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The ICBM Basing Question

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This paper compares and evaluates alternative mutual ICBM basing options for both the US and Soviet Union, assuming both START and finite-deterrence (2,000 warheads per side) force structures. While continued reliance on multiple-warhead silo-based missiles will make ICBMs even more unstable than they already are, stability could be quickly enhanced by replacing multiple warheads with single warheads in present silos. For the longer term: mobile basing is stable if deployed randomly over large land areas, but not if bunched at known garrisons. A 500-warhead rail- or land-garrison force would be vulnerable to short-warning attack by as few as one (for rail-MX and SS-25) to three (for garrison-Midgetman) ballistic-missile submarines. At least two other options are sufficiently promising to warrant full engineering evaluation: superhard silos and multiple silos. If technically feasible, they might be more stable than the mobile modes because, unlike mobile missiles, their survivability does not depend on whether attack warning information is received or acted upon.

INTRODUCTION

Improved US and Soviet ICBM accuracies have made each side's own ICBMs vulnerable to a preemptive strike. In response the United States may move its 50 MX missiles from silos to trains and is developing the land-mobile single-warhead Midgetman missile. The Soviet Union strengthened its ICBM silos, and had, by the summer of 1990, deployed 27 ten-warhead rail-based SS-24 missiles, 40 silo-based SS-24s, and 200 single-warhead land-mobile SS-25 missiles.[1] In the future, as both sides reduce their numbers of warheads and as offensive capabilities such as accuracy and warhead reliability improve even further, it may be especially important to maintain confidence and stability via relatively invulnerable weapons.

Recently, the American Physical Society's Forum on Physics and Society

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undertook a broad study of US missile vulnerability.[2] A key conclusion was that a US decision on how to base its ICBMs is closely tied to the size and character of the other side's forces, and hence to the assumed arms-control scenario. This paper studies both START and "finite deterrence" (2,000 warheads per side)[3] restrictions. While drawing on the APS/Forum study, we study Soviet security as well. Other useful overviews are listed below.[4]

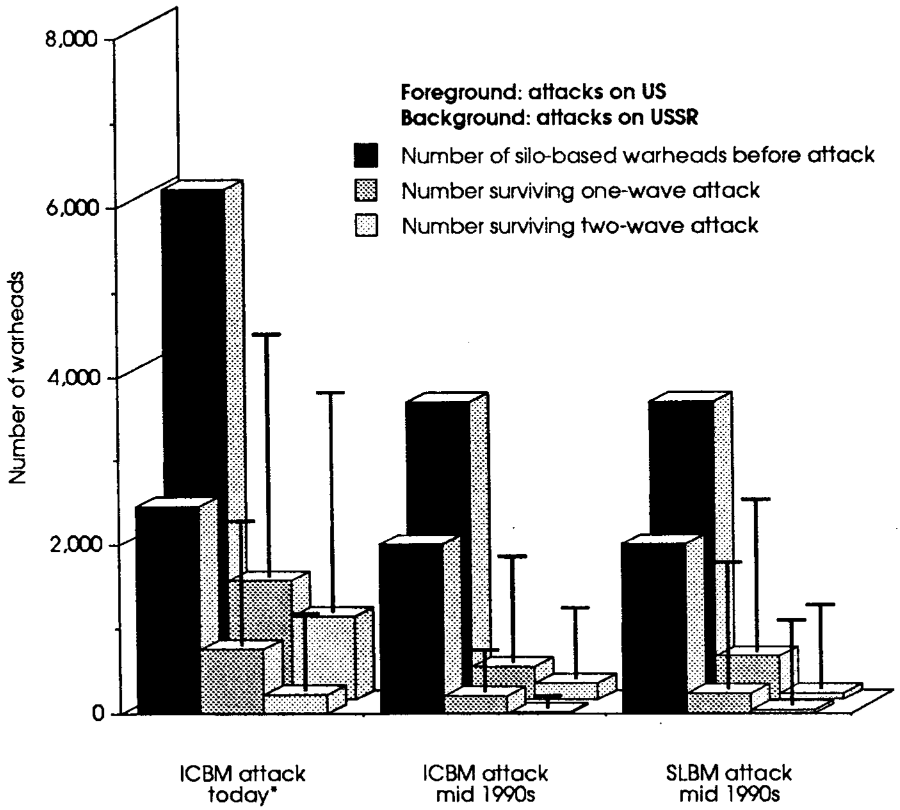

Figure 1: Survivability of silo-based ICBM warheads attacked by ICBMs today and attacked by ICBMs and SLBMs in the mid 1990s assuming continued reliance on highly MIRVed ICBMs (START/MIRV scenario, table 1). The legend refers to: total silo-based warheads before attack; warheads surviving a one-wave (one attacking warhead per silo) attack; warheads surviving a two-wave attack (two attacking warheads per silo). The error bars range from the defense-pessimistic values graphed, to defense-optimistic values. Appendix A gives assumptions and method of calculation.

* Because today the US has too few high-lethality warheads to double-target all Soviet silos, the "two-wave ICBM attack" on the USSR today is actually assumed to be a mixed one-wave/two-wave attack using all available high-lethality warheads.

CONTINUED RELIANCE ON MOSTLY MIRVED MISSILES

Table 1 shows (May 1990) ICBM forces along with representative future ICBM force structures. START/MIRV is a "stand pat" structure that assumes continued reliance on MIRVed missiles in present silos while still complying

Table 1: US and Soviet ICBM and SLBM forces in May 1990, and future force structures: missiles x MIRVing

	1990[a]	START/ MIRV	START/ deMIRV	Finite deterrence
US				
Minuteman II[b]	450 x 1	0	450 x 1	0
Minuteman III	500 x 3	500 x 3	350 x 3	0
MX silo-based[c]	50 x 10	50 x 10	0	0
Midgetman silo-based[b,c]	0	0	0	0
Silo-based warheads	*2,450*	*2,000*	*1,500*	*0*
MX rail-based	0	0	0	0
Midgetman survivable[d]	0	0	0	500 x 1
ICBM warheads	2,450	2,000	1,500	500
SLBM warheads	5,024	2,900	3,400	1,000
	7,474	*4,900*	*4,900*	*1,500*
USSR				
SS-11/13	400 x 1	0	0	0
SS-17	65 x 4	0	0	0
SS-18	308 x 10	154 x 10	0	0
SS-19	320 x 6	265 x 6	360 x 6	0
SS-24 silo-based[c]	40 x 10	40 x 10	0	0
SS-25 silo-based[c]	0	0	370 x 1	0
Total silo warheads	*6,060*	*3,530*	*2,530*	*0*
SS-24 rail-based	27 x 10	27 x 10	27 x 10	0
SS-25 survivable[d]	200 x 1	200 x 1	200 x 1	1,000 x 1
ICBM warheads	6,530	4,000	3,000	1,000
SLBM warheads	3,642	900	1,900	500
	10,720	*4,900*	*4,900*	*1,500*

a. From Arms Control Association Fact Sheet, "Strategic Nuclear Forces of the United States and the Soviet Union" (Washington DC: Arms Control Association, May 1990).

b. Future US single-warhead silo-based missiles could be either Minuteman IIs or Midgetmen.

c. Basing in silos of the present type, having a strength of 100–500 atm.

d. Randomly dispersed over large land areas, or (if they prove feasible) based in superhard or multiple silos.

with START restrictions. START/deMIRV assumes single or low-MIRVed warheads in present silos, but with no new survivable deployments such as new mobile missiles. Finite deterrence assumes 2,000 warheads per side with 1,500 on ballistic missiles allocated as shown.[5]

Figure 1 shows calculated warhead survivability with today's forces, and in the mid 1990s under the START/MIRV scenario for both one-wave attacks (one warhead per silo) and two-wave attacks (two warheads per silo). For the mid 1990s, SLBM attacks could be feasible and are included in figure 1. Appendix A outlines the calculations and gives assumptions and more detailed conclusions. Many observers would conclude from figure 1 that silo-based missiles are unstable, and that matters will get worse under continued reliance on highly MIRVed missiles.

Several points are worth noting. First, SLBM attacks on ICBMs may be quite effective by the mid 1990s. This is significant because a quick attack from offshore submarines can then destroy the silo-based force while simultaneously destroying bombers before take-off.[6] In an attack by ICBMs, timing problems prevent such a simultaneous attack.[7] The prospect of such an attack reduces a side's ICBM–SLBM–bomber triad to a single invulnerable SLBM leg. US Trident II missile deployment, currently under way, makes this a near-term concern for the Soviet Union. Five US submarines can conduct the two-wave SLBM attack on Soviet ICBMs in figure 1, and three submarines can conduct the one-wave attack. For a Soviet attack on the US, this prospect is at least a few years further off,[8] and is less significant because the still-invulnerable SLBMs comprise the strongest US leg.

Today, the limiting factor on the effectiveness of one-wave attacks is missile reliability rather than accuracy. Unreliability stems mostly from boost-phase failure. But such early failures can be easily detected, and could be quickly corrected through use of flexibly preprogrammed ICBMs to take over the missions of the failed missiles. This tactic raises the effective reliability of each attacking missile from an assumed 80 percent to around 90 percent.[9]

The Soviet Union puts 60 percent of its strategic warheads on ICBMs, versus 20 percent for the United States. Thus attacks on the two ICBM forces today would destroy about 5,000 Soviet warheads versus about 2,000 US warheads, if we make defense-pessimistic assumptions. It is not surprising, therefore, that the Soviet Union decided, years ago, to begin moving toward more survivable ICBMs.

DEMIRVING OF PRESENT SILOS

The ICBM dilemma stems from the fact that individual land-based missiles can always be destroyed by a sufficiently large and determined attack, no matter what the basing mode. Neither side can unilaterally guarantee the security of its own ICBMs. It follows that ICBM security must be mutual security, based on tacit or overt agreement.

In particular, in a quantitatively restricted world of START or finite deterrence, a basing mode could assume high survivability of ICBMs if attacks on the missiles required more weapons for a militarily significant attack than the attacking side would plausibly allocate. Given a warhead-limiting arms-control regime, a good evaluation of a basing mode's stability is thus the "price to attack" that mode: the number of warheads needed to attack it per (expected) warhead destroyed. Table 2 gives the prices of two-wave attacks against present silos, as well as the prices to attack the four other basing options discussed below.

The "present silos" attack prices of table 2 demonstrate the destabilizing effect of MIRVing. In the START/MIRV scenario, the overall prices to attack US and Soviet ICBMs, respectively, are only 0.6 and 0.3. As a rule of thumb, attack prices below 1 might be considered destabilizing because they allow an attacker to come out "ahead" by destroying more warheads than are used in the attack. Note that the higher MIRVing of Soviet ICBMs reduces their attack price to half that of US ICBMs, despite the assumption that Soviet silos are twice as strong as US silos.

Stability would be greatly improved by deMIRVing some present silos. For example, under the START/deMIRV scenario (table 1) the overall prices to attack, respectively, US and Soviet ICBMs are 1.1 and 0.7, about double the attack prices under the START/MIRV scenario.

In a finite-deterrence regime based on single-warhead missiles, ICBMs would be rather stable even if they were housed in present silos rather than in survivable basing modes (FD/single silos scenario of table 2). The overall prices for two-wave attacks against US and Soviet ICBMs would be 2.1 and 2.4 respectively. The Soviet Union would need its entire ICBM force for a full (i.e. against the entire force) two-wave attack on the smaller US ICBM force, an attack that leaves 25 surviving US ICBMs. The US could not mount even a full one-wave ICBM attack, and a US SLBM attack against Soviet ICBMs would consume the entire SLBM force while leaving 200 surviving Soviet ICBMs.

