Science & Global Security, 19:167–194, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929882.2011.616127

Routledge
Taylor & Francis Group

One Hundred Nuclear Wars: Stable Deterrence between the United States and Russia at Reduced Nuclear Force Levels Off Alert in the Presence of Limited Missile Defenses

Bruce Blair,[1] Victor Esin,[2] Matthew McKinzie,[3] Valery Yarynich,[2] and Pavel Zolotarev[2]

[1]World Security Institute and Global Zero, Washington, DC, USA
[2]Institute for USA and Canada Studies - ISKRAN, Russian Academy of Sciences, Moscow, Russia
[3]Natural Resources Defense Council, Washington, DC, USA

Nuclear exchange models using Monte Carlo methods were used to test the stability of U.S.-Russian deterrence for reduced nuclear force sizes off alert in the presence of missile defenses. For this study U.S. and Russian weapons were partitioned into a postulated First Echelon, consisting of single-warhead, silo-based ICBM launchers that can be generated in hours to launch-ready status, and into a postulated Second Echelon of more diverse nuclear forces including multiple-warhead, road-mobile and sea-based systems that require days to weeks to become launch ready. Given reasonable estimates of weapons characteristics, First Echelon nuclear forces can survive to retaliate in numbers that satisfy the requirements of deterrence, given limitations on the numbers of missile defense interceptors, a result which is bolstered by the added capabilities of the more deeply de-alerted Second Echelon.

The aim of this study is to assess the impacts of sharply cutting the U.S. and Russian strategic arsenals and lowering their launch readiness on the stability of mutual deterrence. The study also assesses the implications of introducing a limited deployment of missile defense systems into this equation.

Received 7 March 2011; accepted 1 August 2011.
The work discussed in this article was previously summarized in “Smaller and Safer: A New Plan for Nuclear Postures,” *Foreign Affairs*, Volume 89, No. 5.

Address correspondence to Matthew McKinzie, 1152 15th St., NW, Suite 300, Washington, DC 20005, USA. E-mail: mmckinzie@nrdc.org

The methods used in this study involve statistical modeling of scenarios of sudden nuclear war between the United States and Russia. These simulations provide a tool to design and test smaller and safer force postures that may still provide for stable mutual nuclear deterrence. Although we favor building a U.S.-Russian security relationship based on cooperation rather than mutual threat, we recognize that mutual deterrence remains a cornerstone of both nations' strategic planning requirements.

As our baseline scenario, all the strategic nuclear forces on both sides are maintained on a modified alert status in peacetime that requires at least hours for any of them to become launch ready. This hypothetical de-alerted posture departs from the current real-world posture in which the nuclear command, communications, and weapons systems of the United States and Russia stand ready to be fired immediately either preemptively or on warning of incoming strikes. Under launch on warning, missile forces under attack would be fired en masse before the arrival of attacking enemy missiles which have a flight time of half an hour or less. Both the United States and Russia are thus still prepared, despite the Cold War's end, to inflict apocalyptic devastation on one another in a first and second strike: events playing out in less than one hour following a decision executed in minutes resulting in millions of deaths and global environmental ruin.

This high launch readiness carries with it the risk of launch on false alarm, launch as a result of human error, or malicious, unauthorized launch. Given that the targeting and response requirements of deterrence between the United States and Russia are much less demanding now than was the case in the Cold War, there are clear and straightforward benefits to taking nuclear forces off alert: an increase in warning and decision time to reduce the risk of a mistaken launch; and an ability to strengthen safeguards against unauthorized launch. With the ending of the Cold War, the relative dangers of accidental launch or intentional interference with each other's nuclear command and control systems have declined (however, interference by other states as well as non-state actors has simultaneously increased), but in our view they now represent a greater danger than a surprise first strike.

Verifiable, feasible measures to extend the time needed to fire U.S. and Russian nuclear forces—by hours, days, weeks, months, and even years—have been developed.[1] The more deeply these forces are de-alerted, for example, by separating warheads from delivery vehicles and placing warheads in central storage locations, the easier it becomes to verify the weapons' off-alert status. It should be noted that maintaining a large portion of nuclear weapons off alert is an aspect of the current nuclear deterrent relationship between the United States and Russia, where only approximately one-third of today's forces are maintained on alert.[2]

Our model assesses the stability of mutual deterrence after adopting de-alerting measures and slashing the size of the arsenals. By "stability" we mean a situation where both the United States and Russia would not rationally choose to strike first with nuclear weapons, because doing so could provoke a response that inflicts horrific, unacceptable death and destruction from nuclear retaliation. In a stable nuclear deterrent situation, neither the United States nor Russia could deprive the other of its capacity to inflict severe punitive damage in retaliation. Instability would exist if either side possessed a credible capability to strike without fear of reprisal, which could also be wielded as a threat.

