radius of the rapidly expanding fireball has grown to about 500 meters and the temperature inside the fireball has fallen to approximately 75,000 degrees C. The overpressure at the shock front (which at this stage is coincident with the surface of the fireball) is 600 p.s.i. and the wind at the perimeter is blowing outward at several thousand kilometers per hour. After one second the fireball has a radius of 900 meters, an internal temperature of 10,000 degrees C. and a surface temperature of 6,000 degrees. The shock front is now expanding faster than the fireball and has reached a radius of 1,400 meters; at that distance

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detailed performance specifications for every component of the guidance system, which can be combined to yield rough estimates of the overall accuracy of the system. The fact remains that many significant sources of error, such as errors attributable to reentry, cannot be realistically tested on the ground. In addition the interaction of the various components of the guidance system in the demanding vibration, shock and acceleration environment of a rocket boost is extremely complex. Hence only a statistically significant number of realistic full-system flight tests can give accurate estimates of the CEP of a ballistic missile.

Such tests are typically divided into two major categories: (1) research-and-

the overpressure is 40 p.s.i. and the wind is roughly 1,200 kilometers per hour. After 10 seconds the fireball has attained its maximum radius of about one kilometer and has begun to rise. The surface temperature of the fireball is approximately 2,000 degrees C. and the radius of the shock front is about five kilometers. (It is visible only at the top of this frame.) The overpressure at the shock front is about 5 p.s.i. Vertical winds at a speed of about 600 kilometers per hour are beginning to suck dust and other debris from the ground into the stem of the ascending cloud. After one minute the characteristic mushroom-shaped cloud has grown to a radius of 2.5 kilometers and its center has reached an altitude of 6.5 kilometers. The fireball has ceased to radiate at visible wavelengths. Vertical winds at several hundred kilometers per hour continue to hold large particles aloft in the cloud and cloud stem. A second-wave reentry vehicle entering the immediate vicinity at any of these early stages stands a good chance of being destroyed by nuclear or thermal radiation, winds or collisions with the larger particles raised by the detonation of a first-wave warhead. Even at later stages smaller particles raised by the first-wave warheads may affect the second-wave warheads (*see illustration on next two pages*). These destructive effects have been termed "fratricide."

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development tests, which serve to suggest design changes and to provide initial information about the accuracy the missile can attain, and (2) operational tests, which provide estimates of the accuracy and reliability of the deployed force. Because a single ballistic missile often costs in excess of $10 million, flight-test programs are generally limited by budget constraints. As a result both the U.S. and the U.S.S.R. have tended to perform a comparatively small number of flight tests of each missile system, with intensive engineering analysis of each test. For example, in the initial stages of deployment a U.S. ICBM is typically subjected to between 25 and 30 flight tests, which yield the primary estimate of the system's operational accuracy and reliability. These are followed by from five to 10 operational tests in each year of the system's life cycle, to monitor any changes that might result from prolonged storage.

The operational flight tests of the U.S. are designed to ensure that the tests are as realistic as possible. The ICBM's to be tested are chosen randomly from the operational force. The chosen missile is then brought to alert in its silo, ready for immediate firing; this is intended to provide a test of the crew and the launch-silo electronics. If the missile fails to come to alert, it is listed as a failure and is not tested further. If it passes the test, the missile is removed from its operational silo and is sent to the test range at Vandenberg Air Force Base in California. The RV's are sent to a special facility where the thermonuclear warheads are removed and replaced with telemetry equipment. The missile with the modified RV's is then fired from the test silo at Vandenberg by a crew randomly selected from the operational missile crews, and the RV's reenter the atmosphere over Kwajalein atoll in the Pacific.

Telemetry equipment on board the missile broadcasts detailed information about such parameters as the flow of fuel, the thrust of the rocket, the performance of the guidance components and the vibration and shocks to which the missile is subjected. This information is picked up by U.S. stations monitoring the tests and by Russian intelligence ships stationed in the Pacific for that purpose. In addition the flight is carefully monitored by radars and optical telescopes based at Vandenberg and on Kwajalein. The information is then intensively analyzed over a period of several months. As a result far more information is generated by a flight test than simply whether or not the missile worked and how far from the intended target it landed.

Significant uncertainties nonetheless persist. First, the number of full-system flight tests is statistically quite small. Second, in spite of efforts to achieve the greatest possible verisimilitude such peacetime testing is still appreciably different from wartime operations. For example, American test vehicles reenter over Kwajalein lagoon, an area where atmospheric conditions are among the placidest in the world. In addition, since the gravity field of the earth varies from place to place, tests over one trajectory cannot in themselves provide estimates of possible gravitational errors over other trajectories.

Perhaps more significant, the range over which most Russian missiles are tested is 6,500 kilometers long, whereas many wartime trajectories would be nearly 10,000 kilometers long. Although the Russians do perform several full-range flight tests in assessing each of their ICBM systems, most of their tests are over the shorter distance. This difference in range has a marked effect on virtually every source of error in the system. Although adjustments to the resulting accuracy estimates can be made, based on a detailed mathematical model of the performance of the system, additional uncertainty will inevitably result. Given these factors, it cannot by any means be ruled out that the CEP in a large-scale countersilo strike could be 10 percent larger (that is, poorer) than the CEP estimated from shots over test ranges; indeed, we believe this is a conservative estimate. For the warheads we have been considering, an unfavorable variation of 10 percent in the CEP alone would reduce the two-shot kill probability against a Minuteman silo from 72 to 66 percent.