Table 2: Price to attack (warheads used/warheads destroyed) several basing options

US ICBMs attacked	*Price to attack*	*Soviet ICBMs attacked*	*Price to attack*
	PRESENT SILOS[a]		
Minuteman II, Midgetman (× 1)	2.1	SS-25 (× 1)	2.4
Minuteman III (× 3)	0.7	SS-19 (× 6)	0.4
MX (× 10)	0.2	SS-18, SS-24 (× 10)	0.25
START/MIRV scenario[b]	0.6	START/MIRV scenario[b]	0.3
START/deMIRV scenario[b]	1.1	START/deMIRV scenario[b]	0.7
FD/single-silos scenario[c]	2.1	FD/single-silos scenario[c]	2.4
	RAIL (500 warheads)[d]		
Garrison MX:		Garrison SS-24:[e]	
< 30 minute tactical warning[f]	0.04	< 30 minute tactical warning[f]	0.04
1 hour dispersal	0.5	1 hour dispersal	0.5
2 hours	1.1	2 hours	1.1
4 hours	2.9	4 hours	2.9
dispersed (24 hours)	40	dispersed (24 hours)	40
Random MX[g]	40	Random SS-24	40
	LAND MOBILE (500 warheads)[h]		
Garrison Midgetman:		Garrison SS-25:	
< 2 minute dash[i]	0.6	< 2 minute dash[i]	0.2
5 minute dash	2.4	5 minute dash[i]	0.2
10 minute	4.8	10 minute[i]	0.2
15 minute	6.0	15 minute	0.4
30 minute	1.5	30 minute	1.5
60 minute	4.8	60 minute	4.8
Random Midgetman:		Random SS-25:[j]	
nonalert	2.6	nonalert	2.6
5 minute dash	4.4	5 minute dash	2.8
10 minute	6.2	10 minute	3.0
15 minute	8.0	15 minute	3.2
on alert area	5.2	on alert area	5.2
	SUPERHARD SILOS (500 warheads)[k]		
500 Midgetman (× 1)	2.1	500 SS-25 (× 1)	2.1
167 Minuteman III (× 3)	0.7	84 SS-19 (× 6)	0.35
50 MX (× 10)	0.2	50 SS-18 (× 10)	0.2
	MULTIPLE SILOS (500 warheads)[l]		
500 Midgetman (× 1)	11	500 SS-25 (× 1)	11
167 Minuteman III (× 3)	11	83 SS-19 (× 6)	11
50 MX (× 10)	11	50 SS-18 (× 10)	11

Conservative observers might nevertheless consider single warheads in present silos to be unstable, given the possibility of highly effective one-wave attacks. A one-wave attack could, defense-conservatively, destroy 90 percent of the opposing ICBMs at an attack price just above 1. If launched by SLBMs against ICBMs and bombers, this could leave the attacked side with "only" an intact SLBM force. Thus, deMIRVing of present silos might be more plausible

Table 2: *continued*

a. For attacks on present silos, we assume a two-wave ICBM attack in the mid 1990s, reliability = 80 percent, and all other parameters lying midway between the "optimistic" and "pessimistic" assumptions of appendix A. These attack prices would be nearly cut in half if we assumed one-wave attacks at high reliability.

b. Total warheads used/total warheads destroyed, in an attack on the entire silo-based ICBM force described in table 1.

c. This force structure is not listed in table 1. It assumes 500 US and 1,000 Soviet single-warhead ICBMs housed in silos of the present (vulnerable) type.

d. See figure 2 for rail-mobile assumptions.

e. We do not know whether the SS-24 is garrisoned or random. We assume that a garrison-based SS-24 has survivability characteristics similar to those of the MX.

f. Since the trains would not attempt to disperse upon tactical warning, this is a targeted attack on the garrisons. We assume each garrison contains 60 warheads, and is attacked by two 80-percent-reliable warheads. The two warheads need to come from two missiles because of missile unreliability. See text for other details.

g. The US prefers to deploy garrison-rail rather than random-rail. This hypothetical scenario assumes that 500 MX warheads are randomly dispersed over 160,000 kilometers of US railroad lines.

h. See figure 3 for land-mobile assumptions.

i. "Dash time" means time actually spent dashing; the total time to deploy would be some five minutes longer (see endnote 17). Midgetman requires two-minute dash time to get far enough from its garrison to escape a single 0.5-megaton warhead targeted on the garrison; SS-25 requires 10 minutes. For targeted attacks on all 250 Midgetman garrisons, we assume two waves of hard-target–capable (0.5 megatons—see text) SS-N-20 warheads from three Typhoon submarines, targeted on the two Midgetmen and on the (average of) two Minuteman warheads at a garrison, under intermediate assumptions for the mid 1990s. For targeted attacks on all 56 SS-25 garrisons, we assume two waves of Trident II SLBM warheads (although Trident I's would do about as well) from one Trident submarine.

j. The SS-25 is actually garrisoned, not random. This hypothetical scenario assumes that SS-25s are randomly based on 190,000 square kilometers, the area required to give SS-25s the same attack price that Midgetman has on its 10,000-square-kilometer peacetime area.

k. Attacks on superhard silos assume two waves of inertially guided, single-large-warhead (20 megatons), SS-18-type missiles having MX-type accuracy (100 meters) and 80-percent reliability. The use of either high-accuracy MaRVs or earth penetrating warheads could not reduce the two-wave attack price against unMIRVed superhard silos below 2.0. The price for a one-wave attack is 1.3 at 80-percent reliability, and 1.1 at 90-percent reliability.

l. Attacks on multiple silos assume two waves of 0.5-megaton warheads having 100 meters CEP and 80-percent reliability, against 700-atmosphere silos. The price for a one-wave attack is 7.4.

as an interim stabilizing solution than as a longer-term stable solution.

Even without START or finite deterrence constraints, partial deMIRVing, such as the agreed elimination of some of the most highly MIRVed missiles, would improve stability. Moves in the other direction, such as removal of single-warhead US Minuteman II missiles while retaining three-warhead Minuteman IIIs, or further deployment of silo-based SS-24s as replacements for SS-17s or SS-19s, would be destabilizing.

An interim START/deMIRV force structure, on the way to a future finite-deterrence solution incorporating new more stable basing modes, appears desirable and realistic.

RAIL BASING[10]

The remainder of this paper studies candidates for new more stable basing modes. For each, we assume a representative force of 500 warheads.

The US version of rail basing would transfer the 50 silo-based 10-warhead MXs onto 25 trains, each carrying two missiles, and stationed in three- or four-train garrisons at seven air bases. Trains are housed individually in neighboring 250-meter-long "igloos" not strengthened against nuclear attack, having a strength of perhaps 7 atmospheres (100 psi).[11] One of the three or four trains in each garrison is on permanent "track alert," fully manned and ready to move onto the rail network "within a matter of minutes"[12] (or perhaps in "one-half hour or less"[13]) following an order to do so. The other two or three trains per garrison are not normally on alert status and could take several hours to begin to move out. However, in the event of a short-warning attack, the trains would not attempt to move out of garrison but would instead prepare to launch directly from garrison.[14] Once out of their garrisons, trains move at an average 50 kilometers per hour. Their strength against blast pressure is about 0.33 atm (5 psi), implying that a 0.5-megaton optimum-height airburst would destroy trains along about 10 kilometers of track.[15]

As of May 1990, the Soviet Union had deployed 27 rail-based 10-warhead SS-24s on nine trains, three missiles per train. Some trains are apparently housed in long garages at known locations, with three trains reported at one particular location, while others are randomly dispersed and moving from time to time along the 160,000-kilometer main Soviet railroad network.[16]

For any mobile system, there is a crucial distinction between "random basing" at unknown locations over a large region (as may be true of some SS-24s), and "garrison basing" at known locations with carriers ready to dash upon warning (as is true of the MX).

Random rail basing on the 160,000-kilometer Soviet (or similar US) main rail network could not be effectively attacked. Assuming the attacker cannot seek and destroy individual trains, a large-area "barrage attack" would be required. For example, under the above assumptions for rail MX, a 1,500-warhead barrage would cover only a small fraction of the network and destroy only 6 percent of the 500 mobile warheads, implying an attack price of 40!

Random rail basing's stability in a crisis is independent of MIRVing, because warhead bunching is of no help to an attacker who cannot find the launchers. On the other hand, random rail basing is unstable in the "arms race sense" because its extreme bunching (20 per US train and 30 per Soviet train) gives the attacker incentives to develop systems that can seek-and-destroy individual trains. Random rail basing is very unstable to this development, which would drop the attack price from 40 to around 0.1.

Unlike random basing, garrisoned systems require strategic warning. For trains, the needed time is long. Figure 2 shows the number of warheads needed to barrage all 25 MX trains, as a function of "dispersal time" (which we define as the time actually spent dashing, not including the time to prepare the trains to leave the garrisons), and table 2 gives attack prices in and out of garrison, at several dispersal times. A "strategic warning" (i.e. a warning issued prior to the launch of an attack) of several hours is needed to give the system the roughly four hours of dispersal time needed to raise the attack price to about 3 (some 1,200 attacking warheads). Rail-based MX would not try to dash to safety with only "tactical" warning that Soviet missiles have actually been launched (a maximum 30 minutes before explosions occur).

Garrison-based missile survivability is similar to bomber survivability. Like bombers, garrisoned missiles are bunched, soft targets that depend on adequate warning, quick dispersal, and concealment once dispersed, and so they are vulnerable to an attack that is fast rather than accurate. It is instructive to compare the times-to-safety for warning-dependent strategic systems (table 3).[17]

SLBMs are thus the main threat to garrisoned systems. While ICBMs reach US targets in 30 minutes, off-shore SLBMs travel the 2,600 kilometers to the central US in 15 minutes, or 10 minutes if launched along high-energy "depressed trajectories."[18] Fourteen SLBMs from one Typhoon or Delta IV submarine could double-target all seven MX garrisons by devoting two SLBMs to each of the seven garrisons. In fact, only two *warheads* (from two SLBMs, due to missile unreliability) would be needed at each garrison; if the attack were from a Typhoon submarine (10 warheads per SLBM), the other eighteen 0.1-megaton warheads per garrison could be used to barrage about 100 kilometers of track around each garrison.[19]

Thus rail-garrison MX gives the Soviet Union incentives to attack the garrisons from offshore early in a crisis. One additional submarine, added to

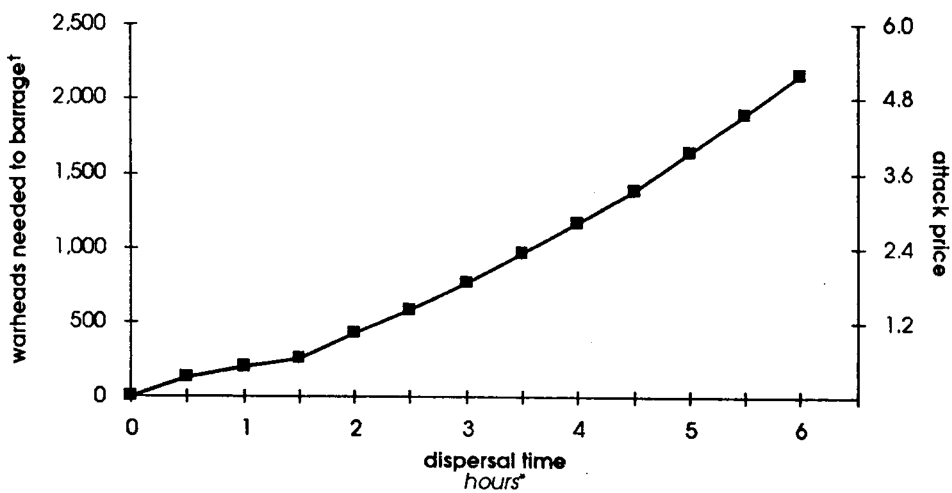

Figure 2: The number of 0.5-megaton warheads needed to barrage 500 rail-garrison MX warheads, as a function of dispersal time.

Assumptions: the MX survival rate is 15 percent due to attacking warhead unreliability; 0.5-megaton optimum-height airbursts, target strength = 0.33 atm (5 psi), 500 warheads carried on 25 trains starting from seven garrisons, speed = 50 kilometers per hour. For more details, see endnote 19.

Notes:

* "Dispersal time" is the time actually spent dashing, not including the time to prepare the trains to leave the garrisons. Under peacetime conditions, the time to prepare the first of the three or four trains per garrison is between a few and 30 minutes (see text), and the time to prepare the remaining trains may be a few hours.

† For yields other than 0.5 megatons, multiply the number of barraging warheads by these factors: 1.7 (0.1 megatons), 1.2 (0.3 megatons), 0.8 (1 megatons), 0.3 (20 megatons).

the SLBM attack that is considered the main threat to the bomber force,[20] could destroy the entire MX force.

Despite random basing's much greater stability, public interface problems have caused the US to choose garrison rather than random rail basing. We do not know the extent of peacetime dispersion of rail-based SS-24s; a truly random system, permanently dispersed over much of the rail network, would be stable. Its future stability would depend, however, on the absence of the problems that have forced the US toward garrison basing, and on the absence of seek-and-destroy systems.

LAND-MOBILE BASING

The US Midgetman is a single-warhead missile carried in a technically sophisticated "hardened mobile launcher" (HML) able to withstand 2 atm (30 psi) of blast pressure. The HML is pulled by a tractor at an average 45 kilometers per hour on and off roads. A deployment decision has not yet been made. Both random and garrison basing are being considered. Random basing would be on 10,000 square kilometers of government land in the southwestern US during peacetime, with random movements often enough to maintain deception. Upon either tactical or strategic alert, HMLs could spread out onto an alert area totaling 20,000 square kilometers, or onto nongovernment land. Garrison basing would be at pairs of soft bunkers a few tens of meters from existing Minuteman silos, from which HMLs dash on warning.

The Soviet SS-25 is a single-warhead ICBM carried in a metal canister on

Table 3: Total times-to-safety for some warning-dependent strategic systems[a]

Alert US strategic bombers	10–15 minutes
Garrison-land-mobile Midgetman	15 minutes
Garrison-land-mobile SS-25	50 minutes
Garrison-rail MX	4 hours

a. Unlike the "dash/dispersal times" discussed in this paper, these are total times, including the time to detect the attack and issue the "go" command, to start up vehicles, and to disperse. For mobile ICBMs, we define "safety" as an attack price of greater than 3, so that some 1,500 warheads would be needed to destroy the 500 mobile warheads. See endnote 17 for justification of these times.