The specter of retaliation is thus the foundation of deterrence.[3] In our model, stable deterrence depends upon keeping a sufficient scale of retaliation at a given probability through the spectrum of scenarios and postures—de-alerted forces in peacetime and re-alerted forces in crises, combined with U.S. possession of a highly capable missile defense system against Russian strategic weapons (a dubious assumption that nonetheless represents a reasonable worst case from a Russian perspective).

Two fundamental criticisms of nuclear de-alerting have been advanced: (1) strategic nuclear forces off alert are vulnerable to a disarming first strike; and (2) a future crisis between the United States and Russia would grow dangerously unstable as missile forces race to return to launch-ready status. De-alerting could, the argument goes, create exploitable advantages from breaking out and re-alerting.[4] This criticism slides past the fact that the *current* nuclear postures are fully geared to generate two-thirds of their arsenals as rapidly as possible during a U.S.-Russian confrontation, and to launch them preemptively or on warning.[5] Our de-alerting scheme in fact suppresses such re-alerting impulses. The solution to a stable nuclear deterrent with all forces off alert is to divide the nuclear forces of both countries into distinct groups, termed Echelons, with different degrees of reduced combat readiness (i.e., different generation times to launch-ready status). By "echeloning" the forces, our model constructs a stable nuclear deterrent whole from more vulnerable, de-alerted parts. The partitioning of nuclear forces into a First and Second Echelon serves both as a barrier to surprise nuclear attack and to a re-alerting race.

The First Echelon of de-alerted nuclear forces consists of equal numbers of U.S. and Russian single-warhead, high-yield, silo-based intercontinental ballistic missiles (ICBMs) maintained off alert. First Echelon forces are substantially vulnerable to a sudden attack, because the opposing First Echelon forces may be secretly brought to high readiness and suddenly launched. Such forces have shorter re-alerting times than the Second Echelon forces—it is postulated that the former can be brought to launch-ready status in a matter of hours (this rapid generation time, we reason, can minimize exposure to follow-on strikes by conventional forces following an initial sudden nuclear strike). Armed with only single warheads, however, as we demonstrate, the First Echelon is incapable of mounting a disarming first strike against the opposing First Echelon.

While lacking capabilities for a disarming first strike, they are highly capable of decimating, or threatening to decimate, opposing economic and administrative sectors (i.e., urban-industrial centers).

The primary role of First Echelons is thus to maintain deterrence on a day-to-day basis between the United States and Russia. They also deter nuclear (and non-nuclear) attack by other states. In other words, the First Echelon is the "front line of deterrence."

The Second Echelon of de-alerted nuclear forces consists of a more diverse group of weapons. Both countries possess roughly equal numbers of total warheads but they are mounted on a wide variety of types of weapons. The deployments are asymmetric reflecting the different preferences for weapons types on each side. The Second Echelon includes both single-warhead and multiple-warhead weapon systems: silo-based ICBMs; submarine-launched ballistic missiles (SLBMs); and Russian road-mobile ICBMs.

Second Echelon forces are highly survivable when alerted and deployed, with submarines put to sea and road-mobile missile units moving and hidden in Siberian forests, for example. But they are highly vulnerable in their day-to-day, off-alert status. It is postulated that these Second Echelon forces take much longer to re-alert than the First Echelon—these Second Echelon weapons can only be brought to launch-ready status over the course of days to weeks. During this re-alerting phase, they are vulnerable to attack. On the other hand, both sides, we postulate, could monitor the de-alert status of the other side's Second Echelon forces. This ability to mutually verify the state of readiness would ensure that the rate of re-alerting of Second Echelon forces would be roughly symmetrical. There could thus be no large advantage gained by breaking out this echelon and racing to launch-ready status.

