All You Ever Wanted To Know About MIRV and ICBM Calculations But Were Not Cleared To Ask

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This paper (1) explains the variables and methods used to calculate the MIRV threat to the fixed-site land-based ICBM forces of the United States and the Soviet Union; (2) attempts to reconstruct the calculations presented in the 1969 ABM debate by Albert Wohlstetter, George Rathjens, and John S. Foster about the number of Minutemen which could be expected to survive an attack by forces of various sizes and characteristics; and (3) applies these methods, together with some plausible assumptions about classified variables, to two other security issues: the import of the SALT limitation on the size of the Soviet SS-9 force and the character of the threat to the Soviet fixed-site ICBM force posed by the American MIRV program.

Introduction

Fixed-site hardened ICBMs are presently central to the deterrent posture of both superpowers. The United States has sought to deter a Soviet first strike by maintaining three different delivery systems (land-based missiles, sea-based missiles, and bombers) in sufficient strength that each would independently be capable of producing "assured destruction" in a second strike. The Soviet Union, which only recently began to build a large sea-based missile force, is perhaps even more dependent on ICBMs for deterrence.

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Recent technological improvements in the capabilities of the missile systems on both sides have, however, caused increasing concern about the prelaunch survivability of these land-based deterrent forces. Specifically, the advent of MIRV (Multiple Independently Targeted Reentry Vehicle) and improvements in the accuracies and reliabilities of missile systems now confront both superpowers with the prospect that a first strike could destroy 95% of their land-based ICBMs and thereby provide a possible incentive for the other side to strike first.

In the United States, the import of these technical developments for the second-strike capability of the American ICBM force has received considerable attention. How soon and under what circumstances the Soviet Union could have an SS-9 force that could destroy a very high percentage of the U.S. Minutemen was one of the central issues in the 1969 debate over the deployment of the Safequard ABM system to defend the land-based force. The question of whether the United States should continue to maintain a mixed strategic force also figured prominently in the review of U. S. strategic objectives undertaken by the Nixon Administration that same year.

Ultimately, the administration announced in the doctrine of sufficiency (Laird, 1973: 65-66) its determination to ensure the pre-launch survivability of the ICBM force as a hedge against future technological developments affecting the submarines or the bombers and to promote crisis stability by providing no incentive for the Soviet Union to strike first. To reduce the potential threat to Minuteman, the administration proceeded with the deployment of Safeguard and entered into negotiations with the Soviet Union to limit the number of Soviet offensive missiles, particularly the large SS-9.[1]

In May 1972, a bargain was finally struck with the signing of the SALT agreements (Survival, 1972: 192-199). The United States and the Soviet Union accepted restrictions on ABM deployment to eliminate the potential instabilities arising from citywide ABM defenses and, as a result, gave up one means of protecting the fixed-site land-based ICBM forces. Instead, the superpowers sought to relieve worries about the survivability

1. The U.S. proposal in August 1970 called for a common ceiling of 1,900 strategic launchers and a 250 limitation on the number of Soviet heavy ICBMs (Senate Committee on Armed Services, 1972: 297).

Wolfowitz, Albert Wohlstetter, and Ted Greenwood. The computational assistance of Jonathan Schilling is also gratefully acknowledged. None of these people, however, has any responsibility for the contents of this article or the calculations presented in it.

of these ICBMs by limiting the overall number of land-based and sea-based strategic launchers and placing a ceiling on the number of heavy Soviet missiles.

The failure of the SALT agreements, however, to control qualitative improvements on these missile systems has provoked renewed debate in the United States about the future of the land-based deterrent. During the congressional debate on SALT, Senator Henry Jackson vigorously attacked the administration for its lack of concern for the survivability of the Minuteman deterrent (Senate Committee on Armed Services, 1972).[2] The question of the future of the fixed-site land-based ICBM has, therefore, not been resolved. The SALT Phase II preparations and negotiations will undoubtedly be characterized by debate over the desirability of ensuring the pre-launch survivability of Minuteman and the most appropriate methods to achieve it.

The purpose of this paper is first to explain, to an interested but nonexpert audience, the variables and methods used to calculate the MIRV threat to the fixed-site land-based ICBM forces of the United States and the Soviet Union. Second, the paper attempts to reconstruct the calculations presented in the 1969 ABM debate by Professor Albert Wohlstetter of the University of Chicago, Professor George Rathjens of the Massachusetts Institute of Technology, and Dr. John S. Foster, Director of Defense Research and Engineering, Department of Defense, about the number of Minutemen which could be expected to survive an attack by SS-9 forces of various sizes and characteristics.[3] In addition to clarifying the methods and variables involved, the explication of these calculations provides an understanding of the technical conditions that will have to

2. The Jackson Amendment, passed by the Senate and concurred in by the House, states that if the survivability of the strategic deterrent forces of the United States were threatened by a failure to achieve a more complete agreement in the next five years, this could jeopardize the supreme national interests of the United States (Congressional Record, 1972: H8718).

3. The differences between Professors Rathjens and Wohlstetter were first joined in Hearings before the Senate Armed Services Committee and then continued in a series of letters to the New York *Times*. Professor Rathjens and two of his colleagues also issued a statement contesting the realism of the calculations advanced by Dr. Foster. The estimates made by these and other participants in the 1969 debate were later reviewed by a special committee appointed by the President of the Operations Research Society of America. The published report of this committee (Operations Research Society of America, 1971) contains the texts of the major statements and arguments involved and a highly instructive analysis of the calculations.

For a critical rejoinder to the ORSA Report, see Rathjens et al. (1971a). See also Rathjens et al. (1971b: 8273-18277).

prevail before the pre-launch survivability of the Minuteman force will be endangered. Third, the paper applies these methods, together with some plausible assumptions about classified variables, to two other security issues: the import of the SALT limitation on the size of the Soviet SS-9 force and the character of the threat to the Soviet fixed-site ICBM force posed by the American MIRV program.[4]

Finally, it is important to note the purposes that this paper does not have. There is no attempt to answer the question of how soon Soviet or American forces will have the capabilities assumed in these various calculations. While all these capabilities are technically possible, when, if ever, these capabilities will be achieved will turn on decisions still to be made by the two governments. Further, the paper does not address the desirability of the various alternatives the United States and the Soviet Union will confront if maintaining the pre-launch survivability of their present ICBM forces proves to be impossible.[5] While the calculations discussed in this paper can contribute to an understanding of the problems involved in some of these choices, the calculations do not in and of themselves point the way toward a choice of any one of them.

Variables, Formulae, Methods

The purpose of this section is to describe the variables, formulae, and methods that are used in the calculations discussed in the sections that follow.

SINGLE SHOT KILL PROBABILITY (SSKP)

The probability that a single, reliable warhead can be expected to destroy a given target is a function of the destructive effect of the warhead on the target and the accuracy of the warhead. The destructive effect of a warhead on a given target is expressed in terms of its Lethal Radius (LR): the distance from the point of the explosion that the warhead will be able to destroy the target. The accuracy of a warhead is expressed in terms of its Circular Error Probable (CEP): the radius of the circle centered on the target within which the warhead has a 50-50 chance of landing (Operations

4. Readers should know that the present writers had no prior experience with the analytical techniques described in this paper. The paper is the result of self-education on their part.

5. These issues are discussed at length in Schilling et al. (1973).

Research Society of America, 1971: 1187n).[6] If the distribution of shots in repeated firings is approximately circular normal, the formula for calculating SSKP (if CEP and LR are expressed in common terms–e.g., feet or nautical miles) is:[7]

$$SSKP = 1 - e^{-0.69315\left(\frac{LR}{CEP}\right)^2}$$

or

$$SSKP = 1 - .5^{\left(\frac{LR}{CEP}\right)^2}$$

Estimating LR

In order to use the formula cited above to calculate the SSKP of a single, reliable warhead against a missile silo, or any other target, the LR of the warhead must be determined. So far as blast effects, which constitute the major way in which nuclear explosions can damage missile silos, are concerned, the Lethal Radius of a nuclear explosion is a function of the yield of the warhead, the hardness of the target, and the altitude of the burst. Warhead yield is expressed in terms of energy equivalents to tons of TNT, either in kilotons (KT) or in megatons (MT). Target hardness is expressed in terms of the pounds per square inch (psi) of pressure over normal atmospheric pressure required to destroy the target. A nuclear explosion produces two kinds of pressure: overpressure caused by the blast wave from the explosion (the maximum value is called peak overpressure) and overpressure produced by the winds caused by the blast wave (dynamic overpressure). In calculating the LR of warheads used against missile silos, the effect of dynamic overpressure can be ignored, for missile silos are far more susceptible to damage from blast than from dynamic pressure. Similarly, variations in altitude need not be considered, since for targets with the hardness associated with missile silos, a surface burst will

6. In the case of repeated firings, the CEP is the median miss distance; 50% of the warheads would miss the target by more than the CEP and 50% by less (Wohlstetter, 1969: 135n).

In a normal circular distribution, 50% of the warheads will fall within a circle whose radius is the CEP; 90% of the warheads will fall within a circle whose radius is 2.4 times the CEP; and 99% within a circle whose radius is 4 times the CEP. See Senate Foreign Relations Committee (1970: 620).