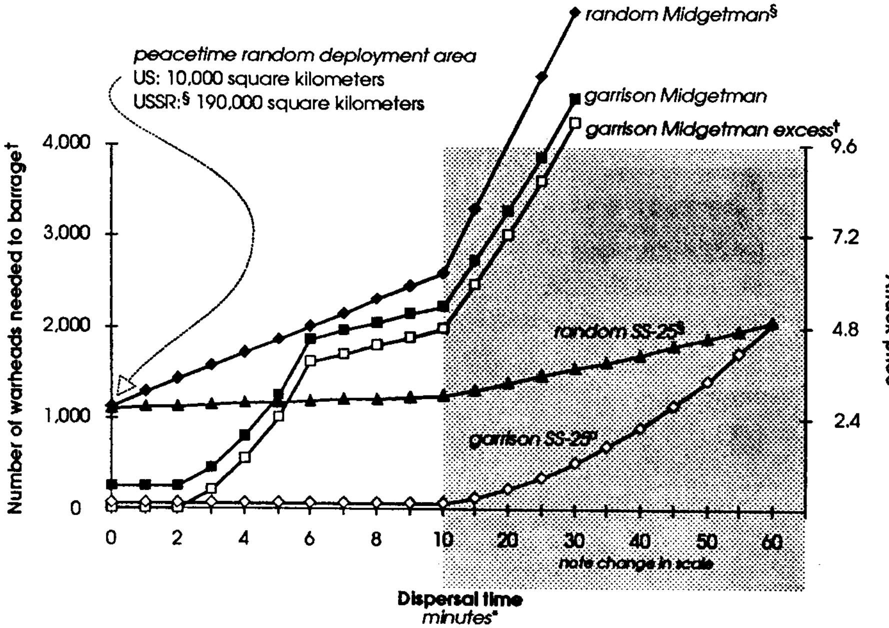

Figure 3: The number of 0.5-megaton warheads needed to barrage the dispersal area, as a function of dispersal time, for the land-mobile Midgetman and SS-25, in both the garrison and random modes. The mobile missile survival rate is about 15 percent due to attacking warhead unreliability; expenditure of 33 percent more barraging warheads gives a tighter barrage and decreases this rate to about 10 percent. The sudden bending in all graphs at t = 10 is due to the change in scale. See appendix B for justification of assumptions, and for details of calculation. Assumptions:

a. 0.5-megaton optimum-height airbursts, 500 mobile missiles, dash speed = 45 kilometers per hour, dash direction random.

b. Midgetman: HML strength = 2 atm (30 psi), thus HML is destroyed at 1.6 kilometers from blast, two HMLs per garrison, garrisons at Minuteman silos 8 kilometers apart, garrisons based on five widely separated Minuteman bases with 50 Midgetman garrisons (100 HMLs) per base.

c. SS-25: TEL strength 0.23 atm (3.5 psi, see error analysis below), thus TEL is destroyed at 7.1 kilometers from blast, nine TELs per garrison, garrisons 90 kilometers apart.

Notes:

* "Dispersal time" means the time actually spent dashing; the total time to deploy would be some five minutes longer (see endnote 17).

† For yields other than 0.5 megatons, multiply the number of barraging warheads by these factors: 2.9 (0.1 megatons), 1.4 (0.3 megatons), 0.6 (1 megaton), 0.09 (20 megatons).

‡ The "garrison Midgetman excess" graph is found by subtracting 250 from the "garrison Midgetman" graph and represents the "excess" warheads needed specifically to attack garrison Midgetman, above those probably targeted at the 250 Minuteman silos at which the HMLs are garrisoned.

§ The two random-mobile graphs assume peacetime dispersal on four areas totaling 10,000 square kilometers (Midgetman) and 190,000 square kilometers (SS-25). The random SS-25 mode is hypothetical; SS-25s are actually garrisoned. The random SS-25 peacetime dispersal area is chosen to make the size of the barrage needed to cover the peacetime area the same as the barrage (1,100 halfmegaton warheads) needed to cover the Midgetman peacetime area.

ᵅ Error analysis of SS-25 TEL strength: the strength is probably in the range 2–5 psi. Assuming 2 psi lowers the garrison SS-25 graph by 50 percent, and implies that the attack price reaches 2.4 at t = 61 minutes; assuming 5 psi raises the graph by 70 percent, and implies that the attack price reaches 2.4 at t = 33 minutes.

a large unhardened "transporter-erector-launcher" (TEL) truck capable of on-road and limited off-road travel. We estimate its strength at more than 2 psi (highway truck) but less than 5 psi (brick house, MX in its rail car)—perhaps 3.5 psi.[21] All 200 deployed missiles are garrisoned in above-ground concrete garages from which TELs can dash if given sufficient warning.[22] An SS-25 garrison consists of nine (sometimes six) TELs in individual garages about 100 meters apart, and typically measures less than 800 meters across. One to four such garrisons are stationed at bases separated typically by 90 kilometers.[23]

Figure 3 shows the calculated number of warheads needed to barrage land-mobile missiles, as a function of dispersal time starting from a nonalert (i.e. peacetime) condition. Assumptions and explanations are given in the figure caption, and appendix B gives all calculations and a detailed statement and justification of the assumptions. Table 2, as well as figure 3, gives the price to attack each mode at various dispersal times.

Several points should be noted. As expected, garrison basing of both Midgetman and SS-25 is far less stable at short times than random basing, although this effect is much less severe than for rail-mobile (cf. figure 2). Garrison Midgetman's stability is further reduced by parking the 500 Midgetmen at 250 Minuteman silos. This makes a surprise attack "free" (attack price = 0) during the first two minutes of dash, in the sense that no "excess" attacking warheads would be needed above those needed to target the silos, and reduces (by 250) the number of warheads needed to attack the system at all times.[24] Another destabilizing factor is the close 8-kilometer spacing of Midgetman garrisons. Expanding at 0.75 kilometers per minute, the individual barrage regions around each garrison meet and coalesce into five large regions[25] at t = 5–7 minutes, producing the bend to a smaller slope seen in the garrison Midgetman graphs of figure 3 at t = 6 minutes.[26]

For comparable basing, the SS-25 is even more vulnerable than Midgetman. For example, garrison SS-25 must dash for 40 minutes to reach an attack price of 2.4 (about 1,000 total barraging warheads), versus five minutes for garrison Midgetman. The soft TEL is the main factor responsible for this. For garrison SS-25, another reason is its bunching into nine TELs per garrison. A factor working in the other direction is the estimated large 90-kilometer spacing between garrisons, versus Midgetman's 8 kilometers.

The survival rate under barrage attack is uncertain, for two reasons: one-wave barrage attacks (two waves require twice as many warheads without destroying many more warheads) produce survival rates that are strongly dependent on the attacking warhead reliability, and reliabilities are not well known. Secondly, it is not known whether missile carriers caught in "gaps" between destruction regions would nevertheless be destroyed by the effects of two or three below-threshold (some 70–80 percent of threshold[27]) blasts. Each effect produces about a 10-percent "error bar" in the survival rate. See appendix B for details, where we argue that a plausible survival figure is 15 percent. In addition, it should be noted that the survival of the mobile missiles as effective retaliatory weapons would also depend on the radioactive fallout blanketing the missile fields, which could be intense.

For area barrages, and for a given barraging missile such as the SS-18 or the Trident II, we show in appendix B that MIRVing does not alter the barraged area very much—the barraged area is roughly independent of the MIRVing of the barraging missile. For example, an SS-18 can barrage about the same area regardless of whether it carries a single high-yield warhead, or is 10-MIRVed. Thus, under START either side might deMIRV some missiles in order to be able to barrage large areas while still complying with START's warhead constraints. For example, a high-yield single-warhead MX or SS-18 could barrage about the same area as the present 10-MIRVed versions, with only a tenth as many warheads. An arms-control yield limit could prevent this development.

Like rail-garrison, land-garrison basing is most plausibly attacked quickly and thus by submarines. Three Typhoon submarines could double-target the 250 Midgetman garrisons, while targeting the 250 adjoining Minuteman silos "for free" if the Soviet Union develops the ability to target silos from submarines. Assuming that the Soviets develop a silo-destroying Trident II–equivalent with 0.5-megaton warheads[28] this targeted attack would destroy any HML within 1.6 kilometers (two minutes of dash time[29]) of its garrison. The attack price is 0.6, if we include the (average of) two Minuteman warheads in each target.[30]

SS-25s are even more vulnerable: a plausible deployment of 500 TELs could be destroyed by 14 Trident II SLBMs (although the less lethal Trident Is would be nearly as effective against these soft targets) from one Trident submarine, implying an overall attack price of 0.2.[31] This targeted attack by 0.475-megaton warheads would destroy any TEL within 7.1 kilometers (10 minutes of dash time) of its garrison.

So garrison-land-mobile missiles do not solve, and in fact exacerbate, the problem of the simultaneous vulnerability of US ICBMs and bombers to a future SLBM attack.

Random basing is rather stable, assuming no seek-and-destroy systems, and assuming that, like the random Midgetman, it is deployed on a large enough peacetime area that some 1,100 halfmegaton warheads (attack price = 2.6) are needed to barrage it even with no warning. In these circumstances, SLBM attacks are implausible because because of the large number of off-shore submarines needed.[32].

Since the SS-25 is not based randomly, figure 3 assumes a hypothetical system for which the peacetime deployment area requires the same 1,100-warhead barrage as does Midgetman on its 10,000-square-kilometer peacetime area. Due to the SS-25's vulnerable TEL, this requires its peacetime area to be 190,000 square kilometers, about the area of Nebraska.[33]

Finite deterrence has the interesting effect of rendering random basing so stable that plans to disperse from the peacetime deployment area would be superfluous. For example, the entire 1,000-warhead Soviet ICBM force would be needed to barrage even the peacetime Midgetman operating area, and some 15 percent of the HMLs would still survive. Thus, plans to disperse on warning could be dropped. Like the superhard-silo and multiple-silo systems studied below, the random-mobile system would then offer no incentive for surprise attack, and require no noticeable change in operations in moving from peacetime to alert status. Furthermore, since the question of HML speed would become superfluous, HML armor could be strengthened further, producing still greater stability and/or reducing the land requirements. In effect, finite deterrence would transform the random-mobile system into a "moveable shelters" system, where the only purpose in mobility is to maintain location uncertainty, and speed is no longer important.

It has been suggested that, in an eventual finite-deterrence regime "the best option for mutual security would be as follows: each side would have approximately 600 light mobile single-warhead ICBMs, i.e., all other types of nuclear weapons and their delivery vehicles would be eliminated."[34] We see, however, that garrisoned land-mobile (or rail-mobile) missiles would be unsuitable for this role, and that random land-mobile missiles should either be deployed on very large nonalert areas (190,000 square kilometers for the SS-25), or carried in very strong vehicles (e.g. Midgetman's 30 psi).

There has been discussion of MIRVing of land-mobile missiles. The greater bunching and probable slower dash speed (due to greater weight) makes MIRVing destabilizing for garrisoned missiles. For random basing, MIRVing is only slightly destabilizing, because bunching is not destabilizing if deception is maintained and because random basing is not so dependent on the dash. However, MIRVing puts a greater premium on the other side developing seek-and-destroy systems and is thus "unstable in the arms-race sense."

SUPERHARD SILOS

The debate over mobile missiles has obscured two other plausible options: superhard and multiple silos. Although a judgement cannot yet be made on their technical or economic feasibility, they warrant consideration and full evaluation. Their noteworthy property, distinguishing them from the mobile options, is that their survivability does not depend on whether attack warning information is received or acted upon. They offer no incentive for surprise attack, and require no noticeable change in operations in moving from peacetime to alert status, so are less likely to introduce instabilities during a crisis.

We define a silo as "superhard" if its primary destruction mechanism is the fracturing and excavation associated with crater formation, rather than airblast pressure. By this definition, a superhard silo is survivable anywhere outside the edge of a nuclear crater.[35] Calculation, coupled with scarce information about nuclear-crater dimensions, indicates that in "beneficial" geology such silos would need to withstand on the order of 7,800 atm (115,000 psi) of blast pressure (appendix A). Appendix C discusses the construction and feasibility of such silos. Non-nuclear–blast tests with smaller-scale models have supported superhard-silo feasibility (appendix C), but full-scale engineering evaluation is needed, and it is not at all clear that such strengths are achievable. Nevertheless, in order to discuss their possible implications, we will assume here that such silos are feasible.

In appendix A, we derive formulas for superhard silo survivability. The result is dependent only on the attacking warhead's "lethality" $L = y^{2/3}/\mathrm{CEP}^2$, where y is its yield in megatons and CEP its inaccuracy (that distance from the target within which there is a 0.5 probability of the warhead hitting) in kilometers.