Uncertainties in the reliability of an ICBM are separate from uncertainties in its accuracy. Simulations on the ground are considerably more useful for estimating rates of failure than for assessing the accuracy of the weapon system. For example, U.S. Minuteman guidance systems are regularly given simulated flight tests, in which the guidance system is subjected to vibrations and shocks similar to those of a missile flight. As with any sensitive and complex technical system, however, high confidence in estimates of overall reliability can be achieved only through full-system tests, and the number of such tests is quite limited. In addition estimates of the overall operational reliability of ICBM's must take into consideration a broad range of human factors that would be involved in an attack: any large-scale countersilo strike would call for the timely cooperation of several hundred people, whose behavior under such circumstances is unpredictable. Thus 10 percent is probably a conservative estimate of the uncertainty in estimates of overall reliability. Again, an unfavorable variation of 10 percent in the reliability we have assumed for an SS-19 Mod 3 would reduce the number of Minuteman silos destroyed in a hypothetical two-on-one attack from 72 to 67 percent.

Estimates of the explosive power of the thermonuclear warheads have un-

MUSHROOM CLOUDS arising from the simultaneous low-level explosion of several 550-kiloton nuclear warheads are shown at two stages: one minute after detonation (*left*) and 10 minutes after (*right*). The explosions were spaced eight kilometers apart, which is roughly the average spacing between missile silos in a Minuteman field. After 10 minutes the individual clouds have merged into one large cloud approximately eight kilometers thick; the top of the cloud has stabilized at a height of about 18 kilometers. Several second-wave reen-

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certainties of their own. This uncertainty is of two interrelated kinds: first, uncertainty about the precise effects of warheads of given yield, and second, uncertainty in the estimates of the yield of a given class of warheads. The peacetime testing of nuclear explosives is limited by considerations of cost, safety, environmental impact, instrumentation and politics. Not least, it is also limited by treaty, including the Limited Test Ban Treaty of 1963 and the still unratified Threshold Test Ban Treaty.

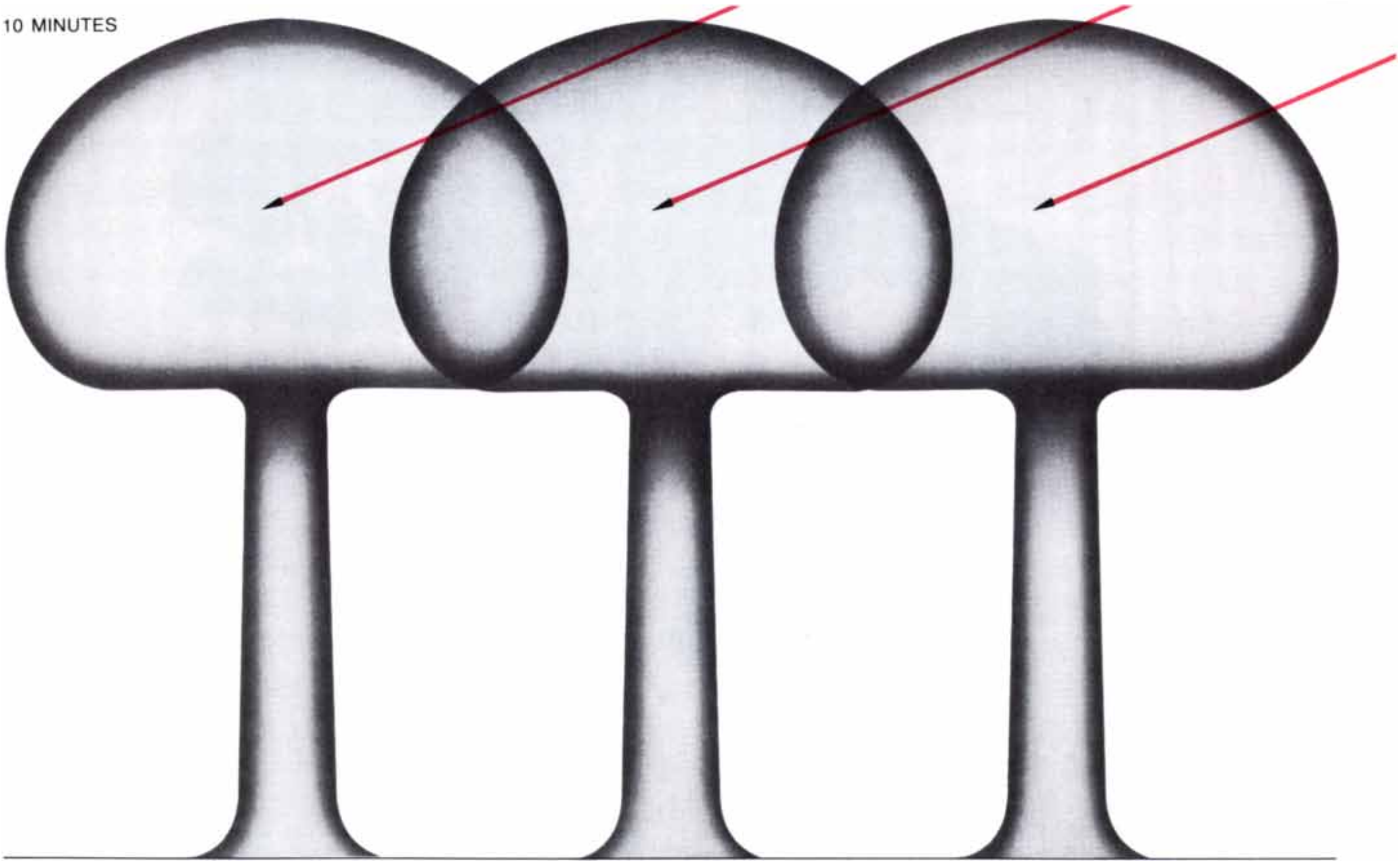
The measurement of overpressures in the extreme range necessary to destroy a modern ICBM silo has been particularly limited, because of instrumental problems and the lack of pressing need. By the early 1960's, when the last American and Russian nuclear tests in the atmosphere were conducted, the hardest targets of interest were roughly an order of magnitude "softer" than current missile silos. As a result there is little in the way of nuclear-test data for overpressures higher than 200 p.s.i., and even less for overpressures higher than 500 p.s.i. The nuclear-test data that do exist for these high overpressures show an enormous degree of scatter, and they often do not agree well with theoretical predictions. Although additional data are available from tests with chemical explosives, large uncertainties are involved in extrapolating such data to predictions of the effects of megaton-range nuclear weapons. The U.S. Defense Intelligence Agency has stated that U.S. estimates of the overpressures to be expected from nuclear explosions in given ranges are uncertain to plus or minus 20 percent.