7. This formula is taken from the General Electric Missile Effectiveness Calculator described later in this section. A nautical mile is 6,080 feet.

produce greater damage than an air burst (Glasstone, 1964: 114, 164).[8]

There are a variety of ways to calculate the LR for warheads used against missile silos, and each approach gives a different value for LR. These differences are, however, probably less significant than those introduced by the uncertainties that attend any estimate of the amount of overpressure it would take to disable a missile silo. *The Effects of Nuclear Weapons*, published by the Atomic Energy Commission, contains a graph showing the distances from ground zero that a 1KT surface burst will produce peak overpressure from .1psi to 1000psi (Glasstone, 1964: 135). The graph thus provides a means of determining the LR of a 1KT warhead against any target that could be destroyed by a given overpressure within that range. Using what is known as cube-root scaling, the LR for any other yield of warhead (Y in kilotons) against a target of the same hardness can be calculated by this formula:

$$LR_Y = LR_{1KT} \times Y^{1/3}$$

For example, to determine the LR of a 5MT warhead against a target that could be destroyed by 300psi, one reads from the graph that a 1KT explosion will produce 300psi out to a distance of *about* 220 feet from ground zero (the graph is not calibrated finely enough to permit more than an approximate reading) and then calculates:

$$LR_{5MT} = 220 \times 5000^{1/3} = 3762 \text{ feet (.619 nautical miles)}$$

This value for LR can then be substituted in the SSKP formula previously cited (to continue the example) to find the SSKP for a 5MT warhead with a CEP of .25 nautical miles (nm) against a 300psi target. The result is an SSKP of .985.

The actual calculations involved can be avoided through the use of a circular slide rule (the "Bomb Damage Effect Computer") manufactured by the RAND Corporation. This computer is based on data from *The Effects of Nuclear Weapons* and provides a rapid means for calculating both LRs and SSKPs for warheads between 1KT and 100 MT over a range of 1-1,000psi. Like the graph published by the AEC, the RAND computer is not finely calibrated. Thus, the computer indicates (for a 5MT

8. This volume contains information about the destructive effects of nuclear explosions on a variety of vehicles and structures. Although this publication does not directly consider the destructive effects of nuclear explosions on missile silos, the volume does treat in detail the blast effects of nuclear explosions.

warhead, .25nm CEP, and a 300psi target) an LR of about 3,800 feet (.625nm) and an SSKP somewhere between .985 and .990.

Those without access to the AEC graph or the RAND computer can calculate LRs with results close to those produced by the graph or the computer by means of the following formula (where LR is in nautical miles, Y is the yield in MT, and H is the hardness of the target in psi):

$$LR = \frac{2.45Y^{1/3}}{H^{1/3}} \left\{ \sqrt{1 + \frac{2.79}{H}} + \frac{1.67}{H^{1/2}} \right\}^{2/3}$$

For hardnesses of 300psi or greater, this formula can be truncated at the first term of the expression and still produce results very close to the readings from the RAND computer.[9] Thus, using again the example of a 5MT warhead, a .25nm CEP, and a 300psi target, the simplified formula produces LR of .626nm (3,806 feet). If this value for LR and the value for the CEP are used in the SSKP formula, the result is an SSKP of .987. The simplified formula for LR can be substituted for LR in the SSKP formula, and the result is:

$$SSKP = 1 - e^{\frac{-4.15Y^{2/3}}{H^{2/3}(CEP)^2}} \quad \text{or} \quad 1 - .5^{\frac{6Y^{2/3}}{H^{2/3}(CEP)^2}}$$

A more convenient instrument for calculating LRs and SSKPs than either the AEC graph or the RAND computer is the "Missile Effectiveness Calculator" manufactured by the Heavy Military Electronics Systems Division of General Electric. This is a circular slide rule more finely calibrated than the RAND computer. The GE calculator also provides the formulae on which its LR scale is based. For targets in the 50 to 1,000psi range, the GE formula for LR (in nautical miles is):

$$LR = \frac{2.9Y^{1/3}}{H^{.35}}$$

9. The present writers are indebted to T. Greenwood of MIT for this formula. It is derived from a formula advanced by Brode (1968: 180). Brode's expression for peak overpressure from a surface burst for a yield Y in MT at R kilofeet is:

$$\Delta P = \frac{3300Y}{R^3} + \frac{192Y^{1/2}}{R^{3/2}} .$$

For a fuller statement of the errors involved in using the truncated expression, see Greenwood (1972: 18-19n.).

The GE formula for LR is derived from test results described by Harold Brode (1960) and produces slightly higher values than the RAND computer.[10] Thus, in the case of a 5MT warhead, a 300psi target, and a .25nm CEP, the GE formula results in an LR of .673nm (4,092 feet) which produces an SSKP of .994. If the GE formula for LR is substituted in the SSKP formula, the expression for SSKP is:

$$SSKP = 1 - e^{\frac{-5.83Y^{2/3}}{H^{.7}(CEP)^2}} \quad \text{or} \quad 1 - .5^{\frac{8.41Y^{2/3}}{H^{.7}(CEP)^2}}$$

There are two qualifications that need to be made about the methods discussed here for calculating Lethal Radius. First, these expressions for LR deal only with the effects of peak overpressure and, therefore, scale LR with the cube root of the yield of the warhead. But the structural characteristics of missile silos are such that the damage they will incur is determined by the duration of the impulse of the overpressure, as well as by its magnitude, and the larger the yield, the longer is this duration. Accordingly, for warheads in the megaton range, expressions for LR based on cube-root scaling underestimate somewhat the actual damage a missile silo will receive. The effect of this pulse duration phenomenon is that there is no one "given hardness" for a target; a silo that could survive 300 psi created by a 50KT warhead could be damaged (because of the greater duration of the impulse) by 300psi created by a 5MT warhead (discussed in Operations Research Society of America, 1971: 1188, 1212; Brode, 1968: 184, 185).[11]

10. For targets where H is less than 10psi, the GE formula for LR is:

$$LR = \frac{6.81Y^{2/3}}{H^{.62}}.$$

For targets where H is greater than 10psi but less than 50psi, the GE formula for LR is:

$$LR = \frac{5.12W^{1/3}}{H^{.5}}.$$

For targets where H is greater than 1000 psi, the GE formula for LR is:

$$LR = \frac{2.62Y^{1/3}}{H^{1/3}}.$$

11. The present writers have not found enough information on the record to be confident of how to adjust LRs to take account of pulse duration. Wohlstetter in his

The second qualification that needs to be made about these expressions for Lethal Radius is that they all employ a simplifying assumption known as the "cookie cutter" approach to the probability of damage. The assumption is that the probability of destroying the target in question is the same (unity) for all distances between the point of explosion and the target that are less than or equal to the Lethal Radius and that the probability of damage drops to zero for all distances between the point of explosion and the target that are greater than the Lethal Radius.

In reality, the ability of a warhead to produce some specific level of damage on a target at any given distance from the point of explosion is influenced by a variety of factors including variations in terrain and weather and chance variations in weapons and targets. As a result, it is possible for the probability of damage to be less than unity for targets closer to the point of explosion than the Lethal Radius and for the probability of damage to be greater than zero for targets separated from the point of explosion by distances greater than the Lethal Radius.

The calculation of the actual probability of damage, at any given distance from ground zero, is made in the case of missile silos by using what is known as a Sigma-20 damage function. The effect of this function, when used in the calculation of SSKPs, is to produce slightly lower SSKPs than those produced by the cookie-cutter approach.[12]

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letter to the New York *Times* of June 29, 1969, states that a 50KT warhead with a .12 SSKP, which would scale to a .61 SSKP for a 1MT warhead using cube-root scaling, would scale to a .69 SSKP using "more exact methods." *Operations Research Society of America* (1971: 1186) implies that in this calculation Wohlstetter was adjusting for pulse duration.

If cube-root scaling is used:

$$PS_{1MT} = PS_{50KT}^{\frac{(1{,}000)^{2/3}}{50}} = PS_{50KT}^{(400)^{1/3}}$$

where PS (probability of survival) = (1 – SSKP). Accordingly, the scaling used by Wohlstetter (n) can be solved with this equation: $.31 - .88^{(400)^n}$ and the value for (n) is .369.

As noted in the text, using the simplified formula, the SSKP for a 5MT warhead (assuming a 300psi target and a .25nm CEP) is .987. The SSKP for a 1MT warhead would be .773.

In contrast, if the simplified formula is used to calculate the LR for a 50 KT warhead (against a 300psi target), and this LR is then scaled for a 5MT and a 1MT warhead using a .369 scaling, the resulting SSKPs (assuming a .25nm CEP) are .998 for the 5MT warhead and .841 for the 1MT warhead.

12. For example, if the LR of a warhead is 3,806 feet, the actual probability of

As far as the present writers can determine, none of the 1969 calculations reconstructed in the next section of this paper adjusted for the effect of pulse duration or used a Sigma-20 damage function. Note that the effects of these two modifications work in opposite directions: adjustment for pulse duration produces higher SSKPs than the LR formulae previously described, and adjustment for a Sigma-20 damage function produces lower SSKPs. For warheads with the yields and accuracies assumed in the 1969 calculations, the effects of these two modifications just about cancel out.[13] Given all the other simplifications that will attend any set of calculations, the use of the formulae previously presented would appear, then, to provide a good approximation for the Lethal Radius and the SSKP.