The so-called single-shot probability of survival for a superhard silo is broken down in figure 4 as a function of CEP for three different yields. We see that superhard silos will remain invulnerable to "conventionally guided" (boost-phase inertial guidance) warheads of up to 0.5 megatons yield. Conventional guidance is limited to some 75 meters accuracy,[36] which is insufficient for 0.5 megatons to destroy superhard silos. If all present and future warheads were of this or less lethal types, superhard silos would be a satisfactory solution to the basing problem.

However, superhard silos will be vulnerable to conventionally guided

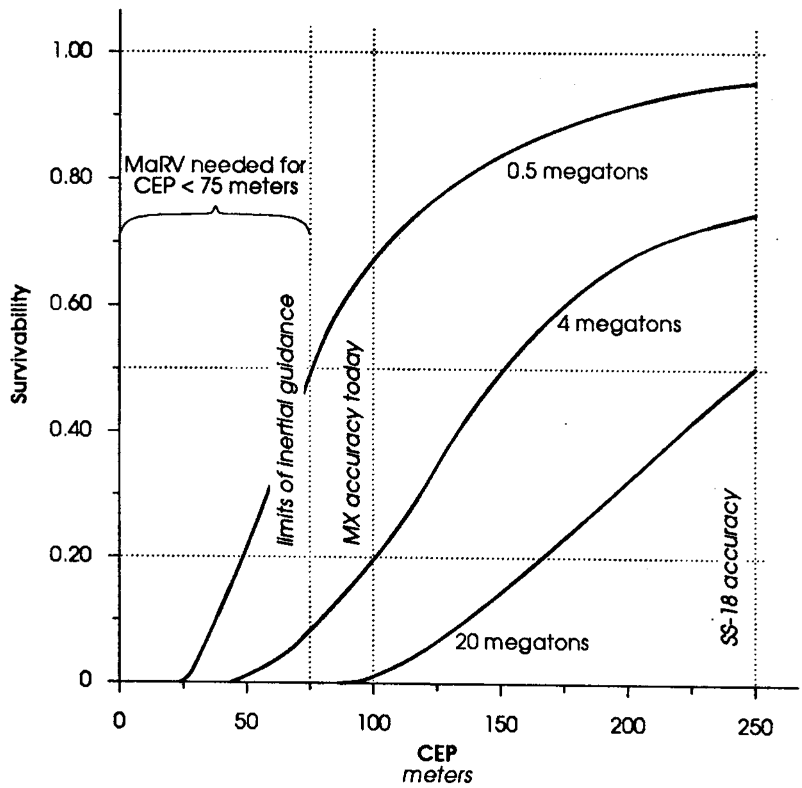

Figure 4: Survivability of a superhard silo attacked by warheads of three different yields, as a function of inaccuracy (CEP). The silo's strength is assumed to be the 7,800 atm (115,000 psi) that we estimate (appendix A) would exist at the crater's edge in "beneficial" geology. The attacking warhead must be a MaRV (maneuverable reentry vehicle) to attain CEP < 75 meters (see endnote 36). A 0.5-megaton yield is typical of today's ICBMs, 4 megatons is the yield of the single-warhead SS-19 mod 2, while 20 megatons is the yield of the single-warhead SS-18 mod 3. (Figure from Barbara G. Levi, Mark Sakitt, Art Hobson, editors, *The Future of Land-Based Strategic Missiles* (New York: American Institute of Physics, 1989).)

4–20-megaton warheads if they approximate MX accuracy. The Soviet Union has two single-warhead candidates, the 20-megaton SS-18 mod 3 and the 4-megaton SS-19 mod 2.[37] With 100-meter accuracy, the SS-18 mod 3 has a 98-percent SSPS against superhard silos, implying a two-wave attack price of 2.1 and a 5-percent survival rate, assuming unMIRVed targets. MIRVed superhard silos of course have lower attack prices, and are destabilizing (table 2).

Superhard silos might put a premium on the attacker developing terminally guided maneuverable re-entry vehicles (MaRVs) or earth-penetrating warheads (EPWs) for greater destructiveness, coupled to "standard" 0.5-megaton yields. The US is developing both and has already deployed MaRVs on the now banned Pershing II intermediate-range ballistic missile.[38] The Pershing II's CEP is estimated at 40 meters,[39] which would enable a 0.5-megaton warhead to destroy a superhard silo (figure 4). EPWs can at least double the crater radius at a given yield, which implies that a 0.5-megaton EPW would act like a 4-megaton surface burst against a superhard silo. Thus a 0.5-megaton EPW obeys the 4-megaton curve of figure 4, so with a 100-meter CEP this warhead could destroy a superhard silo.

On the other hand, there is a weight penalty for MaRVs and EPWs. For example, a Minuteman III missile could not carry even a single Pershing II MaRV to intercontinental distances.[40] An EPW may be two to three times heavier than a non-EPW of the same yield.[41] Thus, large highly accurate conventionally guided warheads may be at least as effective as MaRVs and EPWs against superhard silos.

Superhard silos are nearly invulnerable to SLBMs, because it would be difficult to give SLBMs the required accuracy–yield combination. Conventionally guided high-yield warheads would be heavy for an SLBM to carry. SLBMs armed with MaRVs or EPWs would be feasible only if the weight penalty were not too large. Thus superhard silos will probably not become vulnerable to simultaneous attacks on silos and bombers.

MULTIPLE SILOS

Multiple-silo or "carryhard" basing deceptively disperses a few hundred warheads among a few thousand silos, so that the other side must attack all the silos to destroy the smaller number of warheads. The number of silos should be so large that a militarily significant attack is implausible.

US discussions center on 2,500 silos deployed on several hundred square kilometers of government land. The deployment area is driven by the silo strength and is chosen to preclude the destruction of more than one silo per attacking warhead. The attainable strength, at reasonable cost for this many silos, may be 700 atm (10,000 psi). This is several times Minuteman silo strength, and might be attainable by keeping each missile in a strong capsule that also contains the missile's launch support equipment, and transporting the missile in its capsule, thus simplifying the silos.[42]

An inter-silo spacing of 600 meters would then suffice against warheads up to 1 megaton, and 2,500 silos could be deployed on 1,000 square kilometers (cf. 10,000 square kilometers for peacetime random Midgetman). If larger warheads seemed likely, or if a 700-atm strength is not attainable, the land area would be increased. For example, a doubling of yield or halving of silo strength implies a 60-percent increase in land area to maintain survivability.

To maintain concealment, missiles are moved among shelters every few months. Transport vehicles carrying either a missile or a dummy routinely move between silos, performing real and simulated transfers. In the late 1970s, a major research effort was conducted on maintaining concealment for the similar but horizontally sheltered MX "multiple protective shelter" (MPS) system.[43] Maintaining concealment is easier with multiple silos than it was for the MX system, because the much smaller land area of the multiple shelters simplifies area security problems, and because the missiles would be vertical.[44]

Assuming concealment, the price to attack multiple silos is very high. Even if only one warhead attacks each silo, half the ballistic missile warheads allowed under START are needed to attack all 2,500 silos. If some smaller portion of the silo system is attacked, the two-wave attack price is 11 (table 2), and the one-wave attack price is 6.6. Like random-mobile basing, MIRVing does not affect this price. MIRVing does however increase the other side's incentive to learn which silos are filled, and makes deceptive transportation between silos more difficult by making the missiles heavier.

Loss of concealment dramatically lowers the attack price, to about 2 for two-wave attacks against unMIRVed multiple silos (the same as for attacks against ordinary silos), and about $2/f$ for two-wave attacks against f-MIRVed multiple silos. Thus, multiple silos should perhaps be single warhead, as partial insurance against a failure of deception.

Multiple silos would be invulnerable to SLBM attack, because for example a one-wave attack would require 13 Trident submarines. Thus, like superhard silos, this system has the important effect of maintaining the impossibility of a simultaneous attack on ICBMs and bombers.

SUMMARY AND COMMENT

We summarize the basing candidates and comment on verification and breakout. "Breakout" refers to the prospect that the other side will rapidly deploy non–treaty-compliant weapons that might have a significant military effect. For example, either side might deploy, in a short time, its spare ICBMs on nonprotected launchers. We continue to assume 500 deployed warheads in each considered mode.

Present Silos: MIRVed and deMIRVed

Continued dependence on highly MIRVed ICBMs (START/MIRV, table 1) would be even more destabilizing in the future than it is today, despite START. Attack prices would average only 0.6 for attacks on the US, and 0.3 for attacks on the USSR. Moving to lower-MIRVed ICBMs in present silos (START/deMIRV, table 1) improves this picture considerably, roughly doubling the attack prices to 1.1 and 0.7.

A finite deterrence regime based on single warheads in present silos would be moderately stable, with attack prices greater than 2 for two-wave attacks. However, reliability improvements might render one-wave attacks effective, lowering attack prices to around 1. Moreover, present silos are vulnerable to SLBMs. Even under finite deterrence, a large attack by SLBMs against ICBMs and bombers, or by ICBMs against ICBMs, might then be feasible. Thus present silos might be best suited to an interim solution on the way to longer-term finite deterrence forces with less vulnerable basing modes (table 1).

We now turn to candidates for these survivable basing modes.

Garrison-mobile: Land and Rail

In a tabulation of attack prices (table 2), these modes are standouts at attack prices of 0.04–0.6 at short times. A single surprising Typhoon, Delta IV, or

Trident submarine can attack the entire garrison-MX or garrison-SS-25 force, while three Typhoons can attack the entire garrison-Midgetman force including perhaps the adjoining 250 Minuteman silos. Being vulnerable to submarines, these modes do not reduce the possibility of a simultaneous attack on bombers and ICBMs by SLBMs.

Rail garrison is by far the worst option, requiring four hours advance notice that an attack will be launched. Land garrison requires 15 (for Midgetman) to 50 (for SS-25) minutes. In addition to depending on warning, these modes entail visible and possibly destabilizing alert operations in a crisis.

If deployed, these modes should be accompanied by bans on seek-and-destroy systems and depressed trajectory SLBMs, and by offshore submarine keep-out zones. Neither START nor finite-deterrence restrictions help to stabilize these modes, because the destabilizing attacks on them are so small.

Verification of numbers of missiles in a garrison-based scheme could be done through cooperative measures such as electronic tagging, portal monitoring, periodic lifting of garrison roofs, designated deployment areas, and challenge inspections.[45] Quantitative breakout has little effect on the survivability of garrison-based missiles, because their main vulnerability is to small attacks.

Random-mobile: Land and Rail

These have attack prices of 2.5 (random land mobile, not alerted) to 40 (random rail mobile). In the absence of seek-and-destroy systems, these modes are rather stable. Submarine attacks are implausible (because large), so these modes assume that a simultaneous attack on ICBMs and bombers could not be effectively done. Although these modes do not depend strongly on warning, their survivability is enhanced by warning, and they entail highly observable and possibly destabilizing alert operations in a crisis.

Finite deterrence has the interesting effect of transforming random land-mobile basing into a "moveable shelters" system. Due to insufficient warheads to barrage even the peacetime dispersal area, finite deterrence renders this system so stable that all dash plans can be dropped, so that the system offers no incentive for surprise attack and requires no noticeable change in operations in going to alert. Furthermore, since dash speed is no longer relevant, the launchers' armor can be greatly strengthened. Strengths of greater than 2 atm might be attainable without the sophistication of Midgetman's

HML, which in turn reduces the enormous land area required today in order to stably deploy, for example, the SS-25.

However, all mobile modes are unstable in the "arms race sense" that they put a premium on the other side deploying new seek-and-destroy weapons. Such weapons have a very destabilizing effect. A verifiable ban on seek-and-destroy systems would greatly strengthen the stability of random-basing options.

Quantitative verification of random-mobile modes is complex but feasible using the methods described above for garrison-mobile modes. Expansion of the dispersal area could quickly compensate for any quantitative breakout. The US MX experience has shown however that such expansion might be politically difficult if it requires peacetime operations on nongovernment land.

Silos: Superhard and Multiple

Full engineering studies of both options should be pursued. If it is assumed that the options are technically feasible, one may draw the following conclusion: superhard silos would be invulnerable today, and would remain so under a ban on all very-high-lethality warheads, i.e. a ban on yields above about 1 megaton, on terminal guidance, and on earth-penetrating warheads. Even if such weapons were developed they would not necessarily render superhard silos unstable, but they would lower their attack price to about 2, assuming that warhead unreliability precludes the feasibility of one-wave attacks. Furthermore, the attacking warheads would have to be very high-quality and probably heavy devices, probably requiring large single-warhead ICBMs. Superhard silos should not be MIRVed.

Multiple silos have an attack price of about 10, which precludes a significant attack on them. Multiple-silo stability is independent of MIRVing provided concealment is maintained, although MIRVing puts more of a premium on maintaining concealment while making concealment more difficult.

These modes are not likely to become vulnerable to SLBMs. Unlike the mobile modes, their survivability does not depend on warning and call for no observable alert operations in a crisis. The only developments that could seriously reduce the survivability of these modes are improvements in missile and warhead reliability (to allow one-wave attacks and nearly halve the attack prices), and loss of multiple-silo concealment.