The second uncertainty in estimating the explosive power of thermonuclear warheads, the uncertainty in estimating the average yield of a given class of warheads, arises from similar sources: the number of tests of any given nuclear weapon is small, and there are substantial instrumental difficulties in measuring the energy yielded by an underground nuclear-test explosion.

The yield to be expected from a given warhead design can be estimated theoretically, but an example of the pitfalls of this approach is provided by the warhead developed for the Mark 12A reentry vehicle recently deployed on the U.S. Minuteman III missiles. The first three tests of the weapon revealed that its yield was considerably less than had been predicted, and the original design had to be modified until, in a fourth test, the weapon achieved its full yield. Although this may be an extreme case, the uncertainty in the average yield of a given class of warheads will be at least 10 percent.

For the sake of simplicity we shall combine the two types of uncertainty in the explosive power of a warhead, describing them both as variations in effective yield. Since the peak overpressure is roughly proportional to the explosive yield, a 20 percent variation in overpressure would result from a 20 percent variation in explosive yield; a conservative estimate of the total uncertainty in the effective yield of a given weapon might then be on the order of 25 percent. An unfavorable variation of 25 percent in the yield of the weapons involved would reduce the effectiveness of the hypothetical attack we have described from 72 to 66 percent.

Although the accuracy, reliability and yield of ICBM's are uncertain, they are at least subject to peacetime testing by a nation that might be considering an attack. This does not hold for the hardness of the silos to be attacked. The overpressure at which a silo will fail depends primarily on the technical characteristics of the reinforced-concrete door at the top of the silo, and it is extremely difficult to obtain reliable intelligence on these characteristics. Indeed, from an attacker's point of view this may well be the largest uncertainty of all. Even U.S.



try vehicles aimed at more-distant targets are shown traversing the cloud blanket. High-speed collisions with comparatively small particles in the clouds could have catastrophic fratricidal effects on the second-wave reentry vehicles, severely degrading their accuracy and perhaps even destroying them. ICBM's that survived the first-wave attack could be safely launched through the cloud cover before the second wave of incoming warheads could safely enter the target area. Hence the attacker might succeed only in destroying empty silos.