RELIABILITY, TERMINAL KILL PROBABILITY, AND TARGETING

The formula for Single Shot Kill Probability is based on the assumption that the warhead will arrive at the target and explode. In reality, this is not always the case. There are many points of possible failure in a missile system between the signal to fire the missile and the actual detonation of the warhead, and in order to determine the actual probability of kill, a value must be assigned for the Overall Reliability (OAR) of the missile system.

The OAR represents an estimate as to the probability that first the missile and then the warhead will function properly during the course of the entire flight. Overall Reliability is the product of the individual probabilities that the system will not malfunction during each stage of

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damage to a target at this distance from ground zero (using a Sigma-20 damage function) is not 1.0 but .48. If the target is 1,900 feet from ground zero, the probability of damage is .99, and if the target is 4,567 feet from ground zero (outside the LR) the probability is .15 (not 0 as in the case of a cookie-cutter approach).

Using the cookie-cutter approach and the simplified formula, the SSKP for a warhead with a 3,806-foot LR (assuming a .25nm CEP) would be .987. Using a Sigma-20 damage function, the SSKP would be .961.

The present writers are indebted to Dr. A. J. Hartzler, Operations Analysis Division, U.S. Arms Control and Disarmament Agency, for information about the Sigma damage functions and for the chart and nomogram with which the calculations in this and the following note were made.

13. As explained in note 9, the SSKPs for a 1MT and a 5MT warhead (assuming a 300psi target and a .25nm CEP) when calculated using the simplified formula for LR are .773 and .987, and when adjusted for .369 scaling the SSKPs are .841 and .998. If the SSKPs for these warheads (using the adjusted LRs) are then calculated using a Sigma-20 damage function, the SSKPs are .79 and .984.

countdown and launch (Launch Reliability) and during each stage of flight—the booster phase, the separation of the reentry vehicle, the penetration of the atmosphere, and the detonation of the warhead (Flight Reliability). Assume, for example, a missile system with the following characteristics: a .95 probability of successful countdown and launch; a .95 probability of successful separation following boost; a .95 probability of successful penetration following separation; and a .95 probability of successful detonation following penetration. The Overall Reliability of such a system would be $.95^5$ or .773.

To compute the composite probability of an individual warhead actually destroying a target (Terminal Kill Probability or TKP), the SSKP is multiplied by the Overall Reliability of the missile system: TKP = SSKP x OAR. In the case of the above example, if the SSKP of the warhead was .94, the TKP would be .94 x .773 or .727.

Once the Terminal Kill Probability of a single warhead is determined, the probability of destroying the target if more than one warhead is fired at the same target can be calculated. Assume, for example, that two warheads (one with a TKP of .65 and one with a TKP of .75) are fired at the same target. The probability of the target surviving a hit from the first warhead is $(1-TKP_1)$ or $(1-.65)$, and the probability of the target surviving a hit from the second warhead is $(1-TKP_2)$ or $(1-.75)$. The probability of the target surviving the two hits independently is $(1-TKP_1) \times (1-TKP_2)$ or $(1-.65) \times (1-.75) = .0875$. The probability of kill of the two warheads (PK_{2wh}) is thus $(1-.0875)$ or .913.

In the event that the warheads being fired at the same target have the same TKP, the probability that the target will survive a hit from two warheads is $(1-TKP)^2$ and the $PK_{2wh} = 1 - (1-TKP)^2$. In the case of n warheads (with equal TKPs), the probability of kill can be calculated with this formula: $PK_n = 1 - (1-TKP)^n$.

The results of targeting an entire missile force can be calculated once the Terminal Kill Probabilities for one or n warheads have been computed. For example, if 1,000 warheads (with equal TKPs) are fired at 1,000 targets, the number of targets that could be expected to be destroyed would be 1,000 x TKP. If 2,000 warheads are fired at 1,000 targets, the number of targets that could be expected to be destroyed would be 1,000 x PK_{2wh}.

In the event the number of warheads is not an integer multiple of the number of targets, the warheads should be allocated to targets as evenly as possible in order to maximize the probability of kill on each target. For example, if 1,500 warheads are fired at 1,000 targets, the optimum allocation would be 1,000 warheads targeted 2 : 1 against 500 targets and 500 warheads targeted 1 : 1 against 500 targets.[14] Accordingly, the total number of targets that could be expected to be destroyed would be 500 x PK_{2wh} + 500 x TKP.[15]

The strategy for distributing warheads to targets would be different, however, if the targets are of unequal value. An enemy missile force, for example, might be composed of a mix of missiles, some with multiple warheads and some with single warheads, and the warheads themselves might be of different yields. A different allocation of attacking warheads to targets would be in order, depending on whether one wanted to maximize the number of missiles, the number of warheads, or the amount of megatonnage destroyed.

REPROGRAMMING

In a situation in which the number of attacking warheads is greater than the number of targets, the number of targets destroyed could be increased if the attacking power could identify those missiles that had malfunctioned sometime during the launch or flight (and whose warheads would therefore never reach a target) and could assign other missiles to replace those that had failed. This would improve the chances that all targets would receive at least one warhead and thereby increase the efficiency of the attack. This strategy for allocating warheads to targets requires that the attacker not fire all of his missiles at once. Some must be held in reserve to replace those known to have failed. The ability to identify missiles that have failed and to reprogram other missiles to take their place is called reprogramming, or shoot-look-shoot.

Consider first a case in which no reprogramming is done. Assume 1,000 targets and 1,500 missiles and that the Overall Reliability of the missile system is .773 and the SSKP of each warhead is .94. The TKP for each

14. For any given case, the allocation of warheads to targets can be determined by dividing the number of warheads by the number of targets to identify the ratios in which the warheads should be distributed and then solving for the actual distribution with the use of simultaneous equations.

In the above example, 1,500 divided by 1,000 produces a ratio of 1.5. This indicates that some targets should receive one warhead and others two. If x equals the number of targets to receive one warhead and y equals the number to receive two warheads, then x + y = 1,000. Since x + 2y = 1,500 (the number of warheads), the solution, x = 500, readily follows.

15. If the warheads in the attacking force have differing TKPs, the distribution of warheads to targets should again be such as to make the probability of kill as even as possible for each target.

warhead would then be .727, and the PK_{2wh} would be .925. These variables and the results of the attack can be presented as follows:

#Warheads 1,500		SSKP	.94
OAR .773		TKP	.727
		PK_{2wh}	.925

500 targets at 2 : 1 (500) (.925) = 463
500 targets at 1 : 1 (500) (.727) = 364
827 destroyed

In order to calculate the effect of a reprogramming system, it is necessary to break down the Overall Reliability into two components: Reprogrammable Reliability (RR) and Nonreprogrammable Reliability (NRR). Reprogrammable Reliability expresses the probability that the missile will perform correctly during that part of launch and flight in which failures can be identified, and (1–RR) the probability that the missile will fail during the time failures can be identified. Similarly, Nonreprogrammable Reliability expresses the probability that the missile will perform correctly during that part of the flight when failures cannot be identified, and (1–NRR) the probability that the missile will fail during that time. Note that RR x NRR always equals OAR.

The value for Reprogrammable Reliability can be calculated if one knows the percentage of the total failures in the missile system that can be identified (reported back) and for which missiles held in reserve can be retargeted. If the total number of missiles fired is (T), the percentage of failures that can be replaced (n) equals:

$$\frac{\#\text{replaceable failures}}{\#\text{total failures}} = \frac{T(1 - RR)}{T(1 - OAR)} = \frac{(1 - RR)}{(1 - OAR)}$$

Accordingly, RR = 1 – n(1–OAR). Note that as the percentage of failures that can be replaced approaches 100, then RR approaches as a limit OAR ($\lim_{n \to 1} RR = OAR$) which would be perfect reprogramming, since all failures are replacable. On the other hand, $\lim_{n \to 0} RR = 1$, and if RR = 1, then NRR = OAR, which means no reprogramming is possible.

If the attack takes full advantage of the system's reprogramming potential, the number of warheads available to be assigned to targets after reprogramming would be the total number of warheads minus the number of identified failures. If (T) is the total number of warheads, the number of available warheads (A) = T − T(1−RR) = T(RR). If the attacker could afford to fire his missiles one at a time, this condition could be easily realized. In reality, since most failures occur quite early during launch and flight, and since reserve missiles can be rapidly reprogrammed to new targets, this condition can be closely approached by an attack limited to two or three salvos separated in time by a matter of minutes.[16] Accordingly, the expression T(RR) is normally employed to compute the number of warheads available to be assigned to targets after reprogramming (available whs).

In calculating the effects of an attack using reprogramming, it is important to bear in mind that since all known failures have been replaced, the TKP of each warhead finally going toward a target is calculated by multiplying the SSKP by the Nonreprogrammable Reliability: TKP = SSKP x NRR.

To illustrate the effect of an attack employing a reprogramming, return to the example previously cited for a nonreprogramming attack and assume that the .773 Overall Reliability of the missile system is the product of five reliabilities: .95 probability of successful countdown and launch; .95 probability of successful boost after launch; .95 probability of successful separation after boost; .95 probability of successful penetration after separation; and .95 probability of successful detonation after penetration. Assume further than information is available for all failures during countdown, launch, boost, and separation. The Reprogrammable Reliability of the system would then be $.95^3$ = .857, and the Nonreprogrammable Reliability would be $.95^2$ = .902. The number of available warheads after reprogramming would be 1,500 x .857 = 1,285, and the TKP for each of these warheads should be SSKP x NRR = .94 x .902 = .848.