Superhard silos are easily verifiable by noncooperative means. Multiple silos require simple cooperative means, similar to the measures for the old MX "multiple protective shelter" plan, to which this plan is similar.[46] Basically, some silos are opened periodically for inspection by satellite.

It would be difficult for these modes to compensate for a large breakout, because of the long times needed to build additional silos. This stability thus requires strict arms-control measures precluding breakout.

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5. Feiveson and von Hippel, "Beyond START," p.162; von Hippel and Sagdeev, *Reversing the Arms Race*, p.32.

6. Michael E. Brown, "The US Manned Bomber and Strategic Deterrence in the 1990s," *International Security*, Fall 1989, pp.10–12, 17–24. Also see the follow-up debate: Donald Rice, "The Manned Bomber and Strategic Deterrence: The US Air Force Perspective," *International Security*, Summer 1990, pp.100–128; Michael E. Brown, "The Case Against the B-2," *International Security*, Summer 1990, pp.129–153.

7. This is often given as an important justification for having both strategic bombers and ICBMs. See, for example, Scowcroft, *Report of the President's Commission*, pp.7–8; Secretary of Defense Richard Cheney, quoted in "Cheney: Soviet Nuclear Upgrade Continues," *Aerospace Daily*, 24 August 1989, pp.336–337.

8. *Soviet Military Power 1989* (Washington DC: US Department of Defense, September 1989), p.47.

9. Since at least 1976, individual US ICBMs have been preprogrammable for four or more target sets (a missile's "target set" is an assignment of a specific target for each warhead in that missile) that can be quickly selected immediately prior to launch. See "Targeting Flexibility Emphasized by SAC," *Aviation Week & Space Technology*, 10 May 1976, pp.29–34. Thus an attack by N missiles could be backed up by perhaps only $0.25N$ missiles ready to immediately take over the target set of any boost-phase failure, raising the effective reliability to nearly that of the post-boost phase alone, often estimated at some 90 percent. For further discussion, see John D. Steinbruner and Thomas M. Garwin, "Strategic Vulnerability: The Balance Between Prudence and Paranoia," *International Security*, Summer 1976, pp.148–150; Desmond Ball and Robert C. Toth, "Revising the SIOP: Taking War-Fighting to Dangerous Extremes," *International Security*, Spring 1990, pp.69, 81, 85; David F. Bond, "House Cuts Funding for Modernizing USAF's ICBM Launch Control Centers," *Aviation Week & Space Technology*, 21 August 1989, p.69.

10. For a good overview, see Barry E. Fridling and John R. Harvey, "On the Wrong Track? An Assessment of MX Rail Garrison Basing," *International Security*, Winter 1988/89, p.113–141.

11. Since the 260-meter-long horizontal above-ground "igloos" housing the trains "do

not provide substantial hardening to nuclear attack" (Fridling and Harvey, "On the Wrong Track?"), their strength is surely less than 20 atm (retired Titan ICBM silos). It is probably greater than 2 atm (Midgetman in its hardened mobile launcher). According to Robert Zirkle, "MX Takes to the Rails—But Same Old Problems Ride Along," *Nucleus: Quarterly Report of the Union of Concerned Scientists*, Summer 1987, p.5, igloo strength is 7 atm.

12. "MX Rail System Nears Full-Scale Development," *Aviation Week & Space Technology*, 25 April 1988, pp.18–19.

13. Fridling and Harvey, "On the Wrong Track," p.120.

14. This capability of course does not stabilize the system, but rather is the sort of instability we want to prevent. The launch-on-warning capability confirms that the Air Force believes short-warning attacks are a possibility. For this and other rail-MX deployment details, see "MX Rail System," *Aviation Week*. Fridling and Harvey, "On the Wrong Track," pp.126–128, argues that, in the event of a short-warning attack from submarines, there would be too little time to receive and execute a launch-on-warning command.

15. Although a quick attack on rail garrisons would probably come from submarines, barrages over long rail lines would probably come from ICBMs, which typically carry about 0.5-megaton warheads, because it would be difficult to mount the many offshore submarines needed for a large barrage. A typical 0.1-megaton SLBM warhead would barrage 6 kilometers of track, making the attack price 70-percent larger than for 0.5-megaton warheads.

16. Information about SS-24 rail basing is difficult to come by. Sketchy reports may be found in "Mobile Missiles Still a Problem Despite Wyoming Agreement," *Washington Times*, 26 September 1989, p.4; "US Satellites Detect Marked Increase in Mobile Soviet ICBMs," *Washington Times*, 14 October 1988, p.6; "Soviets Have 9–30 Rail Mobile SS-24s,"*Defense Daily*, 9 May 1989, p.4; "B-2 Only System Able to Attack Relocatable Targets," *Defense Daily*, 7 March 1990, p.356; Steven J. Zaloga, "Land-Based Logic Drives Soviet Mobile ICBM Effort," *Armed Forces Journal International*, November 1988, pp.27–28.

17. Justification of table 3: For alert bombers, Brown, "The US Manned Bomber," p.22, shows that an SLBM flight time of 10–15 minutes allows 65–87 percent of the alert bombers to reach safety. Of this 10–15 minutes, the time for the US early warning system to sound the alarm at SAC bases is said to be 1.5 minutes; the time for SAC crews to scramble to their aircraft, start their engines, and taxi to their runway take-off point is 5 minutes; the actual flight time needed to disperse sufficiently to escape barrage attack is thus the remaining 3–8 minutes. Similar numbers are also given in: Congressional Budget Office, *Modernizing US Strategic Offensive Forces* (Washington DC: US Government Printing Office, 1983), appendix E, pp.99–110. For land-mobile Midgetman and SS-25, we assume the same 1.5 minutes for the US or Soviet early warning system to sound the alarm; we assume only 2.5 minutes for scrambling and starting up (since the vehicles don't taxi), and we assume an additional 1 minute for deployment in a hardened configuration. Thus, the total times-to-safety are 5 minutes longer than the "dash" or "dispersal" times of table 2 and figure 3.

18. Harold A. Feiveson and Frank von Hippel, "The Freeze and the Counterforce Race," *Physics Today*, January 1983, graph on p.42.

19. For an 0.1-megaton SLBM warhead against a 7-atm (100 psi) igloo complex, the radius of destruction = 500 meters. A vulnerability calculation (cf. appendix A), assuming a 200-meter CEP then gives SSPS = 1.3 percent, and a two-shot survival probability of 4 percent at 80-percent reliability. The remaining 18 warheads from the two SS-N-20 SLBMs allocated to each garrison must be allocated within the MIRV "footprint," hundreds of kilometers long by tens of kilometers wide, so could go to the adjoining airbase or rails. In a barrage of the rails, they could cover a track length of 5.9 kilometers per warhead × 18 warheads = 106 kilometers. This amount of track is generated around a single garrison in about 15 minutes of actual dash time (Fridling and Harvey, "On the Wrong Track?"). For seven garrisons, 14 SLBMs are needed. The 14-percent survival rate implies an attack price of 0.04 if only the two warheads needed are counted in the calculation, or 0.4 if both 10-MIRVed SLBMs are counted.

20. Brown, "The US Manned Bomber."

21. An error analysis is given in the caption of figure 3, using 2 psi and 5 psi.

22. Like the rail-garrison MX, the SS-25 can be launched from garrison if surprised. Again, this just confirms the system's instability.

23. Thomas. B. Cochran, William. M. Arkin, Robert. S. Norris,and Jeffrey. I. Sands, *Nuclear Weapons Databook Volume 4*, (New York: Ballinger, 1989) contains information about SS-25 and previous SS-20 intermediate-range ballistic-missile deployments, to which SS-25 deployment is similar. Information about garrison capacity and spacing is inferred from pp.194–195 plus a map of the Soviet Union. Information about garrison size is inferred from the site diagrams appended to the memorandum of understanding for the INF treaty.

24. This assumes that the Soviet Union would attempt to simultaneously target the Midgetman and Minuteman forces. It is also worth noting that garrison-based Midgetmen are not likely in a scenario that excludes silo-based ICBMs, because the reasons for garrison basing are the cost savings and operational simplicity of using Minuteman sites.

25. We assume five separate Minuteman operating areas; see appendix B.

26. The Midgetman graphs in Levi et al., *The Future of Land-Based Strategic Missiles*, pp.53, 201, fail to include this effect, and should thus be corrected to agree with figure 3. The corresponding bend in the SS-25 graph does not appear in figure 3 because it does not occur until t = 60 minutes.

27. See appendix B, endnote 1.

28. From *Soviet Military Power 1989*, p.47: "The Soviets also deployed a modified version of the Delta IV's SS-N-23 missile in 1988, and a modified version of the Typhoon's SS-N-20 missile may begin testing soon. Both programs are geared toward improving the accuracy and increasing the warhead yield of these systems in order to develop an SLBM hard-target-kill capability."

29. Throughout this paper, "dash time" and "dispersal time" mean the actual time spent moving at an average 0.75 kilometers per minute, excluding the time to receive the dash command, start up, and deploy in a hardened configuration. For land-mobile missiles, these operations might require an additional five minutes (see endnote 17).

30. Fifty 10-MIRVed SLBMs (three Typhoon submarines) could double-target the 250 garrisons. Assuming $S = 30$ psi, $y = 0.5$ megatons, CEP = 200 meters, reliability = 80 percent, the two-shot probability of survival is 1 percent, and the attack price is 2/2(0.99) = 1.01 if we count only the Midgetmen as the targets. If we also count the (average of) two Minuteman warheads as targets, their survival rate would be 18 percent, and the attack price becomes 2/(2·0.99 + 2·0.82) = 0.56. It is worth noting that depressed trajectories, although faster, would not be used in an attack that simultaneously targeted silos and HMLs, because of the accuracy problems associated with depressed trajectories.

31. Assuming garage strength = 1 atm, CEP = 140 meters, reliability = 80 percent, and maximum width of garrison = 800 meters, 0.475-megaton Trident I warheads destroy garages with an SSPS (appendix A) of 100 percent, and a two-shot survival probability of 96 percent. Assuming a garage strength as high as 10 atm would not change this. Essentially the same survival probability is obtained in an attack from Trident I SLBMs (CEP = 400 meters, $y = 0.1$ megatons). The implied attack price is 0.2. Today, all 200 deployed TELs (some 22 garrisons of nine TELs each) appear to be located at three operating areas near Perm, 1,000 kilometers east of Moscow. SLBMs would travel the 2,000 kilometers from the Norwegian Sea in 13 minutes, or eight minutes along depressed trajectories (Feiveson and von Hippel, "The Freeze and the Counterforce Race"). A future 500-TEL force might be located in seven operating areas, each operating area containing some eight garrisons of nine TELs each. In this case, each operating area could be destroyed by two 8-MIRVed Trident I or Trident II SLBMs, and all seven operating areas could be destroyed by 14 SLBMs from one Trident submarine.

32. To barrage the peacetime area, 15 Typhoon submarines, each carrying 200 0.1-megaton warheads, would be needed. However, if each submarine carried 200 0.5-megaton warheads (cf. one Trident submarine carrying 192 0.475-megaton warheads on Trident II SLBMs), then just six submarines would be needed.

33. Error analysis: 110,000 square kilometers at 5 psi, 400,000 square kilometers at 2 psi.

34. Committee of Soviet Scientists for Peace and Against the Nuclear Threat, from a study entitled ***Strategic Stability under the Conditions of Radical Nuclear Arms Reductions***, quoted in Thomas K. Longstreth, "Beyond START: Deep Reductions in Strategic Nuclear Forces," ***Federation of American Scientists Public Interest Report***, September 1989, p.11.

35. More precisely, the "edge of the crater" means the edge of the fractured inner bowl as distinct from the outer bowl that is merely pressed down by blast pressure. It should be noted that some authors define "superhard" as simply much harder than most silos, e.g. 500–1,000 atm, while others use our definition.

36. Matthew Bunn, ***Technology of Ballistic Missile Reentry Vehicles***, report number 11, Program in Science and Technology for International Security, (Cambridge, Massachusetts: Massachusetts Institute of Technology, 1984), p.30, shows that the minimum re-entry error for non–terminally-guided warheads is 50–70 meters. This establishes a lower bound on the overall accuracy. Donald MacKenzie, "Missile Accuracy—An Arms Control Opportunity," ***Bulletin of the Atomic Scientists***, June/July 1986, p.15, argues that the practical limit on the overall accuracy of such warheads is the MX's 100 meters.

37. Barton Wright, *Soviet Missiles: Data From 100 Unclassified Sources* (Lexington, Massachusetts: Lexington Books, 1986). These large warheads might not be presently deployed.

38. Matthew Bunn, "The Next Nuclear Offensive," *Technology Review*, January 1988, pp.29–38; Donald MacKenzie, "Missile Accuracy," p.15; "From MaRVs to Microwaves: New Weapons for Nuclear War," *Nucleus*, Spring 1988, pp.1, 4, 5; Ball and Toth, "Revising the SIOP," p.76.