The primary character of this Second Echelon is that it presents the United States and Russia with an option to conduct varied, flexible nuclear operations using additional forces after nuclear war begins.

In our model, nuclear strikes involve two types of targeting: strikes against opposing nuclear weapons, and retaliatory strikes against urban targets. An Attacking State (AS) and a Victim State (VS) will choose different targeting policies. The goal of the AS will be to eliminate the nuclear forces of the VS, in order to achieve dominance. The VS will target the cities of the AS, in order to deter attack in the first instance by threatening to destroy the AS cities in retaliation.

In general, the VS and AS will have limited knowledge about the military forces and actions of the opposing side apart from the VS's detection of the AS starting to re-alert its Second Echelon. By then the AS could have secretly prepared its First Echelon to launch. In the conditions of a real nuclear war the VS would have scant knowledge about AS nuclear forces as they are mobilized and utilized, and would logically target AS cities instead since they are known aimpoints that do not move during a nuclear exchange. By the same token it is logical that the AS must assume that the VS will retaliate against AS cities. The AS must also take into account that the VS could delegate launch authority to duty crews in the wake of a sudden nuclear attack, which will likely reinforce city targeting since the VS higher authority would be cut off from the lower echelons and unable to communicate information about the status of the AS forces to its lower-echelon launchers.

The model estimates the risk to the attacker of initiating a nuclear attack. This risk can be measured with the help of two calculated quantities: the scale of a nuclear retaliation in response to a first strike (i.e., the number of nuclear explosions on the attacker's territory); and the corresponding probability of this event.[6] Because the nuclear arsenals of the United States and Russia are well matched in these scenarios, the modeling of a war between the two states should proceed from the assumption that practically all nuclear warheads will be used. In our view, the notion of a limited or orchestrated nuclear war between the United States and Russia is unrealistic.

Our model falls under the rubric of Nuclear Exchange Models (NEMs), or computer calculations of the consequences of nuclear warfare, whose genesis traces back to the 1960s in the United States.[7] Despite the secrecy associated with nuclear weapons, an open body of literature exists on U.S. NEMs, including legacy code listings.[8] In Russia, any comparable models that exist remain shrouded in secrecy.[9] In the United States, some NEMs have been used to gauge the deterrent capability of the U.S. nuclear arsenal and project the effects of new developments on this capability. More detailed, complex NEMs are computer simulations designed to assist in constructing operational plans and targeting assignments before and during a nuclear conflict.

In general a NEM will have the following code components: the weapon complex, the target complex, the engagement and allocation rules, the damage function, and the algorithm or solution technique.[10] The weapon complex refers to specific weapon characteristic such as circular error probable (CEP), explosive yield, reliability, and defense penetration aids like missile defense decoys, as well as the "reach" or ability of a weapon to hit a target because of range or constrains from the Multiple Independently Targetable Re-entry Vehicle (MIRV) footprint. The target complex contains information about targets—whether they are point targets like missile silos or area targets like cities, whether they are force or economic targets, the "value" of a target to be killed, and its defenses. A NEM can also be categorized on the basis of how many strikes it can compute. Models limited to a single strike are usually focused on evaluating a single goal by a single attacker. A two-strike model can compute the results of an initial attack followed by a retaliatory strike. Models that can handle three or more strikes can look at what reserve forces could persist following a general nuclear war.

In our work we did not construct a single NEM, but built several related NEMs that explored different aspects of the stability of deterrence in our scenarios. These can be characterized as a two-strike model: a counterforce first strike followed by retaliation against value targets. We compute the damage expectancy from the first strike in order to derive the size of the retaliation, but did not explicitly calculate the value damage, equating the size of the retaliation to the number of "hostage cities" for deterrence purposes.

Uncertainty, incomplete knowledge, and chance permeate nuclear deterrence as it continues to be carried out day-to-day between the United States and Russia, and a hypothetical nuclear war relates to a complicated process with many different events. Therefore we used a Monte Carlo modeling technique, where each nuclear war scenario, involving specific offensive and defense components, is run many times (for example 100 computer runs of the model, which speaks to the title of this article). Monte Carlo methods rely on repeated random sampling to calculate results, and are applied to understand complex systems and situations where there are significant uncertainties in the inputs to a calculation. The Decision Analysis software *Analytica*, Release 4.0.0.68[11] was used to model the consequences of nuclear wars for this work. In *Analytica*, a model consists of mathematical objects intended to represent a real-world system. Two probability distributions were used in this work: a uniform probability distribution and a Bernoulli probability distribution.