The results of the attack employing reprogramming can now be presented as follows:

#Warheads		1,500	SSKP	.94
#Available Whs		1,285	TKP	.848
OAR	.773		PK_{2wh}	.977
RR	.857			
NRR	.902			

285 targets at 2 : 1 (285) (.977) = 278
715 targets at 1 : 1 (715) (.848) = 606
884 destroyed
(compare with 827 destroyed without reprogramming)

16. A more detailed discussion of reprogramming is given in Operations Research Society of America (1971: 1201-1208) and Wohlstetter (1969: 132).

To summarize, a reprogramming system, by providing information on a certain percentage of the failures in an attack, enables the attacker to reprogram reserve missiles to replace these known failures. This improves the efficiency of the attack, since only the more reliable warheads are allocated evenly among targets. The returns from a reprogramming system will depend on the percentage of the total failures that can be identified, on the SSKP of the attacker's warheads, and on the ratio of his total number of warheads to targets. In general, the higher the SSKP, the greater the return, particularly if the attacker does not have enough warheads to assign several to each target, since with reprogramming the attacker can be more confident that each target will be covered by at least one warhead. The returns from reprogramming will be less in cases where the attacker has so many warheads that he will be assigning several to each target in any event.

In the case of attacks involving MIRVed missiles, the calculations can be made in the same manner as in the case of missiles with single warheads, although there are certain restraints that follow from what is called the "footprint" problem. A single missile carrying, for example, three warheads cannot be reprogrammed to hit just *any* three targets in order to replace warheads which have failed. A MIRVed missile will be limited in the geographic dispersion possible among the targets of its warheads. To cover the targets, then, of the missiles which failed may require separate missiles for each target. This problem, however, recedes in importance as the number of extra warheads to targets increases, since extra boosters would then be available, and a number of targets would be receiving two warheads anyway (see Operations Research Society of America, 1971: 1207, on this point).[17]

17. In the case of MIRVed missiles, the formula previously cited for calculating the probability of kill for more than one warhead—$PK_n = 1 - (1\ TKP)^n$—can be used only on the assumption that each of the warheads going to the same target is launched by a separate booster, which would require a criss-cross targeting of the MIRVs involved. This makes the case comparable to that of n separate boosters, each launching one warhead to the same target, and permits the Overall Reliability of the missile system to be used in calculating the TKP of the warheads involved.

If the warheads going to the same target are launched by the same booster, the OAR of the system must be broken into two components: Launch Reliability (the probability that the system will perform correctly through the successful separation of the warheads) and Flight Reliability (the probability that the warheads will perform successfully through penetration and detonation). PK_n then becomes the product of two independent probabilities: the probability that the warheads will be successfully launched (LR) and the probability that they will destroy the target—$[1 - (1 - FR \times SSKP)^n]$. Note that the resulting expression—$PK_n = LR\,[1 - (1 - FR \times SSKP)^n]$—will produce a lower value for PK than the expression—$PK_n = 1 - (1 -$

TABLE 1
WOHLSTETTER STATEMENT

Calculations on the Vulnerability of the Minuteman Force in the Late 1970's
If No Extra Protection

Difference Between Assumptions Used by Dr. Rathjens and Myself

Number of SS-9's	: Same (500)	
Over-all reliability	: Same	
Accuracy	: Same	
Minuteman Blast Resistance	Dr. Rathjens'	: 2/3 higher than official estimate
	Mine	: Official estimate
SS-9 payload	Dr. Rathjens'	: 4 reentry vehicles at 1 MT (less than SS-9 capability)
	Mine	: 3 at 5 MT (SS-9 capability)
Use of partial information on missile malfunctions	Dr. Rathjens'	: Not used
	Mine	: Used

Effect of Assumptions on Minuteman Survivability	*% Minuteman Surviving*
Dr. Rathjens' result	25
Adjust for correct Minuteman blast resistance and three 5 MT MIRV per SS-9	16
Alternatively adjust for correct Minuteman blast resistance and number of 1 MT MIRV warheads the SS-9 is capable of carrying	7.3
Using correct Minuteman blast resistance, three 5 MT MIRV per SS-9, and information as to missile malfunctions before or during laungh only	8.7
Using correct Minuteman blast resistance, the correct number of 1 MT warheads per SS-9, and information as to missile malfunctions before and during launch only	6
Using correct Minuteman blast resistance and *either* the 5 MT MIRV or the 1 MT MIRV option, and information as to missile malfunctions including one-half those that fail after launch	5

SOURCE: Wohlstetter (1969: 133).

Reconstruction of 1969 Calculations

The purpose of this section is to show how the methods and formulae described in the preceding section can be used to reproduce or closely approximate the calculations of Albert Wohlstetter, George Rathjens, and John Foster regarding the percentage of the Minuteman force that could be expected to be destroyed in a first strike by Soviet SS-9 forces of various sizes and capabilities.

The first calculations considered are those of Wohlstetter and Rathjens. Wohlstetter has conveniently summarized the assumptions and results of his own and Rathjens' calculations in Table 1. Five variables are not identified in this statement: the Overall Reliability (OAR) and the accuracy (CEP) that they assigned the Soviet force; the differing estimates each made about the hardness of Minuteman silos; and the number of 1MT warheads that Wohlstetter stated the SS-9 was capable of carrying.

Before the calculations can be reproduced, it is necessary to determine these missing values. The overall reliability they assumed can be easily fixed, for in testimony before the Senate Armed Services Committee in 1970 (Senate Committee on Armed Services, 1970: 2383), Wohlstetter stated that he used .75 for this value. The identification of their assumptions about CEP and Minuteman hardness is more complex. In his commentary on Rathjens' calculations, Wohlstetter (Operations Research Society of America, 1971: 1163) stated that a 5MT warhead, given the official estimate for Minuteman hardness and the CEP that he and Rathjens assumed, would have a SSKP close to 99%. Although this statement would hold for any number of possible combinations of CEP and hardness, the statement does provide a means for determining the identity of either the CEP or the hardness, provided the other is known.

Actually, both the CEP and the hardness Wohlstetter assumed can be identified with reasonable confidence from public sources. Many knowledgeable sources have assigned a hardness of 300psi to the Minuteman silo, and since Foster (Senate Committee on Foreign Relations, 1970: 512) assumed a .25nm CEP for the SS-9 in his 1969 calculation, it is plausible that Wohlstetter did the same.[18] These values are, moreover, internally

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TKP)^n–where TKP = OAR X SSKP = LR X FR X SSKP. Damage to a target will be more likely, for example, if two warheads are launched by two separate boosters than if they are launched by the same booster.

18. Wohlstetter (1969: 128) refers to a 1954 statement about the time when a Soviet missile might have a 1,500 CEP and notes how closely the figure matches the

consistent, for, as noted in the preceding section, a 5MT warhead (given a .25nm CEP and a 300psi target) does have close to a .99 SSKP. Once these variables are fixed, the number of 1MT warheads Wohlstetter assigned the SS-9 has to be 6, for this is the only number (as will be seen) that can reproduce his calculations. Moreover, Beecher in the New York *Times* of April 27, 1969, reported that the number of 1–2MT warheads government experts believed the SS-9 could carry was 6.

It is now possible to work through Wohlstetter's calculations. (There are problems in reproducing Rathjens' result, and his calculations are more conveniently considered later.) Using the truncated formula for SSKP cited earlier

$$\text{SSKP} = 1 - .5^{\frac{6Y^{2/3}}{H^{2/3}(\text{CEP})^2}}$$

the SSKP for a 5MT warhead (given a 300psi target and a .25nm CEP) is .987 and that for a 1MT warhead is .773. As explained in the preceding section, the Terminal Kill Probability for one warhead is TKP = OAR x SSKP, and the Probability of Kill of n warheads is Pk nwh = $1 - (1 - \text{TKP})^n$. In the case of reprogramming, TKP = SSKP x NRR.

Wohlstetter's first estimate was for the case in which each SS-9 carried 3 5MT warheads, and he calculated that 16% of the 1,000 Minutemen would survive.

Wohlstetter's First Case

#Missiles	500	PSI	300
#Warheads	1,500	CEP	.25
OAR .75		SSKP	.987
		TKP	.740
		Pk2wh	.932

500 targets at 1 : 1	(500) (.740) =	370	
500 targets at 2 : 1	(500) (.932) =	466	
		836	destroyed
		16.4%	survive

Wohlstetter's second estimate was for the case in which each SS-9

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performance characteristics now discussed in connection with the SS-9.

Several statements assigning 300psi to the Minutemen silo have been made (see the Institute for Strategic Studies, 1971: 90; Senator Symington in Senate Committee on Armed Services, 1969: 1874; York, 1970: 199; Beecher in the New York *Times* of December 6, 1970).

carried 6 1MT warheads, and he calculated that 7.3% of the 1,000 Minutemen would survive.

Wohlstetter's Second Case

#Missiles	500	PSI	300
#Warheads	3,000	CEP	.25
OAR .75		SSKP	.773
		TKP	.580
		Pk3wh	.926

1,000 targets at 3 : 1 (1,000) (.926) = 926 destroyed
7.4% survive

Wohlstetter's third estimate was for the case in which each SS-9 carried 3 5MT warheads and information was available to permit reprogramming for failures before and during the launch, and he calculated that 8.7% of the 1,000 Minutemen would survive. Since Wohlstetter did not indicate what percentage of the total number of failures assumed in his .75 OAR would occur before or during launch, it is not possible to calculate directly his Launch Reliability (which he assumed to be reprogrammable). However, this figure can be derived by working back from the number of surviving Minutemen involved in his estimate.[19] This calculation indicates that he assumed a .834 Launch (or Reprogrammable) Reliability and a .90 Flight (or Nonreprogrammable) Reliability.