39. Bunn, "The Next Nuclear Offensive," p.31.

40. MacKenzie, "Missile Accuracy," p.15.

41. John R. Harvey, Allan B. Schaffer, Roger Speed, and Anthony F. Todaro, *Carry Hard ICBM Basing: A Technical Assessment*, Center for Technical Studies on Security, Energy, and Arms Control (Livermore, California: Lawrence Livermore National Laboratory, 1989), p.13.

42. Ibid., pp.3–6. In this study, the silo is an open-top structure consisting of a corrugated steel inner liner backfilled with grout around the outside, constructed in porous geology to reduce transmitted ground shock, and filled with water to several meters above the top of the (closed) capsule. Tests have shown that, as the shock wave propagates down the water, radial expansion of the silo liner attenuates a 700-atm airblast on the top of the water to 200 atm at the top of the capsule. The shock-isolated missile inside its capsule is then able to withstand the remaining shock.

43. Office of Technology Assessment, *MX Missile Basing*, pp.35–40.

44. Vertical transport and insertion reduce and perhaps eliminate seismic and vibrational signatures that were a problem for the MPS system. Studies indicate that vertical transport is feasible for the Midgetman or Minuteman III, and that even the large MX missile could be transported vertically. Among the priorities of a multiple silos development program would be demonstration of concealment and vertical transport. See Harvey et al., *Carry Hard ICBM Basing*, pp.6–8.

45. Levi et al., pp.101–122; Feiveson and von Hippel, p.174.

46. Office of Technology Assessment, *MX Missile Basing*, pp.58–59.

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Appendix A

CALCULATING SILO-BASED MISSILE VULNERABILITY

Art Hobson

Standard Model of Silo Vulnerability

We summarize the standard model of silo vulnerability.[1] It is generally agreed that this idealized model is accurate enough for most purposes, in the sense that its inaccuracies are small compared to the uncertainties caused by the numerical inputs to the model.[2]

The attacking warhead's impact point is assumed to have a two-dimensional Gaussian probability distribution whose density is

$$f(\mathbf{r}) = \frac{\pi\sigma^2}{2}\exp\left(\frac{-\mathbf{r}\cdot\mathbf{r}^2}{2\sigma^2}\right) \qquad \text{(A-1)}$$

where $\mathbf{r}$ is the vector, in the impact plane, from the target silo to the impact. We make the "cookie cutter" assumption that a particular warhead type has a fixed radius of destruction *RD* against a particular silo type. Integrating equation A-1 over $r > RD$, the "single-shot probability of survival" (SSPS) of a silo attacked by one exploding warhead is then

$$\text{SSPS} = \exp\left(\frac{-RD^2}{2\sigma^2}\right) \qquad \text{(A-2)}$$

Defining the CEP by Prob($r <$ CEP) = 0.5, equation A-2 implies $0.5 = \exp(-\text{CEP}^2/2\sigma^2)$ because SSPS = 0.5 when *RD* = CEP. Using this result to eliminate σ from equation A-2,

$$\text{SSPS} = 0.5^x \text{ where } x = \frac{RD^2}{\text{CEP}^2} \qquad \text{(A-3)}$$

Experimentally, the peak airblast pressure *P* (in atmospheres above atmospheric pressure) from a groundburst of yield *y* (megatons) at a distance *r* (kilometers) from the blast is[3]

$$P = \frac{6.31y}{r^3} + 2.20\sqrt{\frac{y}{r^3}} \text{ (groundburst)}$$

$$\approx \frac{7.04y}{r^3} \text{ (correct to within 5 percent for standard silos, } 30 < P < 250 \text{)} \qquad \text{(A-4)}$$

$$\approx \frac{6.45y}{r^3} \text{ (correct to within 3 percent for harder silos, } P > 250 \text{ atm)}$$

Assuming the destructive mechanism is blast pressure, and that a peak pressure S (the silo's "strength") destroys the silo,[4] we have $P = S$ when $r = RD$, and equation A-4 implies

$$\sqrt{\frac{y}{RD^3}} = \frac{\sqrt{5.21S+1}-1}{5.74} \text{ (groundburst)} \approx 0.398\sqrt{S} \text{ (standard silos)} \quad \text{(A-5)}$$

Equations A-5 (approximated form, valid for today's silos) and A-3 together imply

$$\text{SSPS} = 0.5^x \text{ where } x = \frac{3.42L}{S^{2/3}} \quad \text{(A-6)}$$

where

$$L = \frac{y^{2/3}}{\text{CEP}^2} \quad \text{(A-7)}$$

is the warhead's "lethality" in $MT^{2/3}/km^2$.

The warheads "reliability" R is the probability that it will be delivered successfully and will detonate with its full explosive yield. Taking reliability into account, the probability of survival (PS) of one silo attacked by one warhead becomes

$$\text{PS} = 1 - R(1 - \text{SSPS}). \quad \text{(A-8)}$$

If a silo is attacked by two warheads, the overall probability of survival of the silo becomes

$$\text{Two-shot PS} = \text{PS}\cdot\text{PS}' \quad \text{(A-9)}$$

where $\text{PS}' = 1 - R'(1 - \text{SSPS}')$ is the probability of survival of the silo under the second warhead conditional on survival under the first warhead, where R' and SSPS′ are the (degraded, due to "fratricide") values appropriate to the second warhead.

Assumptions and Calculations for Figure 1

There is of course a lot of uncertainty about what numerical values to use for yields, CEPs, etc. Tables A-1 and A-2 list the range of plausible present and future values.[5]

The data of tables A-1 and A-2 were used, with equations A-6–A-9, to calculate the PS and the two-shot PS of US and Soviet silos. The "ICBM attack today" column assumes the 1990 mix of attacking and attacked ICBMs shown in table 1, while the "ICBM attack mid-1990s" and "SLBM attack mid-1990s" columns assume the START/MIRV mix of ICBMs and SLBMs shown in table 1. The resulting probabilities of survival were then translated into actual overall fractions of surviving silos, again assuming the force structures of table 1, as well as into total numbers of surviving warheads. Tables A-1 and A-2 list these results, and figure 1 graphs the warhead results.

Superhard Silo Vulnerability[6]

From the "harder silo" approximation of equation A-4, the blast pressure at the crater's edge is

$$P_R = \frac{6.45y}{R^3} \qquad \text{(A-10)}$$

where R is the crater's radius. By definition, $RD = R$ for superhard silos, so equation A-3 becomes, using equations A-10 and A-7,

Table A-1: Survivability of present US silo-based ICBMs and warheads to attack today and in the mid-1990s, assuming force structures that rely heavily on MIRVed silo-based ICBMs (START/MIRV scenario of table 1): assumptions (defense-pessimistic and defense-optimistic) and calculated results

	ICBM attack today	**ICBM attack mid-1990s** pessimistic / optimistic	**SLBM attack mid-1990s**
Assumptions:			
SS-18 CEP *meters*	200 / 250	90 / 125	
SS-18 yield *megatons*	0.5	0.5	
Soviet SLBM CEP *meters*			120 / 300
Soviet SLBM yield *megatons*			0.5[a]
Minuteman/MX silo strength *atmospheres*	130 / 200	130 / 200	130 / 200
Reliability *percent*	90 / 80	90 / 80	90 / 80
Fratricide probability[b] *percent*	0 / 5	0 / 5	0 / 5
Number of silos attacked	1,000	550	550
Number of warheads attacked	2,450	2,000	2,000
Results:			
Fraction of silos surviving one-wave attack *percent*	31 / 60	10 / 25	12 / 75
Fraction of silos surviving two-wave attack[c] *percent*	9 / 37	1 / 7	2 / 50
Number of warheads surviving one-wave attack	760 / 1,470	200 / 500	240 / 1,500
Number of warheads surviving two-wave attack	220 / 906	20 / 140	40 / 1,000

a. Assumes Soviet silo-destroying SLBMs will have warhead yields similar to the US Trident II's 0.475 megatons.

b. The probability that the second attacking warhead (against a single silo) will be destroyed by the first.

c. "Two wave" means two attacking warheads per silo.

Table A-2: Survivability of present Soviet ICBM silo-based ICBMs and warheads to attack today and in the mid-1990s, assuming force structures that rely heavily on MIRVed silo-based ICBMs (START/MIRV scenario of table 1): assumptions (defense-pessimistic and defense-optimistic) and calculated results

	ICBM attack today[a]	ICBM attack mid-1990s[b] pessimistic / optimistic	SLBM attack mid-1990s[c]
Assumptions:			
MX CEP *meters*	90 / 110	90 / 110	
MX yield *megatons*	0.3	0.3	0.3
Minuteman IIIA CEP *meters*	220	220	220
Minuteman IIIA yield *megatons*	0.335	0.335	0.335
Trident II CEP *meters*			120 / 160
Trident II yield *megatons*			0.475
SS-17/18/19/24 silo strength *atmospheres*	200 / 470	200 / 470	200 / 470
SS-11/13 silo strength *atmospheres*	70 / 200		
Reliability *percent*	90 / 80	90 / 80	90 / 80
Fratricide probability *percent*	0 / 5	0 / 5	0 / 5
Number of silos attacked	1,133	459	459
Number of warheads attacked[d]	6,060	3,530	3,530
Results:			
Fraction of silos surviving one-wave attack *percent*	36 / 58	11 / 37	15 / 51
Fraction of silos surviving two-wave attack *percent*	21 / 50	5 / 25	2 / 28
Number of warheads surviving one-wave attack	1,398 / 2,900	384 / 1,250	510 / 1,800
Number of warheads surviving one-wave attack	978 / 2,617	186 / 840	70 / 984

a. There are not enough US high-lethality warheads today to carry out a two-wave attack against today's 1,133 Soviet silos. Thus, this scenario assumes an attack by today's 1,400 high-lethality US ICBM warheads, allocated as follows: 500 MX in one wave on 308 SS-18 silos, 40 SS-24 silos, and 152 SS-19 silos; 534 Minuteman IIIA in two waves on 168 SS-19 silos, 65 SS-17 silos, and 34 SS-11/13 silos; 366 Minuteman IIIA in a one-wave assault on 366 SS-11/13 silos.

b. The two-wave mid-1990s ICBM attack on 459 silos assumes 459 MX warheads in the first wave, and 41 MX plus 418 Minuteman IIIA warheads in the second wave.

c. The two-wave mid-1990s SLBM attack on 459 silos requires 918 hard-target-capable (i.e. with the Mark 5 warhead, carrying 0.457 megatons) Trident II warheads, or 115 Trident II SLBMs, carried on five Trident submarines.

d. These figures include only silo-based warheads, not mobiles.

$$\text{SSPS} = 0.5^x \text{ where } x = \frac{R^2}{\text{CEP}^2} = \frac{3.46L}{P_R^{2/3}} \qquad \text{(A-11)}$$

where L is the attacking warhead's lethality. Note that SSPS depends only on L and on the blast pressure at the crater's edge.

Plausible values of P_R can be inferred as follows: although the volume of nuclear-weapon–generated craters is not precisely understood, the inner bowl's volume should be roughly proportional to the energy released, so $R^3 \approx cy$ where c depends on the local geology, but not on the attacking warhead. Furthermore, $P_R \approx 6.45/c$ from equation A-10, so the limiting pressure P_R depends only on geology (and not on y).[7] The constant c can be evaluated roughly from knowledge of a single crater radius in the geology likely to be chosen for superhard silos. The standard reference[8] gives R = 97 meters for y = 0.5 megatons in dry hard rock. However, engineered rock or some natural formations produce still smaller craters (appendix C). In fact, a Defense Nuclear Agency official has stated that an 0.5-megaton blast produces R = 60–90 meters,[9] and it has also been stated that an 0.5-megaton blast produces $R \approx$ 75 meters in typical superhard silo geology.[10] Using R = 70–80 meters for y = 0.5 megatons to evaluate c and using this to evaluate P_R, we find P_R = 7,800 ± 1,500 atm (115,000 ± 20,000 psi). The feasibility of actually attaining such silo strengths is discussed in appendix C.

Finally, putting the central value P_R = 7,800 atm back into equation A-11,

$$\text{SSPS} = 0.5^x \text{ where } x = 0.00895L = \frac{L}{112} \qquad \text{(A-12)}$$

Equation A-12 is graphed, as a function of CEP for three values of y, in figure 4.

NOTES AND REFERENCES

1. For further details, see Barbara G. Levi, Mark Sakitt, and Art Hobson, eds., *The Future of Land-Based Strategic Missiles* (New York: American Institute of Physics, 1989) pp.123–128.

2. For a discussion of the validity of the standard model see Walter C. Beckham, *Physical-Vulnerability Calculations for Nuclear Weapons Using DIA Green Book Methods* (Livermore, California: Lawrence Livermore Laboratory, 1975).

3. Kosta Tsipis, *Arsenal* (New York: Simon & Schuster, 1983), p.271; Kosta Tsipis, *Nuclear Explosion Effects on Missile Silos*, (Cambridge, Massachusetts: MIT Center for International Studies, 1978), p.20; originally given in *Air Force Manual for Design and Analysis of Hardened Structures* (New Mexico: Kirtland Air Force Base, 1974).