Any single run may represent the actual outcome of a nuclear war. From our perspective, the fact that the outcome of a particular modeling run may appear to be atypical of the others (i.e., unusual) does not make such a result less significant. A real nuclear war is possible only one time, and its outcome may be similar to any one of the model outputs, however "unexpected" it may seem. If the worst consequences of initiating a nuclear attack are unacceptable, then the decision-makers in the potential nuclear aggressor state are obliged to anticipate this disastrous result, even if a better outcome for the aggressor was more probable. A necessary step in achieving the reduction and de-alerting of U.S. and Russian nuclear forces is a reliable, openly published analysis of the maintenance of the national security of both countries after this fundamental change to their nuclear postures.

THE FIRST ECHELON

Consider First Echelons of nuclear forces in the United States and Russia consisting of equal numbers of silo-based ICBM launchers, each with a single, high-yield warhead. In our scenarios these missiles are maintained off alert—a launch cannot occur between the moment when an incoming attack is detected and the missile silos are struck. The modeling will seek to answer the following question: for given First Echelons, can an attacker gain an advantage by striking first? If an attacker can so disarm their opponent, denying the attacked state its retaliation from the opposing First Echelon, then deterrence would risk being unstable.

In specifying the types of forces in the First Echelon we rejected the concept of a First Echelon ballistic missile submarine force (an SSBN force), like the current, smaller arsenals of the United Kingdom and France. In our findings the main requirements for a stable de-alerted deterrent are the maximum symmetry of forces and the clearest predictability of nuclear war outcomes. Russia and the Unites States currently maintain different SSBN patrol rates. If a First Echelon SSBN is in port during peacetime then it is vulnerable to destruction by one or few nuclear warheads, along with all of the nuclear weapons it carries. If a First Echelon SSBN is at sea during peacetime then there will be a substantial difference between U.S. and Russian SSBN vulnerability to detection and destruction by opposing naval forces. Russia would never accept these risks, and therefore we propose a First Echelon force based on single-warhead, silo-based ICBMs.

In the model a key input is the probability that a missile silo would survive a single nuclear strike and be able to launch a retaliatory strike, a variable we term Psurvive. We first model Psurvive for both U.S. and Russian silo-based ICBMs using open-source information.[12]

The Lethal Radius (LR) is defined as the distance from the point of the nuclear explosion that the warhead will be able to destroy its target. The formula for LR (in meters) as a function of Yield (Y–in Megatons) and silo hardness (H –in overpressure pounds per square inch or psi) is given by:

$$\text{LR (in meters)} = 4540 \times (\text{Y}^{1/3}/\text{H}^{1/3}) \times [(1 + 2.79/\text{H})^{1/2} + 1.67/\text{H}^{1/2}]^{2/3} \quad (1)$$

The single-shot kill probability (SSKP) is the probability that a single, fully reliable warhead can be expected to destroy a given target. The formula for SSKP in terms of LR (in meters) and warhead accuracy (circular error probable—CEP also in meters) is given by:

$$\text{SSKP} = 1 - 0.5\hat{}\,(\text{LR}/\text{CEP})^2 \quad (2)$$

Finally the SSKP must be multiplied by the Overall Reliability (OAR) of the attacking missile/warhead system to get the probability of destroying the silo, Pdestroyed, therefore:

$$\text{Pdestroyed} = \text{SSKP} \times \text{OAR} \quad (3)$$

Table 1 presents ranges of values for U.S. and Russian silo-based ICBM systems. For the United States, the Minuteman III missile may or may not be loaded with a Peacekeeper re-entry vehicle and warhead. Therefore we take as a range of values the yields and accuracies of the W78 and W87 systems. The silo hardness of the Minuteman III has been described in open literature as either 2,000 or 2,200 psi. For the Russian weapons, we have found warhead

Table 1: Ranges of values used in the calculation of First Echelon survivability

	Attacking warhead yield (Y - Megatons)	Attacking warhead accuracy (CEP - meters)	Attacked silo hardness (overpressure - psi)	Overall attacking missile reliability (OAR)
United States: Minuteman III	0.170–0.335	90–130	2,000 – 2,200	80%–90%
Russia:SS–18, SS–19, SS-27 (silo)	0.550–0.750	200–400	1,500–2,000	80%–90%

yields of either 550 kt or 750 kt cited for silo-based ICBMs. The Kataev archive at Stanford University provided the first open-source data on Russian CEP and silo hardness as given in Table 1.[13] Various values of OAR are cited in Congressional testimony or Russian statements and a range was chosen based on these.