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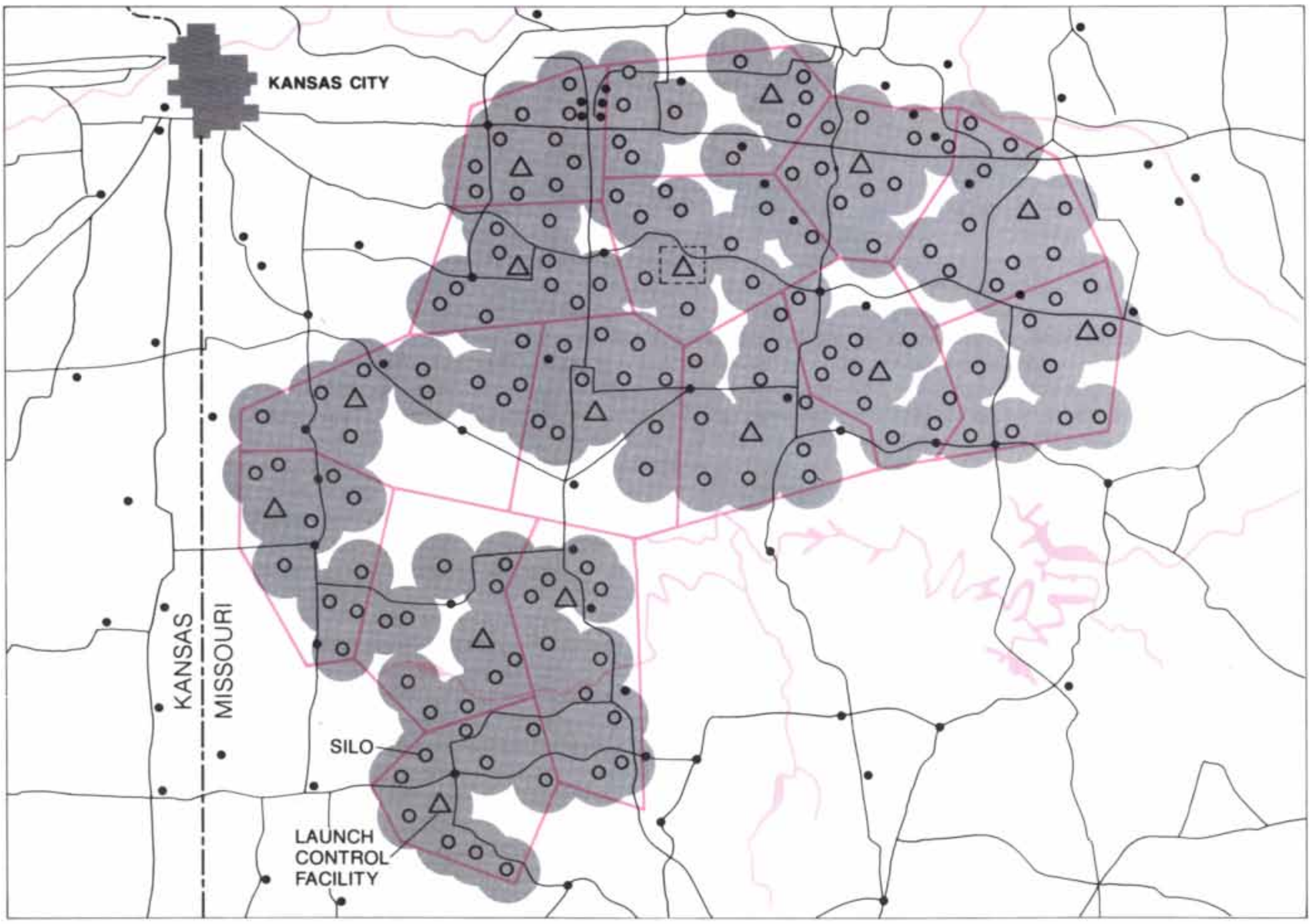
estimates of the hardness of U.S. silos include significant uncertainties; the fact is that no silo has ever been exposed to a nuclear weapon in any test. Estimates of silo hardness are based entirely on theoretical structural considerations and tests of scale models with chemical explosives. Thus from an attacker's point of view the uncertainty in the hardness of the silos to be attacked is likely to be at least 20 percent, if not considerably more. If the silos under attack were capable of withstanding overpressures 20 percent higher than expected, the effectiveness of the hypothetical attack we have been describing would be reduced from 72 to 68 percent.

Another significant uncertainty arises from the interference among the hundreds of warheads that would be involved in an attack. Up to this point we have been assuming that the warheads involved in a countersilo attack would be statistically independent of one another, in other words, that the detonation of one warhead would have no effect on other warheads participating in the attack. This is not at all the case: thermonuclear explosions can have extremely destructive effects on other reentry vehicles, constituting the phenomenon ironically termed fratricide.

In its first milliseconds a thermonuclear explosion gives off an intense burst of radiation, including neutrons, X rays and gamma rays, which in turn generate a powerful electromagnetic pulse. This short-lived burst of radiation is followed by the rapid expansion of a fireball of hot, compressed gases. The fireball expands faster than the speed of sound, reaching a radius of several hundred meters in less than a second. Since the superheated gases in its interior are orders of magnitude less dense than the surrounding air, the fireball begins to rise quite rapidly, much like a hot-air balloon. This creates a vertical wind of several hundred kilometers per hour; indeed, the drag of the wind created by a half-megaton explosion is sufficient to hold aloft a two-ton boulder. In the case of a weapons burst at the optimum height for an attack on a silo hardened to 2,000 p.s.i. the fireball will be in contact with the ground for several seconds; as a result the powerful updraft winds will suck up thousands of tons of dust and other debris, creating the characteristic mushroom cloud.