4. S is an idealized concept. The shock wave from a nuclear blast is a dynamic phenomenon, and the silo responds in a dynamic way. The overpressure's time-dependence, especially its duration at peak values, is an important consideration, as is the silo's dynamic elasticity and ductility under short-duration shocks. See the discussion in appendix C, and also Beckham, *Physical-Vulnerability Calculations.*

5. For justification of these values, see Levi et al., *The Future of Land-Based Strategic Missiles*, pp.128–135

6. Barbara G. Levi et al., pp.267–273.

7. For a given geology, it would be pointless to build a silo that could withstand more than this pressure, because pressures > P_R would be felt only inside the crater where the silo would be destroyed anyway by "cratering" (fracturing etc.) effects. According to former Secretary of Defense (and physicist) Harold Brown, "you can't harden a shelter enough so that it will survive being in the crater from a nuclear explosion" (quoted in Steve Smith, "MX and the Vulnerability of American Missiles," *ADIU Report*, May/June 1982, p.3). See also Kosta Tsipis, "The Operational Characteristics of Ballistic Missiles," in *SIPRI Yearbook 1984* (London: Taylor & Francis, 1984), p.384.

8. Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear Weapons*, (Washington DC: US Department of Defense, 1977), chapter 6. $R = 97$ meters may be determined from the "Nuclear Bomb Effects Computer" furnished with the book.

9. George Ullrich, Shock and Strategic Structures Division, Defense Nuclear Agency, quoted in Jonathan Medalia, *Congressional Research Service Report: Small Single-Warhead ICBMs* (Washington DC: Library of Congress, 1983).

10. Air Force Assistant Secretary Thomas E. Cooper, quoted in "SS-18 Not Capable of 250-foot CEP," *Defense Daily*, 22 May 1985, p.121. The article states "The Soviet Union could destroy any existing or planned US hardened missile silo if it could put that silo within the 500-foot-diameter crater created by the detonation of a reentry vehicle from its SS-18 ICBM."

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Appendix B
CALCULATING MOBILE MISSILE VULNERABILITY
Art Hobson

Number of Warheads Needed for Area Barrages

Figure B-1 shows the hexagonal close-packed pattern that might be used for area barrages. The open "destruction circles" are within the radius of destruction *RD* (against one launcher) of each blast, and the shaded regions are gaps within which a launcher theoretically survives. But many launchers in these gaps, feeling three near-threshold (70–80 percent of threshold) blasts,[1] would be disabled. Straightforward geometry shows that the fractional area covered by circles of destruction (the "coverage") is 91 percent, and the number of warheads needed per square kilometer for a 1-wave barrage is

$$N/A = 0.289\ /RD^2 \text{ (hexagonal close-packed barrage)} \qquad \text{(B-1)}$$

Other non-overlapping patterns use fewer attacking warheads but have (approximately) proportionally smaller coverage, so would probably not be used. An overlapping hexagonal pattern having 100-percent coverage would require many more (33 percent more) warheads, because of the "wastefulness" of the overlapping. As we will

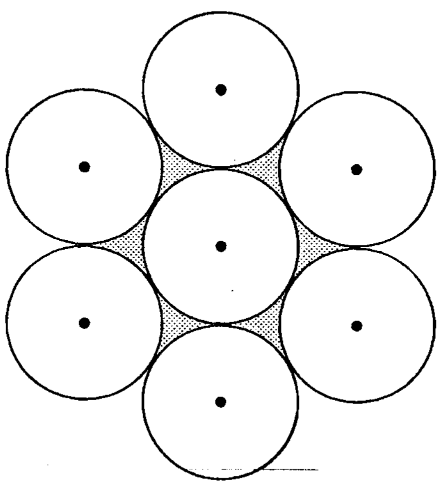

Figure B-1. A small portion of the hexagonal close-packed barrage pattern assumed in this paper to be used against land-mobile missiles.
Notes:
a. The shaded regions are the "theoretical survival gaps," although many launchers located in these regions would probably be destroyed by the effects of the three near-threshold blasts.
b. The pattern shown here neglects warhead unreliability and inaccuracy (see text).

see below, this overlapping hexagonal pattern is likely to produce only a few percent increase in disabled launchers, so we assume an attacker would use the hexagonal close-packed pattern.

Target Survival Rate

The barrage pattern will be laid down imperfectly, due to unreliability and inaccuracy. Consider, first, unreliability alone. At $R = 1$ with total deployment area A, the covered area is $0.91A$. At $R < 1$, the covered area becomes $0.91RA$, so

Table B-1: The number of barraging warheads needed per square kilometer of barraged area, and the relative inaccuracy μ = CEP/*RD*, for several attack cases

	Yield[a] *megatons*	**CEP**[a] *kilometers*	***RD***[b] *kilometers*	***N/A***[c] *warheads·km*$^{-2}$	μ
Attacks on Midgetman by:					
SS-18	0.5	0.11	1.6	0.113	0.07
Soviet SLBM-A[d]	0.1	0.21	0.94	0.327	0.22
Soviet SLBM-B[d]	0.5	0.21	1.6	0.113	0.13
Attacks on SS-25 by:					
MX	0.3	0.10	6.0	0.0080	0.02
Minuteman III	0.335	0.22	6.2	0.0075	0.04
Trident I	0.1	0.40	4.2	0.016	0.10
Trident II-A[e]	0.1	0.14	4.2	0.016	0.03
Trident II-B[e]	0.475	0.14	7.0	0.0059	0.02
0.5 megaton[f]	0.5		7.1	0.0057	

a. Yields and CEPs are mid-1990s estimates from tables A-1 and A-2.

b. Radii of destruction assume that Midgetman's HML has a strength of 2 atm (30 psi), and SS-25's TEL has a strength of 3.5 psi, and that the attacking warhead airbursts at a height optimized for the target strength. Radii of destruction are then found from the "Nuclear Bomb Effects Computer" in Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear Weapons*, (Washington DC: US Department of Defense, 1977), although they may also be found from the groundburst result, equation A-4, with the help of Glasstone and Dolan's graphs showing the effect of altitude on *RD*.

c. Calculated from equation B-1.

d. Soviet SLBM-A and SLBM-B are analogous to the two versions of the US Trident II missile, described in note e below.

e. There are two versions of the Trident II missile, designated here by "A" and "B," which the Navy plans to purchase in roughly equal numbers. The first carries eight 0.1-megaton warheads while the second, designed for attacks against ICBM silos, carries eight 0.475-megaton warheads. See Edward Kolcum, "Successful Launches Verify Design Fixes to Trident 2 D5 ICBM," *Aviation Week & Space Technology*, 8 January 1990, pp.50–51.

f. The hypothetical 0.5-megaton case is added in order to have a basis for the 0.5-megaton calculations in figure 3. CEP and μ are not needed for these calculations.

$$\text{coverage} = 0.91R \text{ (unreliability effect, assuming CEP} = 0) \quad \text{(B-2)}$$

Now consider inaccuracy, assuming $R = 1$. Inaccuracy randomly displaces the circles of destruction. Defining the "relative inaccuracy" $\mu = \text{CEP}/RD$, the barraging warheads must satisfy $\mu \ll 1$ if imperfections are not to leave large areas uncovered. Table B-1 gives μ and N/A (equation B-1), for nine attack cases. Note that $\mu \leq 0.13$ for all but one case.

Assuming $\mu \ll 1$, we can estimate the area uncovered by inaccuracy: In figure B-1, displace only the central circle downward by the typical (median) amount d = CEP. The net excess area uncovered is just the area of the three regions of overlap between the displaced circle and the three circles below it. Geometry shows that, to lowest order in μ, this area is

$$\Delta A = RD^2\mu^{3/2} + 2\sin(30)^{3/2} RD^2 \mu^{3/2} \quad \text{(B-3)}$$

where the first term comes from the overlap with the bottom circle, and the second term comes from the two lower (i.e. the left-lower and right-lower) side circles. Since all seven circles are displaced, rather than just the central circle, we choose the center of the central circle as coordinate origin and move the six surrounding circles. For simplicity, assume purely radial motions, and assume the "median" case where three circles are displaced inward, and three outward, by d = CEP. The effect is to multiply equation B-3 by 3. This is the overlap in a typical hexagon, defined by the centers of the six outer circles.[2] Dividing by this hexagon's area $6\sqrt{3}RD^2$, and subtracting from 0.91,

$$\text{coverage} \approx 0.91 - 0.49\mu^{3/2} \text{ (inaccuracy effect, assuming } R = 1) \quad \text{(B-4)}$$

Putting equations B-2 and B-4 together, the general result is

$$\text{coverage} \approx 0.91R - 0.49R\mu^{3/2} = R(0.91 - 0.49\mu^{3/2}) \quad \text{(B-5)}$$

since for $R < 1$ the overlap $0.49\mu^{3/2}$ should be replaced by $0.49R\mu^{3/2}$, because only a fraction R of the circles is now present.

Table B-2 tabulates equation B-5. Coverage as a function of R and μ has also been machine-calculated by simulating barrages with random-sampling techniques, with results identical to table B-2 to within rounding errors.[3] Note that the effect of inaccu-

Table B-2: "Theoretical" fraction[a] of mobile missile carriers destroyed in the hexagonal close-packed barrage pattern, as a function of the reliability R and the relative inaccuracy μ = CEP/RD of the attacking warheads, from equation B-5

		μ					
		0.00	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**
R	**1.0**	0.91	0.90	0.89	0.88	0.87	0.85
	0.90	0.82	0.81	0.80	0.79	0.78	0.76
	0.80	0.73	0.72	0.71	0.70	0.69	0.68
	0.70	0.64	0.63	0.62	0.62	0.61	0.59

a. As explained in the text, the actual fraction would be larger than this.

racy on coverage is less than 6 percent for μ as large as 0.25, and that all the attack cases listed in table B-1 are accurate enough to fall within this range of μ-values. At 80-percent reliability, the theoretical coverage is 68–73 percent, or roughly 70 percent (30-percent survival rate). Assuming that half the launchers located in the theoretical survival gaps are actually destroyed (see discussion above), a plausible survival rate is then 15 percent.

If the tighter, overlapping, hexagonal barrage pattern were used, having 100-percent "ideal" (i.e. at $R = 1$, $\mu = 0$) coverage, then the theoretical survival rate should be 74–80 percent at $R = 0.8$, because the inaccuracy effect should again be in the range 0–6 percent. The actual survival rate might be 10–13 percent, only a small reduction from the 15 percent of figure B-1.

Number of Warheads to Barrage Midgetman and SS-25 (Figure 3)

Garrison Midgetman

After a short dash time t, the deployment area is 250 circles (assuming the dash direction is random[4]) of radius vt (v = speed = 45 km/hr = 0.75 km/min) and total area $250\pi v^2t^2$, centered on 250 Midgetman silos. From table B-1, the number of warheads needed to barrage N is $0.113 \cdot 250\pi v^2t^2$. But this result is only valid for $N > 250$, i.e. for $t > 2.2$ minutes, because at least 250 warheads must be used against the 250 separate regions. Furthermore, this result holds only until the 250 individual circles begin to meet. This meeting time depends on the distance between deployment sites.

500 Midgetmen would be based on three to six US ICBM bases (table B-3). Minuteman/MX ICBM silos are separated by about 8 kilometers, deployed as shown and described in figure B-2.[5] Each of the six bases of table B-3 contains three or four 50-silo Minuteman "squadrons." Since the "natural" Minuteman unit is the 50-silo squadron with its five interlinked and mutually supporting launch control centers (LCCs), it is reasonable to assume that Midgetmen would be deployed in 100-launcher "complexes," with each complex occupying all 50 silos of one Minuteman squadron in order to make efficient use of that squadron's LCCs and other support equipment.[6] For maximum separation, the five complexes (500 launchers in all) might then be located on five different Minuteman bases.