These variables were given a uniform distribution for the given range, and input in an *Analytica* Monte Carlo model to calculate the probability of a U.S. missile destroying a Russian silo, and a Russian missile destroying a U.S. silo. In the SSKP calculations, the higher yield range of the Russian warhead is offset by the smaller CEP of the U.S. missile systems, and so the mean U.S. probability of destroying a Russian silo using a single, ICBM-launched warhead (independent of OAR) was calculated to be higher than that for a Russian single, ICBM-launched warhead destroying a U.S. silo (independent of OAR). The probability that a missile silo would survive a single nuclear strike and be able to launch a retaliatory strike, Psurvive, is simply given by: 1—Pdestroyed. Figure 1 shows the Monte Carlo calculations of Psurvive for U.S. missiles (above) and for Russian missiles (below).

Note the clustering of Russian values of Psurvive around the mean, and the broader spread of U.S. values of Psurvive. The values of Psurvive for such attacks are very different for the United States and Russia, for today's ICBMs, to the extent that the input data ranges are accurate. The mean value of Psurvive for U.S. Minuteman III was calculated to be 0.52 ± 0.12, and for Russian silo-based ICBMs the mean value of Psurvive was calculated to be 0.18 ± 0.04.

We now explore the implications of the United States and Russia maintaining First Echelon forces of a given size off alert, given the calculations of Psurvive, above. Consider first the case of First Echelon sizes of 100 single-warhead ICBMs, each, for the United States and Russia. In this nuclear exchange scenario the entire First Echelon nuclear force of single-warhead ICBMs of the VS is struck by the entire First Echelon nuclear force of single-warhead ICBMS of the AS. The attack is one-to-one, AS missile against VS launcher, and