The cloud rises at high speed; within a minute it reaches an altitude of several kilometers. It then slows down, reaching its maximum height some 10 minutes after the detonation. In the case of a half-megaton weapon the top of the cloud will stabilize at an altitude of some 18 kilometers, with the bottom of the cloud roughly eight kilometers below. By 10 minutes after the detonation the cloud will have covered an area of some 100 kilometers; indeed, the cloud from such an explosion will be so large that in an attack on the ICBM silos in a U.S. Minuteman field the clouds from explosions over individual silos will merge into a single blanket of dust over the entire field.

The significance of the dust and other debris raised by the explosion arises



EXTENT OF CLOUD COVER that would be created by the explosion of the first wave of nuclear warheads in a hypothetical counterforce attack on the Minuteman field in the vicinity of Whiteman Air Force Base in Missouri is indicated on this map. By 10 minutes after the detonation of a 550-kiloton nuclear warhead over each of the 150 Minuteman silos and the 15 launch-control facilities in the target area the merged mushroom clouds would have essentially covered the entire field. If the first-wave warheads were detonated at ground level, the resulting cloud cover would contain millions of tons of dust and larger debris. Even at the greatest height possible for an effective attack on such hardened targets with 550-kiloton warheads, the interfering blanket of particles would still contain hundreds of thousands of tons of material sucked up by the rising fireballs. Population centers, main roads and major rivers are also represented.

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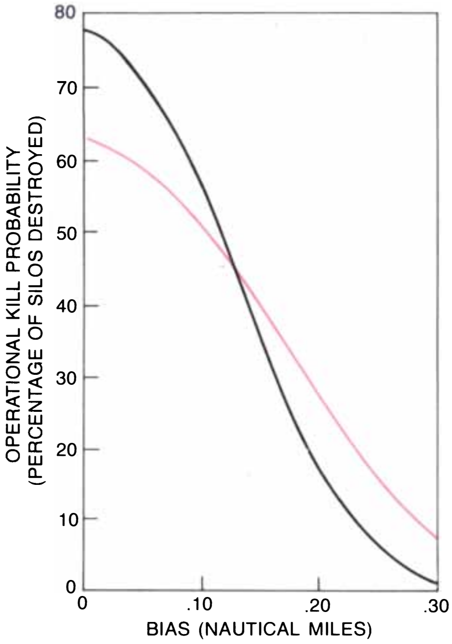
from the fact that reentry vehicles traverse the atmosphere at extremely high speed. When an RV reentering the atmosphere in the area of an earlier explosion encounters the cloud, it will be traveling some six kilometers per second. Therefore if the RV collided with a particle weighing several grams, it would probably be destroyed outright; such a collision would take place at several times the speed of a rifle bullet. The smaller particles and dust in the cloud could have catastrophically abrasive effects on an RV: the effect of such high-speed passage through the dust cloud would be equivalent to exposure to an extraordinarily powerful sandblaster. The resulting ablation of the RV's nose cone would severely degrade its accuracy; in extreme cases it could cause the RV to burn up. Moreover, the earlier explosion (or explosions) would have completely changed the density and wind profiles throughout the area in ways that are essentially unpredictable and would have drastic effects on the accuracy of reentering RV's.

Obviously the problem of fratricide would have to be carefully considered in planning the timing of any attack calling for more than one RV targeted on each silo. If two RV's were targeted on each silo simultaneously, and neither RV failed, then the radiation from the first warhead to explode would destroy the second. If the attack were organized in two waves separated by several seconds, the RV's of the second wave would encounter the fireballs, powerful winds and lethal particles raised by the explosions of the first wave. Although the high temperatures and the outward winds generated by the explosion would subside within the first few seconds, particles large enough to be lethal to an RV would take up to 20 minutes to fall back to the ground, and the clouds of smaller particles and dust would remain until they were dispersed by atmospheric winds. Therefore unless the attacker allowed at least several minutes between the first wave and the second, so that the largest particles would have fallen out of the cloud before the second wave arrived, it seems unlikely that any very large proportion of the second wave would get to its target and do so with the accuracy necessary to destroy it. Even if the attacker allowed several tens of minutes between the two waves, the second wave would still face the dust blanket and the severe atmospheric disturbances created by the explosion or explosions of the first wave.

Since fratricide has never been tested, its effect on incoming RV's cannot be assessed precisely; only the roughest order-of-magnitude estimates are possible. Suppose, in the case of a second wave reentering 10 minutes after the first wave, that passage through the dust cloud and encounters with large particles destroyed only 5 percent of the RV's, and that on the average the effect of the dust and atmospheric disturbances increased the fraction of the CEP attributable to reentry by a factor of two. This, in our view, is a quite conservative estimate of the fratricide such a wave would suffer, given the extreme conditions we have described. These effects alone would reduce the kill probability of a two-wave attack by SS-19 Mod 3 warheads on U.S. Minuteman silos from 72 to 65 percent.