Since Midgetman shelters are 8 kilometers apart, the 50 circles arising from one 100-Midgetman complex begin to meet after $t = 5.3$ min of dash. Overlap of these circles is completed at $t = 7.5$ min, assuming the shelters form a square array with

Table B-3: US ICBM bases, and missiles currently deployed at each. All six are candidates for garrison Midgetman basing

	Minuteman II	Minuteman III	MX
Ellsworth AFB *South Dakota*	150	–	–
F. E. Warren AFB *Wyoming*	–	150	50
Grand Forks AFB *North Dakota*	–	150	–
Malmstrom AFB *Montana*	150	50	
Minot AFB *North Dakota*	–	150	–
Whiteman AFB *Missouri*	150	–	–

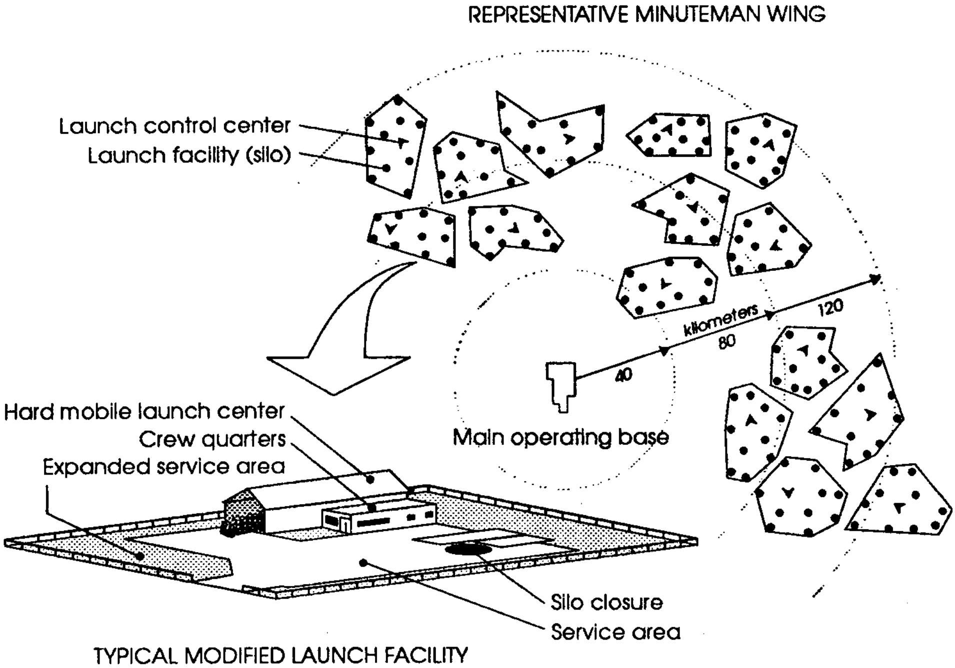

Figure B-2. Midgetman at Minuteman facilities basing concept, showing a typical Midgetman garrison. The figure shows three representative Minuteman "squadrons" of 50 missiles (i.e. silos) each, each squadron organized into five 10-missile "flights" each with an associated LCC, all located on one of the six ICBM bases of table B-3. A squadron's five LCCs are interconnected in such a way that the release of any single flight must be authorized by two LCCs.

Source: based on US Air Force drawing in EIS, endnote 5

8-kilometer separation (a simplification). We assume that an attacker who expected more than about 5.3 minutes of dash would simply barrage the entire 50-silo area, rather than trying to avoid the small gaps between the widening and overlapping circles during 5.3–7.5 minutes. Making the simplifying assumption (cf. figure B-2) that Midgetman peacetime complexes are circular (thus of radius 31.9 kilometers), the deployment area of one complex at $t > 5.3$ minutes is $\pi[31.9 + v(t - 5.3)]^2$. For figure 3, multiply by five complexes and by 0.113 from table B-1.

Random Midgetman
The 10^4-square-kilometer peacetime deployment area would be drawn from the six "complexes" listed in table B-4.[7] The Florida and Washington complexes can accommodate only 50 launchers; each of the remaining complexes can accommodate up to 200. We will model this by assuming that deployment would be in four 125-launcher complexes, each with a 2,500-square-kilometer peacetime deployment area.

Figure B-3 shows a representative complex.[8] The peacetime deployment area is along the perimeter of the complex, with the additional alert area (which is equal to the peacetime area) inside the peacetime area. An all-out dash beginning from the

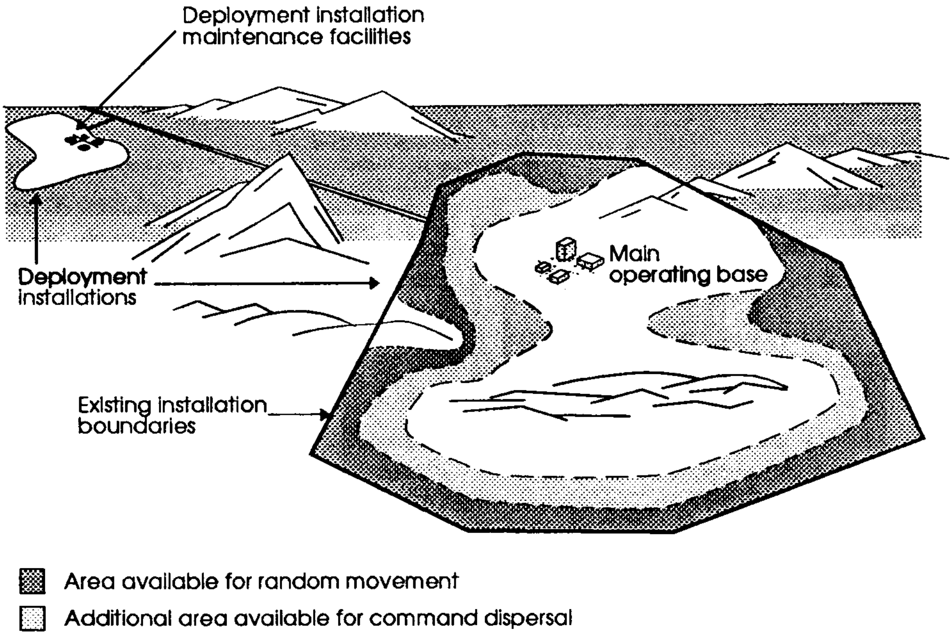

Figure B-3. Random Midgetman basing concept.

Source: based on US Air Force drawing in EIS, endnote 5

Table B-4: Six candidate "complexes" for random Midgetman basing, and areas available for peacetime deployment (the areas available for alert are not listed)[a]

	Square kilometers
Luke Air Force Range and Yuma Proving Ground, Arizona	4,600
Eglin Air Force Base, Florida	800
Nellis Air Force Range and Nevada Test Site, Nevada	4,600
Fort Bliss, Holloman Air Force Base, and White Sands Missile Range, New Mexico	4,700
China Lake Naval Weapons Center, Edwards Air Force Base, and Fort Irwin National Training Center, California	2,400
Department of Energy Hanford Site and Yakima Firing Center, Washington	1,000

a. Source: Air Force EIS; see endnote 5.

peacetime area would proceed both inward onto the alert area, and outward onto non-government land. We model this by assuming that each of the four peacetime areas is a 2,500-square-kilometer ring (radii 40 kilometers and 28 kilometers) surrounding a 2,500-square-kilometer circle. Under these assumptions, the deployment area of a single complex at dash time t, beginning from the peacetime area, would be $\pi(40 + vt)^2 - \pi(28 - vt)^2$ = 2,500 square kilometers + $136\pi vt$ (the quadratic terms cancel). The inner (alert) circle is covered in a time $t = 28/v$ = 37 minutes, after which the deployment area is $\pi(40 + vt)^2$ (although figure 3 stops at t = 25 minutes for Midgetman). To obtain figure 3, multiply by four complexes, and by 0.113 from table B-1.

Garrison and Random SS-25
For garrison SS-25, we assume that only a single nine-TEL garrison is stationed at each of 500/9 = 56 SS-25 bases, and that bases are 90 kilometers apart.[9] After a dash time t, the TELs are spread out over an area $56\pi v^2t^2$. This result is valid until the 56 circles begin to meet, which however does not occur until t = 60 minutes. To obtain figure 3, multiply by 0.0057 from table B-1.

For random SS-25, we imagine a system that requires the same 1,100-warhead attack price as does random Midgetman on its peacetime area. Using table B-1, this peacetime area is 1,100/0.0057 = 190,000 square kilometers, about the area of Nebraska. Continuing the parallel with random Midgetman, suppose that random SS-25 was deployed on four operating bases. Assuming they are circular (they would surely not be perimeters, since they already occupy so much land), their radii would be 124 kilometers. After a dash time t, they expand to $\pi(124 + vt)^2$. To obtain figure 3, multiply by four bases and by 0.0057 from table B-1.

MIRVing the Attack Makes Little Difference

That is, a given missile could barrage about the same area regardless of whether it were single-warhead, or low-MIRVed, or high-MIRVed.

This follows from the empirical observation[10] that, for an f-MIRVed missile having individual warhead yield y, the "equivalent megatonnage" $fy^{2/3}$ is roughly independent of the fractionation f: $fy^{2/3} \approx$ constant. Equation A-5 tells us that $RD^2 \propto y^{2/3}$, so $fy^{2/3}$ is

Table B-5: Comparison of the equivalent megatonnage $Y^{2/3}$ for three single-warhead missiles with the equivalent megatonnage $fy^{2/3}$ for the same three missiles with f-MIRVed warheads. To a rough approximation, equivalent megatonnage is independent of MIRVing. The ranges represent error bars in the tabulated quantities[a]

	Y megatons	y megatons	f	$Y^{2/3}$	$fy^{2/3}$
SS-17	3.6–6	0.75	4	2.4–3.3	3.3
SS-18	20	0.5	10	7.4	6.3
SS-19	4.3–5	0.5–0.55	6	2.6–2.9	3.8–4

a. Data from Barton Wright, *Soviet Missiles: Data From 100 Unclassified Sources* (Lexington, Massachusetts: Lexington Books, 1986).

proportional to the area $f\pi(RD)^2$ barraged by all f warheads (this is why $fy^{2/3}$ is called the missile's "equivalent megatonnage"). Thus the rule $fy^{2/3} \approx$ constant implies that the barraged area is (roughly) independent of fractionation.

To check this rule, we look at three examples: The Soviet SS-17, SS-18, and SS-19. Each missile comes in a single-warhead and a MIRVed model. Table B-5 shows that $fy^{2/3}$ is roughly the same for the single-warhead and the MIRVed model. More precisely, the equivalent megatonnage $fy^{2/3}$ (and the barraged area per missile) appears to follow the slow variation noted by Bennett,[11] rising by perhaps 25 percent around $f = 4$ to 6, and dropping back down by $f = 10$.

It is not surprising that the total yield of the MIRVed missile, $fy \approx Y/\sqrt{f}$, is much less than Y, because inspection of MIRVing geometry[12] shows that the MIRVed warheads cannot fill the entire volume, inside the missile's nose cone, available to the single warhead. Closer consideration of this geometry reveals the possible reason for the fractionation rule $fy^{2/3} \approx$ constant. The bases of the f conical warheads of radius r must be fit onto the same circular area as the single warhead of base radius R, so $f\pi r^2 \approx \pi R^2$. But the ratio of the single and MIRVed warhead volume is $V/v = R^3/r^3$, so $fv^{2/3} \approx V^{2/3}$. Assuming that warhead yield is proportional to warhead volume, $fy^{2/3} \approx Y^{2/3}$.

NOTES AND REFERENCES

1. The center of a gap is a distance 1.15·*RD* from each of the three neighboring blasts, so equation A-4 (unapproximated form) implies the surface-blast pressure against a 30-psi target (Midgetman) is 22 psi or 73 percent of threshold, and the surface-blast pressure against a 3.5-psi target (SS-25) is 2.7 psi or 79 percent of threshold. Airburst pressures should be below threshold by similar fractions.

2. Note that this procedure avoids double-counting.

3. Barbara G. Levi, Mark Sakitt, and Art Hobson, eds., *The Future of Land-Based Strategic Missiles* (New York: American Institute of Physics, 1989), p.194.

4. It is defense-optimistic to assume that the direction is random. Actually, the dash would be on the roads connecting the Minuteman silos, with a last-minute off-road movement. But it is not clear that the offense would try to preferentially target the roads, since a last-minute off-road movement could defeat this attack plan, and thus an actual attack might be based on something close to the random direction assumption.

5. Figures B-2 and B-3, and other information about Minuteman and Midgetman deployment, may be found in: Air Force Regional Civil Engineer, *Legislative Environmental Impact Statement (EIS): Small Intercontinental Ballistic Missile Program*, (Norton Air Force Base, California: US Air Force, November 1986).

6. Information on US ICBM deployment can be found in ibid.; Levi et al., p.183; Ashton B. Carter and David N. Schwartz, eds., *Ballistic Missile Defense* (Washington DC: The Brookings Institution, 1984), p.123; Dietrich Schroeer, *Science, Technology, and the Nuclear Arms Race* (New York: John Wiley & Sons, 1984), p.154; Barry Miller, "ICBMs Get Major Modernization," *Aviation Week & Space Technology*, 10 May 1976, p.63.

7. *EIS*, pp.18–20, 27, section 1.

8. *EIS*, p.10, section 1. See also R. Jeffrey Smith, "A Scheme to Attract Missiles and Deter an Attack," *Science*, 27 June 1986, p.1592.

9. These are defense-optimistic assumptions, because some bases may contain more than one garrison, and because some bases are under 90 kilometers apart.

10. Ian Bellany, *Nuclear Vulnerability Handbook*, (Lancaster, UK: Center for the Study of Arms Control, 1981); Bruce Bennett, *Assessing the Capabilities of Strategic Nuclear Forces*, (Santa Monica, California: Rand Corporation, June 1980), p.75, notes that $fy^{2/3}$ is a slowly varying function of f, rising by about 25 percent as f increases from 1 to 3, and falling back by 25 percent as f increases from 3 to 10. So this rule is an approximation.

11. Ibid.

12. See, for example, Schroeer, p.150; Thomas B. Cochran et al., *Nuclear Weapons Databook Volume I: US Nuclear Forces and Capabilities* (New York: Ballinger, 1984), p.75.