19. Reprogrammable Reliability (RR) can be solved if one knows SSKP, OAR, the total number of targets, the total number of warheads, and the total number of targets destroyed.

Thus, in this case, if x = the number of targets fired at 1 : 1 and y = the number of targets fired at 2 : 1, and Z = Pk2wh, then: TKP(x) + Z(y) = 913.

All of the terms in this equation can be expressed in terms of RR or givens (SSKP, OAR).

It is known that x + y = 1,000 and that x + 2y = 1,500RR. Therefore, x = (2,000 – 1,500RR) and y = (1,500RR – 1,000).

$$\text{TKP} = (\text{SSKP})\,(\text{NRR}) \text{ and } \text{NRR} = \frac{\text{OAR}}{\text{RR}} \text{ therefore } \text{TKP} = \frac{(\text{SSKP})\,(\text{OAR})}{\text{RR}}$$

$$Z = \text{TKP} + \text{TKP}\,(1 - \text{TKP}) \text{ or } Z = 2\text{TKP} - \text{TKP}^2$$

$$\text{Therefore, } Z = \frac{2\text{RR}(\text{SSKP})\,(\text{OAR}) - [(\text{SSKP})\,(\text{OAR})]^2}{\text{RR}^2}$$

Wohlstetter's Third Case

#Missiles		500	PSI	300
#Warheads		1,500	CEP	.25
#Available Whs		1,251	SSKP	.987
OAR	.75		TKP	.888
RR	.834		Pk2wh	.987
NRR	.9			

749 targets at 1 : 1	(749) (.888) =	665
251 targets at 2 : 1	(251) (.987) =	248
		913 destroyed
		8.7% survive

Wohlstetter's fourth estimate was for the case in which each SS-9 carried 6 1MT warheads and, as in the third case, information was available to permit reprogramming for failures before and during launch. He calculated that 6% of the 1,000 Minutemen would survive.

Wohlstetter's Fourth Case

#Missiles		500	PSI	300
#Warheads		3,000	CEP	.25
#Available Whs		2,502	SSKP	.773
OAR	.75		TKP	.696
RR	.834		Pk2wh	.908
NRR	.9		Pk3wh	.972

498 targets at 2 : 1	(498) (.908) =	452
502 targets at 3 : 1	(502) (.972) =	488
		940 destroyed
		6.0% survive

Wohlstetter's final estimate was for the case in which the SS-9 carried either 3 5MT or 6 1MT warheads and information was available to reprogram for all launch failures and about one-half of the flight failures. He calculated that 5% of the 1,000 Minutemen would survive whichever MIRV configuration was used. The .9 Flight Reliability (FR) used in cases three and four is now assumed to be the product of the Reprogrammable Flight Reliability (FR_{RR}) and the Nonreprogrammable Flight Reliability (FR_{NRR}). Solving for Reprogrammable Flight Reliability once it is known that 50% of the flight failures can be replaced, $FR_{RR} = 1 - 50\% (1-FR)$ or .95. The Nonreprogrammable Flight Reliability is then the Overall FR divided by FR_{RR} or .947; and the total Reprogrammable Reliability (Launch and Flight) is .79.

Wohlstetter's Fifth Case

#Missiles	500	PSI	300
#Warheads	1,500	CEP	.25
#Available Whs	1,185	SSKP	.987
OAR	.75	TKP	.935
RR	.79	Pk2wh	.996
NRR	.947		

815 targets at 1 : 1	(815) (.935) =	762
185 targets at 2 : 1	(185) (.996) =	184
		946 destroyed
		5.4% survive

Attention can now be turned to Rathjens' estimate that 25% of the Minuteman force would survive an attack from 500 SS-9s each carrying 4 1MT warheads. If Wohlstetter assumed a 300psi hardness for Minuteman and Rathjens' estimate was two-thirds higher, Rathjens would have been assuming a hardness of 500psi. In addition to an OAR of .75, Rathjens told Wohlstetter that in his calculations he had used a .6 SSKP (which would only approximate the SSKP for a 1MT warhead with a .25nm CEP against a 500psi target).[20] However, with these assumptions Rathjens should have calculated 30% surviving Minutemen.

#Missiles	500	SSKP	.6
#Warheads	2,000	TKP	.45
OAR	.75	Pk2wh	.697

1,000 targets at 2 : 1	(1,000) (.697) =	697 destroyed
		30.3% survive

When Wohlstetter, in the New York *Times* of June 29, 1969, questioned both the reality of Rathjens' assumption of a 500psi hardness for Minuteman and the accuracy of his calculation, Rathjens (1971a: appdx. A) responded by stating that he was using a .68 SSKP which he had derived through three alternative calculations.[21] The one most easily

20. Rathjens (Operations Research Society of America, 1971: 1183) set forth his assumptions in a note to Wohlstetter of April 22, 1969.

21. Two of the calculations involved identifying the hardness of a Minuteman silo from a chart introduced into the FY 1970 budget hearings by Deputy Secretary of Defense Packard (Senate Committee on Armed Services, 1969: 1709g.) and then computing the CEP required for a 50KT warhead to achieve a .145 SSKP against a target of this hardness. One calculation was based on a reading of the chart in statute miles and the other on a reading in nautical miles. In this second instance, he read a hardness of 320psi, deduced a CEP of 1,430 feet for a 50KT warhead, and then calculated a .68 SSKP for a 1MT warhead (given a 320psi target and a CEP of 1,430

duplicated was based on the testimony of Deputy Secretary of Defense Paul Nitze (1967: 27-48) that a "possible" U.S. missile could carry 10 50KT warheads and that this missile would be able to destroy 1.2 to 1.7 hard targets. The SSKPs for these 50KT warheads would, then, range from .12 to .17. Rathjens took the median value (.145) and scaled for a 1MT warhead using the following formula (Y_1 is the yield in KT of the larger warhead, and Y_2 the yield of the smaller):[22]

$$SSKP_1 = 1 - (1 - SSKP_2)^{\left(\frac{Y_1}{Y_2}\right)^{2/3}}$$

$$SSKP_{1MT} = 1 - (1 - .145)^{\left(\frac{1,000}{50}\right)^{2/3}} = .685$$

An SSKP of .685 does in fact approximate Rathjens' estimate that 25% of the Minuteman force could be expected to survive.

#Missiles	500	SSKP	.685
#Warheads	2,000	TKP	.514
OAR .75		Pk2wh	.764

1,000 targets at 2 : 1 (1,000) (.764) = 764 destroyed
23.6% survive

However, if the lower estimate, .12 SSKP, is scaled for a 1MT warhead, the SSKP is .61, and an attack by the same 500 SS-9s could destroy only 71% of the Minuteman force, leaving 29% surviving. Alternatively, if the higher estimate, .17 SSKP, is scaled for a 1MT warhead, the result is a .747 SSKP and 19% of the Minuteman force survive (which is not all that different from Wohlstetter's first case: 16%). An attack employing 6 1MT warheads and an SSKP of .747 would leave 8.5% surviving which is close to Wohlstetter's second case: 7.3%.

These calculations reveal how sensitive the results are to which SSKPs are scaled from the Nitze data and demonstrate how Rathjens' and Wohlstetter's differences turn not only on assumptions about either the

feet). In addition to the assumption that the hard targets mentioned by Nitze were the same hardness as a Minuteman silo, Rathjens appears to have used a formula for LR different from those discussed in the second section.

22. In his explanation to Wohlstetter, Rathjens erroneously calculated an SSKP of .683.

number of SS-9 warheads or the reprogramming capability of the Soviet missile system, but also on the SSKPs assigned.

The last calculation reviewed in this section is the estimate advanced by Dr. John S. Foster that a Soviet 420 SS-9 missile force with a 3 5MT MIRV configuration could destroy about 95% of the 1,000 United States Minuteman silos in a first strike.[23] The reconstruction of his calculations is more difficult than those of Wohlstetter and Rathjens because neither the SSKP of the MIRV warheads nor the Overall Reliability of the SS-9 system assumed by Foster is part of the public record.

Foster (Senate Committee on Foreign Relations, 1970: 437) does, however, state that he was assuming a .25nm CEP. Elsewhere, Foster states (Operations Research Society of America, 1971: 1241) that the projected SS-9 missile system would have a "20% failure rate" and suggests that the system would be able to "reprogram another missile to make up for failures." Finally, he states (Senate Committee on Armed Services, 1969: 1713) that the SS-9 force would have a "retarget capability." Although this 80% reliability figure suggested by Foster could be interpreted as either an Overall Reliability or as a Reprogrammable Reliability, it has been generally assumed to be a Reprogrammable Reliability.[24] Such a .8 Reprogrammable Reliability would mean that Foster was assuming that 84% of the failures in the missile system could be replaced.