Fratricide introduces an uncertainty that may be even more significant: if the attacker must allow several minutes to elapse between the first and the second wave of his attack, it is quite possible that the ICBM's surviving the first wave will have left their silos before the second wave arrives. Since an ICBM rising out of its silo travels much slower than an RV entering the atmosphere, the particles and dust in the cloud will have comparatively little effect on it. As a result the surviving ICBM's could be safely launched before the second wave of RV's could safely reenter the atmosphere. Although a nearby nuclear explosion that failed to destroy the silo might still keep an ICBM from getting off immediately, in those cases where the first-wave warhead failed the ICBM in its hardened silo would remain undamaged, still available for launching. In the attack scenario we have been considering, involving weapons with a reliability of 75 percent, this would mean that at a minimum 25 percent of the ICBM's could be launched between the first and the second wave of the attack. Combined with the fratricide effects postulated above, this would reduce the fraction of the ICBM silos destroyed in the hypothetical attack we have been considering to 56 percent. Since the vulnerability of an ICBM increases sharply when it leaves its protective silo, however, it is possible that the attacker could keep these weapons from being launched by detonating additional warheads over the silo field at regular intervals so that any ICBM launched from its protective silo would be destroyed; this tactic is called pindown.

Up to this point we have been considering the uncertainties of a countersilo attack on an individual basis. In any real countersilo attack, however, all these uncertainties would be present, making the final outcome of the attack even harder to predict. For example, if all the variables we have been describing were to turn out unfavorably for an attacker, even in the absence of significant bias only 45 percent of the U.S. Minuteman silos would be destroyed. Although it may be unlikely that an attack would be subject to large unfavorable variations in all the uncertain parameters simultaneously, it should be noted that an unfavorable variation in any two of the parameters, combined with fratricide, would reduce the effectiveness of the attack to less than 55 percent, even ignoring the possibilities of bias error and of ICBM's escaping between the two waves. Moreover, we believe the degrees of uncertainty we have postulated are conservative. Thus it would be difficult for a planner to have reasonable confidence that a two-wave attack by SS-19 Mod 3 and SS-18 Mod 4 warheads would destroy significantly more than half of the U.S. Minuteman force.



EFFECT OF BIAS on the operational kill probability of an incoming warhead in a hypothetical countersilo attack is shown in this graph for two ICBM reentry vehicles: a Russian SS-19 Mod 3 warhead (*colored curve*) and a U.S. Minuteman III Mark 12A warhead (*black curve*). (Bias is defined here as the distance from the target to the average point of impact of a random sample of warheads aimed at the target.) In both cases the warheads are assumed to have been fired at targets hardened to survive an overpressure of 2,000 p.s.i. In addition it is assumed that each system has a reliability of 100 percent, that the explosive yield of each warhead is 550 kilotons for the SS-19 and 335 kilotons for the Minuteman III and that the circular error probable is .14 nautical mile for the SS-19 and .1 nautical mile for the Minuteman III. (Circular error probable, or CEP, is defined as the radius of the circle within which half of the warheads aimed at the target will fall.) The important thing to note is that for both missiles a bias of less than about .05 nautical mile (roughly 100 meters) would have very little effect on the kill probability, but that a much larger bias could be quite significant.

It is possible that a planner would choose to launch more than two warheads against each silo, or to launch larger warheads. In the case of an attack

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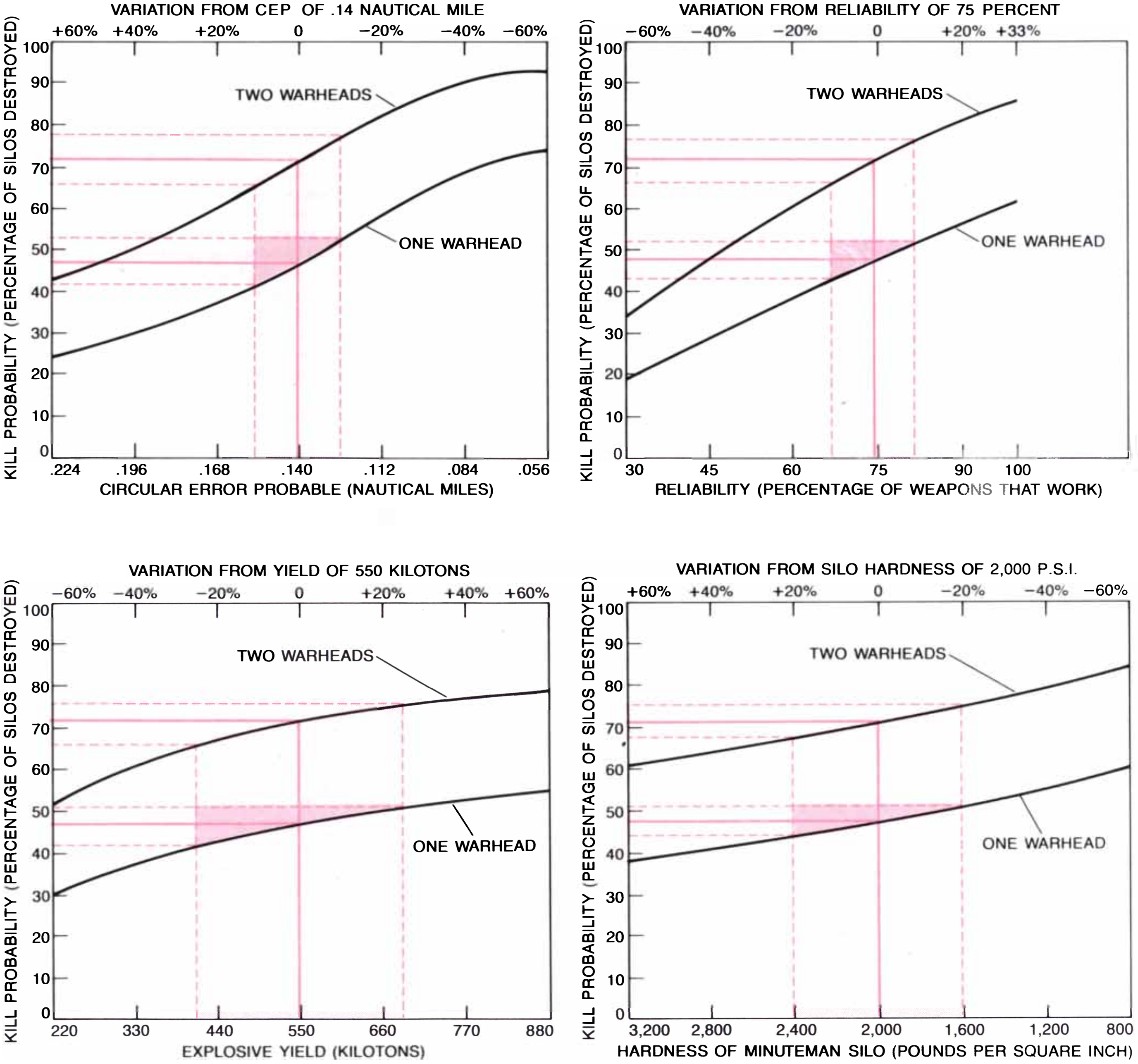
on the U.S. Minuteman force, however, neither of these options would be very attractive. For example, a third wave would encounter fratricide effects from both of the first two waves, and it would allow more time after the second wave during which the surviving ICBM's might be launched. Even if the surviving ICBM's did not escape, a third wave would only raise the overall percentage of the silos destroyed from 45 to 57 percent. Since the 1,000 U.S. Minuteman silos contain 2,100 warheads, this would mean an expenditure of 1,000 additional Russian warheads in order to destroy 250 American warheads; such an attack would disarm the U.S.S.R. faster than the U.S. In addition to its ICBM's armed with MIRV's the U.S.S.R. has 100 SS-19's and SS-18's armed with single large warheads; these, however, are clearly much too few for an attack on the 1,000 U.S. ICBM silos.

For a smaller number of more important targets neither of the two preceding arguments would apply. For example, if the U.S. were to deploy 100 MX ICBM's in Minuteman silos, as has been proposed by the Reagan Administration, the 100 Russian large-warhead missiles could be used to attack them. If these weapons were equipped with the accurate guidance systems now deployed on the MIRVed versions of the same missiles, an attack involving one such warhead on each MX silo, followed by a half-megaton warhead, would destroy 77 percent of the MX force, even allowing for unfavorable variations and fratricide. Since each MX carries 10 warheads, this would mean that even under less than ideal conditions 200 Russian warheads could destroy 770 MX warheads. The expenditure of additional Russian warheads would provide even higher operational kill probabilities.



EFFECT OF INDIVIDUAL VARIATIONS in each of four parameters—CEP, reliability, explosive yield and silo hardness—on the outcome of a hypothetical countersilo attack on the U.S. Minuteman force is projected in this set of graphs. In each case it is assumed that the attack is carried out with one or two waves of SS-19 Mod 3 or SS-18 Mod 4 warheads having a nominal CEP of .14 nautical mile, a nominal reliability of 75 percent and a nominal yield of 550 kilotons. The Minuteman silos are assigned a nominal hardness of 2,000 p.s.i. (Nominal values are indicated by solid-color lines.) The light-color bands show the effects on operational kill probability of a conservatively estimated uncertainty of 10 percent in both CEP and reliability, of 25 percent in explosive yield and of 20 percent in silo hardness.

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ASSUMPTIONS	BIAS (NAUTICAL MILES)			
	0	.05	.10	.15
100 PERCENT RELIABILITY	86%	84%	76%	63%
75 PERCENT RELIABILITY	72%	70%	62%	50%
LIGHT FRATRICIDE	65%	62%	56%	45%
UNFAVORABLE VARIATIONS	45%	43%	38%	31%

EFFECT OF COMBINED UNCERTAINTIES on the outcome of a countersilo attack is presented in this table. The columns correspond to four different projections of bias. The rows indicate the effects of different assumptions about the technical capabilities of the weapons employed in the attack (and, in one instance, of the hardness of the silos under attack). The first row shows the outcome in terms of operational kill probability of an ideal attack with perfectly reliable weapons on silos with no variation in hardness from the nominal value. The second row shows the results of a somewhat more realistic attack employing weapons with a nominal reliability of 75 percent. The third row shows the effect of a minimal amount of fratricide. The fourth row shows the outcome of an attack in which light fratricide is combined with unfavorable variations (for the attacker) in all the other parameters. In this case the accuracy and reliability turn out to be 10 percent less than the nominal values, the yield of the attacking weapons is 10 percent less and the silos under attack are 25 percent harder than predicted. Even in the absence of significant bias only 45 percent of the Minuteman silos would be destroyed.