If Foster were using the GE formula for Lethal Radius and the Minuteman silos were hardened to 300psi, then the SSKP of the 5MT warhead would be .994. Once the SSKP is calculated and the Reprogrammable Reliability of the missile system is known, then the Overall Reliability and the Nonreprogrammable Reliability can be derived given Foster's conclusion that 95% of the Minuteman force could be expected to be destroyed in a first strike by the 420 SS-9 missiles. In the case of a .994 SSKP and a .8 RR, Foster would have used an OAR of .763 and a NRR of .954.[25]

23. This 420 SS-9 estimate is given in Senate Committee on Foreign Relations (1970: 437, 512) and Senate Committee on Armed Services (1969: 1713, 1714).

24. Wohlstetter (Senate Committee on Armed Services, 1970: 2406) states that Foster was using a .8 Reprogrammable Reliability in his 420 SS-9 calculation. Based on their reading of Foster's statements, the ORSA Committee (Operations Research Society of America, 1971: 1200) also interpreted this .8 figure as Reprogrammable Reliability. In his critique of Foster's 420 SS-9 estimate, Rathjens et al. (1971b: 18273-18277) seem to interpret the .8 reliability both ways. In the text, Rathjens criticizes Foster's contention that "an 80 per cent overall reliability can be achieved." Then later in a footnote and in his own calculations involving the 420 SS-9 force, he assigns a .8 Reprogrammable Reliability to the SS-9 system.

25. The values for OAR and NRR can be derived from the formulae presented in

#Missiles	420	PSI	300
#Warheads	1,260	CEP	.25
#Available Whs	1,008	SSKP	.994
OAR	.763	TKP	.948
RR	.80	Pk2wh	.998
NRR	.954		

992 targets at 1 : 1	(992) (.948) =	940
8 targets at 2 : 1	(8) (.998) =	7
		947 destroyed
		94.7%

Post-SALT MIRV Threats

The purpose of this section is to show how these computational techniques (with some plausible assumptions as to the technical performance of the missile systems) can be used to discover the effect of the limitation on the number of Soviet modern heavy ICBMs under the SALT Interim Agreement and to determine the character of the threat posed by the U.S. MIRVed missile force to the Soviet ICBM force.

Article II of the Interim Agreement on Strategic Offensive Arms (Survival, 1972: 195) states that the "Parties undertake not to convert land-based launchers for light ICBMs, or for ICBMs of older types deployed prior to 1964, into land-based launchers for heavy ICBMs of types deployed after that time." U.S. government officials have announced that in May 1972 the number of Soviet modern heavy ICBMs built or under construction was 313 (Senate Committee on Armed Services, 1972: 9). What effect will this limitation have on the prelaunch survivability of the U.S. fixed-site land-based Minuteman force?

A 313 SS-9 force with a 3 5MT MIRV configuration, an Overall Reliability of .76 (RR .80, NRR .95) and a SSKP of .994 could be expected to destroy only 70.9% of the 1,000 Minuteman force in a first strike.[26] Given these same assumptions, but changing the MIRV configura-

note 19 once the RR, SSKP, total number of targets, total number of warheads, and total number of targets destroyed are known.

26. All the calculations in this section of the paper use the GE formula for LR.. Only 1,000 Minuteman silos are targeted in this hypothetical attack for two reasons. The threat posed to the Minuteman force has caused the most concern in recent years, both in the ABM debate and in the statements of Secretary Laird and Admiral Moorer, Chairman of the Joint Chiefs of Staff. Further, under the SALT agreements, the United States has the option of converting the 54 Titan-II missile launchers into SLBM launchers. Over time, then, the Titan force may be phased out.

tion to 6 2MT warheads, an attack by 313 SS-9s could be expected to destroy 94.1% of the Minuteman force.[27]

#Missiles	313	PSI	300
#Warheads	1,878	CEP	.25
#Available Whs	1,502	SSKP	.94
OAR .76		TKP	.893
RR .80		Pk2wh	.989
NRR .95			

498 targets at 1 : 1	(498) (.893) =	445
502 targets at 2 : 1	(502) (.989) =	496
		941 destroyed
		94.1%

Finally, if the MIRV configuration on the SS-9 were changed to 20 warheads each with a yield of .5MT, the 313 Soviet missiles could be expected to destroy 99% of the U.S. Minuteman force.[28]

Thus, even with the number of modern heavy ICBMs limited to 313, the Soviets could deploy a force which would be capable of destroying over 95% of the Minutemen. Today, however, as stated in the New York *Times* of March 21, 1971, the United States is in the process of upgrading 550 of the Minuteman silos to 900psi. What effect would this program have on the survivability of these land-based missiles, given the 313 limitation? Such a force, assuming the 6 2MT MIRV configuration, and the same assumptions as to accuracy and reliability, would be capable of destroying only 88.7% of the Minutemen. If this hardening program were expanded to include all 1,000 Minuteman silos, the 313 SS-9 force would then be able to destroy only 79.3% of the Minutemen.[29]

The effect of these hardening programs can be offset, however, if the CEPs of the Soviet SS-9 warheads were to drop to .16nm or about 1,000 feet. In the case of the 6 2MT MIRV configuration, the Soviets in a first strike could again be expected to destroy 95% of the Minuteman force.[30]

27. For the U.S. concern over the threat from a 6 2MT warhead configuration, see the New York *Times* of February 27, 1971.

28. William Beecher reported in the New York *Times* of August 5, 1972, that "an improved larger version of the SS-9, built but not yet test-fired, is potentially able to carry 20 warheads of one-half to one megaton each."

29. A 313 SS-9 force with a 3 5MT warhead configuration against 1,000 silos hardened to 900psi could be expected to destroy only 64.4% of the Minuteman force. This same force deployed with 20 .5MT MIRVs against 1,000 silos hardened to 900psi could be expected to destroy 90.5%.

30. The 313 Soviet SS-9 force configured with 20 .5MT MIRVs and a CEP of .16nm could be expected to destroy 99% of the Minuteman force.

Alternatively, if the SS-9 accuracies remained at .25nm but the other land-based missiles, the SS-11s and the SS-13s, should improve to .25nm CEP, then a combined attack of the 313 SS-9s and the 1,096 SS-11s and SS-13s (each with a 1MT warhead) could be expected to destroy 90% of the Minuteman force.[31] Finally, the Soviet Union might consider using its submarine-launched ballistic missiles in combination with the 313 SS-9s. Under the Interim Agreement, the Soviets are permitted to deploy 950 modern ballistic missile launchers on submarines. Assume that each SLBM is MIRVed with 10 40KT warheads each with a CEP of .25nm and that the missile system has an Overall Reliability of .8.[32] If 40% of these submarines were on station, then a combined attack by 313 SS-9s (6/2MT, CEP .25nm) and these SLBMs would increase the percentage of Minutemen destroyed from 79.3 to 84.6. In summary, a 313 limitation on the number of Soviet heavy missiles and the 900psi hardening program could postpone the time when close to 95% of the Minuteman force could be destroyed by a Soviet first strike; but they cannot prevent such a future if Soviet CEPs improve.[33]

The second security issue this paper addresses is the character of the threat posed by the U.S. MIRVed missile force to the Soviet fixed-site land-based missiles. Is Dr. John S. Foster (House Committee on Foreign Affairs, 1969: 244-245) correct when he argues that while a MIRVed Soviet SS-9 force would be a potential threat to the survivability of the U.S. ICBM force, the U.S. MIRV program poses no similar threat to the Soviet Union?

Under the SALT Interim Agreement, the United States is permitted 1,000 light ICBM launchers (the Minuteman force), 656 SLBM launchers (the Polaris force) plus 54 additional strategic launchers—either the existing Titan-IIs or 54 new SLBM Launchers. The overall composition of

31. At the time of the signing of the SALT agreements in May 1972, the Soviets had built or under construction 1,618 land-based missiles: 210 SS-7s and SS-8s, 313 SS-9s, and 1,096 SS-11s and SS-13s (Senate Committee on Armed Services, 1972: 9). According to the Institute of Strategic Studies (1972: 65) the SS-11 warhead has a yield of 1-2MT and the SS-13 warhead a yield of 1MT. See the testimony of Dr. John S. Foster (Senate Committee on Armed Services, 1969: 179) on the possibility of improving the accuracies of the SS-11s and SS-13s and their potential threat to Minuteman.

32. This assumption that the Soviet SLBM missile force will be designed to imitate the United States is admittedly most arbitrary. However, these calculations are intended to demonstrate the effect the use of Soviet SLBMs having these capabilities might have on the survivability of the U.S. Minuteman force.

33. For a discussion of the possibilities for reducing CEPs to 100 feet or .016nm, see Hoag (1971).

the U.S. MIRVed strategic missile force permitted under the five-year Interim Agreement and assuming the MIRV program continues to its presently planned deployment, will be: 54 Titan-II; 450 Minuteman-II; 550 Minuteman–III (each with three warheads); 31 Polaris submarines each carrying 16 Poseidon missiles (an average of 10 warheads each) and 10 Polaris submarines each with 16 A-3 missiles (3 MRV warheads each).