Thus although the current Russian ICBM force could present a severe threat to a small number of particularly valuable targets, it could not provide a planner with reasonable confidence of destroying significantly more than half of the current U.S. ICBM force. The common practice of citing the probable result of such an attack to two significant figures, with no mention of the attending uncertainty, is grotesquely misleading; all that can realistically be said is that such an attack would *probably* result in the destruction of between 50 and 90 percent of the U.S. ICBM force. We conclude that the magnitude of the threat presented by the current generation of Russian ICBM's has been greatly exaggerated.

This comparatively comforting conclusion may not, however, remain valid indefinitely. Strategic-weapons technology is almost never in stasis, and foreseeable improvements in weapons-delivery systems could drastically alter the situation we have been describing. In the past the accuracy of American and Russian ICBM's has generally improved by roughly a factor of two every seven years; the improvement of strategic-weapons technology may slow somewhat as the room for improvement narrows, but there is little reason to expect that in coming years the pattern will be fundamentally different.

Hence sometime in the late 1980's or in the 1990's the U.S.S.R. may have deployed a force of ICBM's twice as accurate as its current weapons. In addition reentry vehicles specifically designed to penetrate dust clouds are currently under development in the U.S., and possibly in the U.S.S.R. as well. These technological changes could significantly reduce the effect of the uncertainties we have described. If the CEP of the SS-19 Mod 3 were reduced by a factor of two, for example, a two-on-one attack would result in the destruction of more than 80 percent of the U.S. Minuteman force, even allowing for a certain amount of fratricide and unfavorable variations in the attack parameters. In essence, an uncertainty of 10 or 20 percent no longer has a significant effect if the weapon is twice as accurate as it needs to be to destroy its target.

The purely technical uncertainties we have been describing, however, are only the tip of the iceberg. The planner of a real countersilo attack would have to consider a host of other uncertainties, mainly centering on the reaction of the nation under attack. For example, a nation with ICBM's has the option of adopting the policy of "launch on warning" or "launch under attack": launching missiles immediately on receiving intelligence that another nation has launched missiles against it. The U.S. has renounced such a policy, because of the possibility of catastrophic error, but it would be difficult for a planner to have any confidence that this policy would hold in the event of an attack. Nearly 30 minutes would pass between the first detection of a massive launch and the detonation of warheads over U.S. silos; the actions of U.S. policy makers in this period and afterward would be impossible to predict.

If in addition to the U.S. land-based ICBM's the rest of the U.S. strategic nuclear forces are taken into account, a serious problem would arise for the putative planner of an attack. First, the thousands of U.S. nuclear weapons in submarines at sea will be invulnerable to attack for as far into the future as it is possible to predict. Second, it would not be possible to destroy both the U.S. ICBM force and the U.S. strategic bomber force. Part of the bomber force is on a constant 15-minute alert, meaning that the only missiles that could destroy them before they got off the ground would be submarine-launched ones with short flight times. Current Russian SLBM's, however, are much too inaccurate to be effective against hardened silos, meaning that the silos would have to be attacked by ICBM's with longer flight times. If this were done, nuclear weapons would begin detonating over U.S. bomber fields more than 15 minutes before the RV's targeted on the ICBM silos could reach their targets, making it very likely that the ICBM's would be launched before the attacking RV's arrived.

Even if these difficulties could be surmounted, an attack involving more than 2,000 near-ground explosions of megaton-range nuclear weapons would cause between 20 and 40 million civilian casualties. Such an attack cannot realistically be described as "a surgical nuclear strike." It is impossible to believe the U.S. would not respond, relying on some fraction of the thousands of bomber and submarine-based warheads that would surely have survived. In all probability the conflict would quickly escalate to an all-out strategic exchange, which would destroy the attacker as completely as it would destroy the victim of the initial attack.

In the more distant future even these inherent uncertainties might be somewhat reduced by advances in technology. The development of accurate SLBM's, already under way in the U.S., will erode the relation between the alert bomber force and the ICBM force. If extremely accurate maneuvering reentry vehicles are deployed, hardened silos could be destroyed with weapons of much smaller yields, sharply reducing the number of civilian casualties such an attack would inflict. This might at first glance seem desirable, but the possibility of a genuinely "surgical" strike, combined with increased confidence in predictions of its outcome, would increase the temptation to launch such a strike, lowering the nuclear threshold and increasing the probability of nuclear war.

Thus although the current situation is stabler than is commonly believed, the progress of weapons technology bodes ill for the future. It is still possible, however, that stringent limitations on the testing and deployment of ballistic missiles could forestall many of these undesirable technological advances. Far from locking the U.S. into a position of vulnerability, such limitations, if they were effective, could prevent the rapid erosion in U.S. security that will otherwise occur in the years to come. Limitations on the testing and deployment of ballistic missiles could be an important component of arms-control efforts, and they deserve more careful study than they have had to date.

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