The specific capabilities of this U.S. missile force cannot be definitively established from public sources. The following yields and CEPs have been assigned as plausible assumptions:[34]

Titan-II	10 MT warhead	.75nm CEP
Minuteman-II	1.5 MT warhead	.35nm CEP
Minuteman-III	.17MT warhead	.25nm CEP
Poseidon	.04MT warhead	.25nm CEP

Further, the U.S. land-based missiles have been given the overall and reprogramming reliabilities posited by Foster for the Soviet SS-9 force: Overall Reliability .76 and Reprogrammable Reliability .80. Because the submarine system may be more reliable than the land-based systems, a

34. The yields and accuracies of the Minuteman-III and Poseidon warheads are the most easily established. William Beecher reports in the New York *Times* of March 21, 1971, that the Minuteman-III warhead has a yield of 170 kilotons; later he says (New York *Times* of March 21, 1972) that the yield of the Poseidon is 40 kilotons. In that same article, Beecher further claims that the accuracy of the Minuteman–III warhead is .25nm. Professor Wohlstetter (Senate Committee on Armed Services, 1970: 2265) stated in his testimony before the Senate Armed Services Committee that the Poseidon is designed to deliver weapons with the same CEP as the Minuteman-III, hence, the .25nm CEP for Poseidon.

The 1.5 yield of the Minuteman-II is derived from the Institute of Strategic Studies (1972: 65) estimate that the warhead has a yield of between 1-2MT. The .35nm assumption for the CEP of the Minuteman-II is, however, more difficult to explain. Department of Defense officials stated that Minuteman-II would have one-half the CEP of Minuteman-I. Jeremy Stone (1966: 134, 139) implies that the Minuteman-I had a CEP of .75nm. If, in fact, Minuteman-I had a CEP of .75nm, then the CEP of Minuteman-II would be approximately .38nm. The .35nm CEP was finally assigned because of Secretary Laird's testimony (House Committee on Armed Services, 1972: 9546) that the Minuteman-II accuracy has improved considerably.

York (1970: 47) assigns a yield of 10MT to the Titan-II warhead. The accuracy of the Titan-II warhead was crudely assumed to be the same as Minuteman-I, or .75nm.

Finally, the characteristics of the A-3 missile are not included since none of these missiles is used in any of the subsequent hypothetical U.S. MIRV attacks. These missiles are stationed in the Pacific and are deployed primarily as a deterrent against China. Further, these Polaris submarines are due to be replaced by the Trident submarine beginning in 1978.

TABLE 2
U.S. ATTACK AGAINST 1,054 SOVIET ICBMs (no reprogramming)

Missile	*RVs*	*Ratio*	*Target*	*Pk*	*#K*
MM-III	140	1 : 1	140 (5psi)	.759	106
T-II	54	1 : 1	54(100psi)	.646	35
MM-III	32	2 : 1	16(100psi)	.768	12
MM-II	450	2 : 1	225(300psi)	.770	173
MM-III	758	2 : 1	379(300psi)	.527	200
MM-III	720	3 : 1	240(300psi)	.674	162
Totals	2,154		1,054		688
					65.3%

TABLE 3
U.S. ATTACK AGAINST 1,054 SOVIET ICBMs (no reprogramming)

Missile	*RVs*	*Ratio*	*Target*	*Pk*	*#K*
Pos	280	2 : 1	140 (5psi)	.96	134
T-II	54	2 : 1	27(100psi)	.875	24
Pos	172	4 : 1	43(100psi)	.734	32
MM-II	450	2 : 1	225(300psi)	.77	173
MM-III	1,648	4 : 1	412(300psi)	.776	320
Pos	616	11 : 1	56(300psi)	.824	46
Pos	1,812	12 : 1	151(300psi)	.85	128
Totals	5,032		1,054		857
					81.3%

higher Overall Reliability of .8 has been assigned these missiles (Brown, 1970: 194-198).

First, what calculations might Soviet policy makers have made in 1969 when they reached numerical equality with the United States in land-based missiles (1,054)? Consider the first case when the United States uses only its land-based missiles (1,054) with no reprogramming in its attack. In a first strike against 1,054 Soviet targets (assuming 140 are soft, 40 are hardened to 100psi, and the remaining 844 to 300psi), 65.3% of these could be expected to be destroyed (see Table 2).[35] In the second case,

35. The allocation of American warheads in this and the subsequent attacks was designed to achieve approximately equal kill probabilities against all Soviet targets. Implicitly, this assumes that each Soviet target is equally valuable. This, of course, may not be the case, especially if only part of the enemy's missile force is MIRVed. Alternatively, the attack could have been designed to reduce either the number of

assume that of the 31 Polaris submarines with Poseidon missiles, 60% of these are on station and that these SLBMs are also used in a first strike.[36] Then, 81.3% of the 1,054 Soviet targets could be expected to be destroyed (see Table 3). Finally, if the United States reprogrammed its land-based missiles in these two attacks, these missiles alone could be expected to destroy 71.2% and the combined land- and sea-based forces 82.8%.

If the Soviet Union had terminated deployment of its land-based missiles when they reached equality, the land-based U.S. MIRVed force would have posed no serious threat. If Soviet planners had calculated that the United States would use its submarine missiles on station in a first strike, they would have confronted a more serious problem, although 198 missiles would still have survived. This is not to argue that the Soviets either considered stopping at 1,054 or did such calculations. But if the Soviets had made calculations similar to these, these calculations could well have armed both sides in the debate over which policy to follow. Advocates of stopping at equality could point to the 198 surviving missiles and claim that this constituted a sufficient deterrent to a U.S. first strike. On the other hand, Soviet planners, worried about improvements in U.S. missile accuracies and the possibilities of a U.S. ABM defense, might have questioned whether these 198 missiles over time could be expected to provide a secure second-strike capability.

Next, what might Soviet planners today calculate to be the effect of a U.S. first strike against the number of land-based missiles which the Soviet Union may deploy under the SALT Interim Agreement? The Soviet Union has a choice: either to maintain all 1,618 land-based missiles currently deployed or under construction or to dismantle its older SS-7s and SS-8s

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warheads or the amount of megatonnage the Soviet Union could deliver on the United States in a second strike.

Of the 210 SS-7s and SS-8s, 140 are in soft sites (hence, the 5psi figure) and 70 are assumed to have been hardened to the same degree as the U.S. Titan-I (100psi) (on this point, see Institute for Strategic Studies, 1969: 27 and Stone, 1966: 130). The remaining Soviet missiles were assigned a hardness of 300psi. Again, there is no reason to believe the Soviets imitated the United States in designing their silos; however, no information exists on the public record as to the hardness of the Soviet silos built since 1964.

36. The use of the Poseidon missiles in the American attack force is questionable. The communications problems with the submarines are such as to make their use in a coordinated first strike very difficult. On the other hand, if counterforce strikes have not been considered for the Poseidon missile, it is hard to understand why the missile has been designed with a CEP similar to Minuteman-III. For a discussion of the problems of communication with the submarines, the capabilities of the Poseidon force, and the 60% estimate of the submarines on station, see Brown (1970).

TABLE 4
U.S. ATTACK AGAINST 1,408 SOVIET ICBMs (no reprogramming)

Missile	R Vs	Ratio	Target	Pk	#K
T-II	54	2 : 1	27(300psi)	.694	19
MM-II	450	1 : 1	450(300psi)	.52	234
MM-III	212	1 : 1	212(300psi)	.312	66
MM-III	1,438	2 : 1	719(300psi)	.527	379
Totals	2,154		1,408		698
					49.6%

TABLE 5
U.S. ATTACK AGAINST 1,408 SOVIET ICBMs (no reprogramming)

Missile	R Vs	Ratio	Target	Pk	#K
T-II	54	2 : 1	27(300psi)	.694	19
MM-II	450	2 : 1	225(300psi)	.77	173
MM-III	756	2 : 1	378(300psi)	.527	199
MM-III	894	3 : 1	298(300psi)	.674	201
Pos	2,880	6 : 1	480(300psi)	.612	294
Totals	5,034		1,408		886
					62.9%

and replace them with modern SLBMs. Consider the case in which the Soviet Union dismantles its 210 SS-7s and SS-8s, leaving 1,408 strategic launchers hardened to 300psi. The U.S. land-based force of 1,054 missiles could only be expected to destroy in an attack without reprogramming 49.6% of these 1,408 Soviet targets (see Table 4). If the United States also used its 18 Polaris submarines with Poseidon missiles in a first strike, then 62.9% of the Soviet land-based force could be expected to be destroyed (see Table 5).

If, instead, the Soviets determined to maintain 1,618 land-based missiles (140 soft, 70 hardened to 100psi, and the remaining 1,408 hardened to 300psi), the United States could expect to destroy in a first strike, using only its land-based missiles with no reprogramming, 49.3% of this 1,618 Soviet force. When pondering their option to convert the older SS-7s and SS-8s to SLBMs, what conclusions might Soviet planners draw if they were to do such calculations? If the 210 SLBMs could all be considered invulnerable to a U.S. first strike, then the Soviets would clearly gain by such a conversion. However, if only those SLBMs on station could be considered invulnerable, the Soviet Union would have to maintain 50% of their SLBMs on station to ensure the same number (100) missiles survived.

Even if the United States were to deploy a reprogramming system on its missiles, this would not significantly change the potential number of Soviet land-based forces surviving. Against 1,408 targets, only 27 more targets would be destroyed, and nearly 50% of the total force would still survive. In a combined attack by U.S. land- and sea-based missiles, reprogramming of the land-based missiles would increase the percentage of targets destroyed by only 2.7, up to 65.6%.[37] Thus, the self-restraint shown by the United States in not deploying a reprogrammable system may not only be, as some have argued, that it would add little to the U.S. *second*-strike capability but also that little is gained by such a reprogramming capability even in a U.S. *first*-strike, given the size of the U.S. missile force and the yields of the warheads on these missiles.[38]

If the United States were interested in improving the first-strike capability of these MIRVed missile forces to pose a more serious threat to the Soviet ICBM force, what effect would the following measures have: (1) MIRVing all the U.S. Minuteman force, (2) improving the accuracies on the Minuteman-III warheads, and (3) increasing the yield on the Minuteman–III warheads? First, assuming the same reliabilities, yields, and hardnesses as in the previous calculations, an attack without reprogramming by 1,000 Minuteman–III missiles and 54 Titan–II missiles could alone be expected to destroy only 55.5% of the 1,408 Soviet silos, an increase of only 6%.[39]

If, instead, the accuracies of the U.S. Minuteman–III were improved to .15nm CEP, the United States force of 450 Minuteman–II, 54 Titan–II, and 550 Minuteman–III could be expected to destroy 70% of the Soviet 1,408 missile force.[40] With the addition of the 18 submarines, the United States could be expected to destroy almost 80% of this same Soviet force. Of the two changes, the reduction in accuracies would be more significant.

37. In an attack against 1,608 Soviet land-based missiles, the percentage destroyed by the deployment of a reprogramming system on the U.S. land-based missiles would increase from 49.3 to 52.7.

38. The American decision not to deploy a reprogramming system for Minuteman (TAPS: Target Accuracy Prediction System) is described in Senate Committee on Armed Services (1970: 226, 1969: 1171-1760).

39. In an attack using the 18 submarines with Poseidon missiles, reprogramming the land-based missiles would increase the percentage of the Soviet force destroyed from 62.9 to 68.5.

40. Indeed, according to Tsipis (1972: 28), the United States may already have achieved these accuracies on the Minuteman-III.

However, individually, these changes in the U.S. MIRVed strategic forces still do not threaten the Soviet land-based missiles. Combine the reduction in Minuteman–III accuracies with the conversion of all Minuteman-II to Minuteman-III, then the U.S. land-based force of 1,054 and the submarine force on station could be expected to destroy 87.9% of the 1,408 Soviet silos. While 171 Soviet missiles would still survive, the U.S. MIRV force would look more threatening.

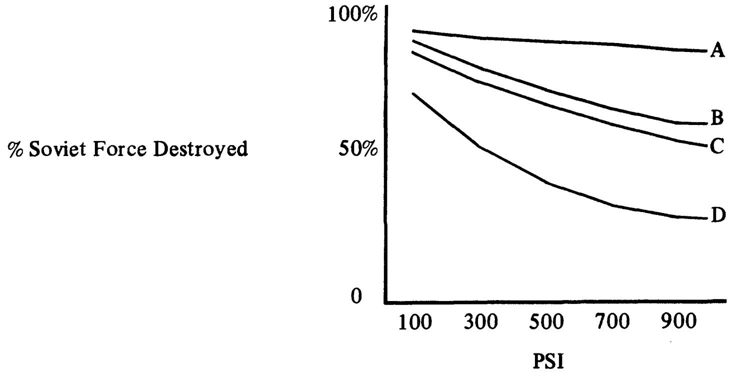
Finally, what effect would an increase in the yield of the Minuteman-III warheads have on the threat of the United States MIRVed strategic forces? According to Beecher in the New York *Times* of August 5, 1972, the yield of the Minuteman-III warhead could be increased by a factor of four. Against 1,408 Soviet targets hardened to 300psi, the U.S. force of 54 Titan-II, 450 Minuteman-II, and 550 Minuteman-III (CEP .25nm, yield .68MT) could be expected to destroy without reprogramming 68.2% of this force. If all 450 Minuteman-II missiles were converted to Minuteman-III and the yield of the warheads were increased to .68MT, 82.2% of the Soviet force could then be expected to be destroyed.

As described in Table 4, given a CEP of .25nm and a yield for Minuteman-III of .17MT, the U.S. ICBM force could be expected to destroy 49.6% of the Soviet 1,408 ICBM force. If either the Minuteman-III accuracies improve to .15nm CEP or the yield of the warhead increases by a factor of four, approximately 20% more Soviet targets could be expected to be destroyed. Combine these two improvements, and the number destroyed would be increased to 81.3%. Finally, if the 450 Minuteman-II missiles were converted to Minuteman-III and these improvements were made in both the accuracies and yield of the MIRV warheads, the United States could be expected to destroy in a first strike 93.7% of the 1,408 Soviet missile force. Only 89 Soviet ICBMs would survive. All these improvements would therefore have to be made before the U.S. MIRVed missile force could ensure the same degree of destruction against the Soviet land-based missile force as projected by Dr. Foster for the Soviet SS-9s alone.

Interestingly enough, the United States could achieve the same percentage destroyed by using its 1,000 Minuteman force alone in this attack against the 1,408 targets. Consequently, when the U.S. Minuteman force achieves the capabilities posited in this final calculation, the United States would have nothing to lose in terms of its first strike capability by converting its 54 Titan-II missiles into SLBMs.

In response, the Soviets have the option of further hardening their 1,408 land-based missiles. If, for example, the Soviets hardened their missile silos to 900psi, the number of Soviet silos the United States could expect to destroy in a first strike by 1,000 Minuteman-III missiles (yield .17MT and .25nm CEP) would be only 32% or 310 fewer missiles than such a Minuteman force could be expected to destroy if the Soviet silos were hardened to only 300psi. The Soviets could expect to save about the same number of missiles through such a hardening program, even if the United States improved the accuracies on the Minuteman-III to .15nm CEP *or* increased the yield of the warheads by a factor of four. Not until the United States combines an increase in the yield with a reduction in the CEPs of the Minuteman-III warheads would the hardening program have a significantly smaller effect. At that time, such a Soviet hardening program could reduce the percentage of Soviet missiles destroyed from 93.7 to 86.9%, although 100 additional Soviet missiles could still be expected to survive (see Figure 1).

In summary, the U.S. MIRV program as currently planned does not pose a threat similar to Dr. Foster's projected Soviet SS-9 force. Even if improvements are made in the U.S. MIRVed strategic missile forces, the Soviets always have the option of hardening their missile silos. Nevertheless, the U.S. MIRVed missile force could inflict substantial destruction on



	Yield	CEP
A	.68 MT	.15nm
B	.17	.15
C	.68	.25
D	.17	.25

Figure 1: 1000 MM-III vs. 1408 SOVIET LAND-BASED ICBMs

the fixed-site Soviet land-based missile force and is undoubtedly taken quite seriously by Soviet planners.

Prospects

This paper's brief delineation of the MIRV threat to the future pre-launch survivability of the superpowers' fixed-site land-based ICBMs has shown that as long as technological improvements can be made in their missile systems, the United States and the Soviet Union will continue to have this issue on their military agenda. The SALT agreements, signed in May 1972, do enhance the survivability of both superpowers' land-based ICBMs. The 313 SS-9 limitation, given the technical characteristics assumed in the 1969 estimates and a 3 5MT MIRV configuration, could be expected to reduce the percentage of Minutemen which could be destroyed in a first strike from 95 to 70. The limitation of the United States to 1,000 light ICBMs and 54 Titan-II missiles places even greater constraints on the capability of the United States to threaten the Soviet land-based missile force. Indeed, improvements would have to be made in the presently planned U.S. land-based MIRV force for those missiles simply to destroy half of the Soviet ICBM force in a first strike.

Nevertheless, the failure of the SALT agreements to control qualitative improvements on the missile systems raises doubts about the effectiveness over time of these SALT Phase I limitations. Only a change in the Soviet SS-9 MIRV configuration is required to confront the United States again with the possibility that the Soviet Union could destroy 95% of the Minuteman force in a first strike. While the United States would have to improve its MIRVed missile force more significantly to destroy the same percentage of the Soviet land-based force, Soviet planners could face over time a similar problem.

The effect of the SALT agreements, therefore, is to put off, not solve, the threat to the pre-launch survivability of the fixed-site land-based ICBMs. Moreover, these agreements also prohibit certain alternative means to protect the ICBM deterrent. The ABM Treaty restricts deployment of ABMs for ICBM defense. Hiding or faking missile silos is excluded by Article V of the Interim Agreement which prohibits the use of deliberate concealment measures to impede verification by national means. Super-hardening of missile silos is eliminated, since the existing silos cannot be relocated under the Interim Agreement. Intermediate hardening, up to 1,000psi, is still possible but, as shown in the preceding section, this method of protection is only effective until improvements are made in the accuracies of yields of the MIRV warheads. Finally, the United States has made a unilateral statement that deployment of operational land-mobile ICBM launchers during the period of the Interim Agreement would be considered inconsistent with the objectives of the agreement.

Provided the superpowers are determined to maintain over time the prelaunch survivability of their fixed-site land-based ICBMs, they will confront the following alternatives: (1) to prepare to launch the ICBMs on warning; (2) to pursue qualitative limitations on the MIRVs, throw-weights, or accuracies of these missiles at SALT Phase II; (3) to refuse to renew the Interim Agreement after five years and build additional land-based ICBMs or mobile ICBMs; (4) to abrogate the ABM Treaty; or some combination of the above.

This is not to argue either in favor of or against the maintenance of the land-based ICBMs. Rather, these are the possible choices which the two superpowers will have to consider in the future design of their strategic forces and in the preparations for SALT Phase II. The purpose of this paper has been to present the concepts, variables, and methods involved in calculating the effects of MIRVed missile attacks on fixed-site hardened ICBMs to provide the reader with an ability to come to an independent judgment about some of these choices.

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