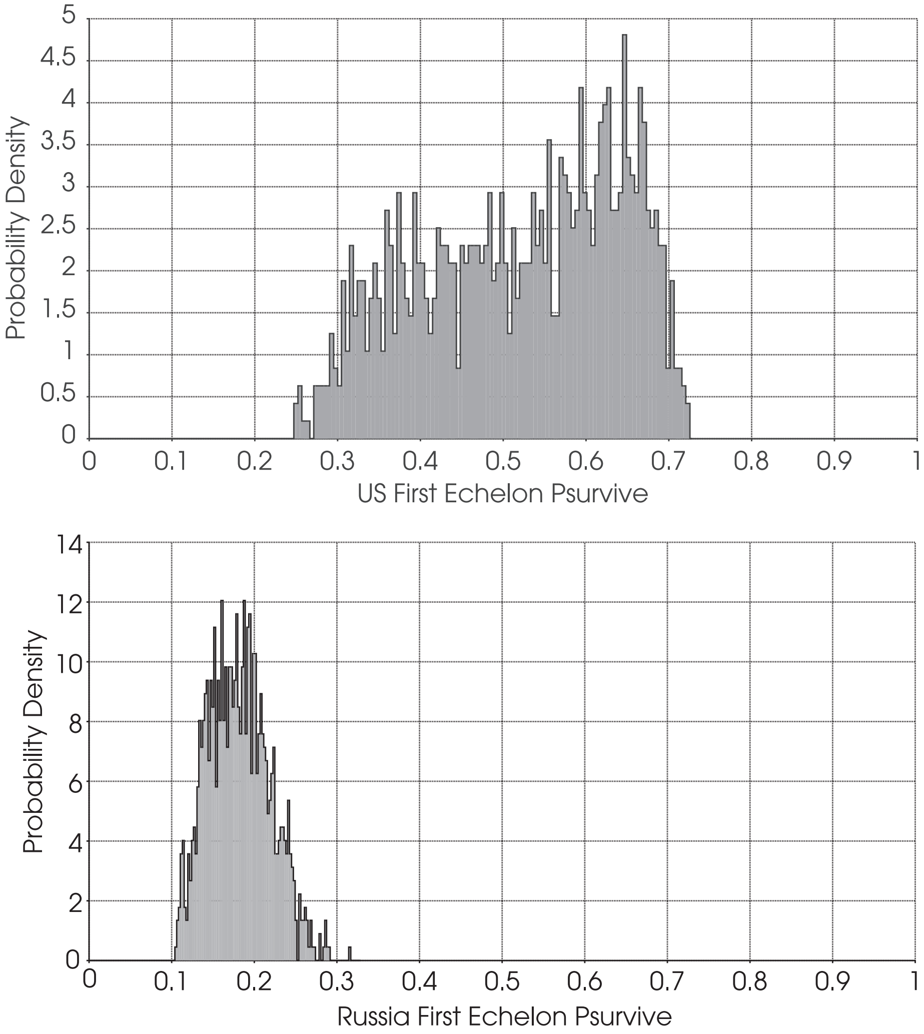

Figure 1: *Analytica* Result Windows (probability densities) for calculations of Psurvive for U.S. (above) and Russian (below) First Echelons—single-warhead, silo-based ICBMs over 1,000 Monte Carlo runs.

synchronous in time. After the first strike by the AS on the VS, the VS retaliates with all surviving launchers.

This simple model of a surprise first strike of one group of single-warhead ICBMs against an equal number of missile silo targets illustrates a key aspect of this study: the outcome of a sole nuclear war is unpredictable. Given the unpredictable outcome, what is the basis of deterrence—the mean or outlier results? Tables 2 and 3, present results for surviving First Echelon retaliation at various First Echelon force sizes

For a First Echelon size of 10 single-warhead ICBMs, Monte Carlo runs occurred where there was no retaliation by the VS after a first strike by the

Table 2: Statistical results for Russian First Echelon retaliation following a U.S. First Echelon strike, for a given First Echelon size (100 Monte Carlo runs)

Number of initial First Echelon launchers	Russian min. retaliation	Russian mean retaliation	Russian max. retaliation	Std. dev.
500	46.0	90.9	141.0	20.1
400	41.0	72.5	113.0	17.1
300	28.0	54.8	93.0	13.2
200	13.0	36.3	58.0	9.6
100	6.0	18.1	31.0	5.1
50	3.0	9.3	19.0	3.2
25	0.0	4.6	12.0	2.3
10	0.0	1.8	4.0	1.1

AS. Given the mean survivability of Russian First Echelon forces of 0.18, the chance that a strike by 10 U.S. ICBM warheads could thereby disarm Russia is 14 percent. Similarly, given the mean survivability of U.S. First Echelon forces of 0.52, the chance that a strike by 10 Russian ICBM warheads could thereby disarm the United States First Echelon is about a tenth of a percent. Therefore as the number of First Echelon launchers is reduced to very low numbers there arises a transition to a more turbulent or chaotic aspect, where a first strike has a substantial probability of disarming the VS First Echelon forces.

However, given equal numbers of First Echelon single-warhead missiles, an attacker would incrementally disarm themselves with each missile used to strike first, for a probability of survival of an attacked missile silo greater than zero as we have seen from the Psurvive calculations. But we posit that additional nuclear forces beyond the First Echelons, the more deeply de-alerted Second Echelons, would be weeks or more (see above) away from launch ready status. De-alerting should not create exploitable advantages from breaking out

Table 3: Statistical results for U.S. First Echelon retaliation following a Russian First Echelon strike, for a given First Echelon size (100 Monte Carlo runs)

Number of initial First Echelon	U.S. min. retaliation	U.S. mean retaliation	U.S. max. retaliation	Std. dev.
500	138.0	260.3	360.0	60.5
400	103.0	209.7	291.0	46.3
300	80.0	155.9	221.0	38.4
200	52.0	104.7	153.0	25.2
100	17.0	54.0	82.0	14.2
50	8.0	26.1	43.0	7.2
25	4.0	13.1	20.0	3.7
10	1.0	5.3	10.0	1.8

and re-alerting. Both the United States and Russia should therefore engage in transparent and verifiable means of de-alerting their Second Echelons, to preclude sudden and secret generation of these forces. It especially should not be possible to seize a disarming first-strike advantage by reconstituting faster than an opponent can. Retaliatory forces need to be sufficiently survivable under normal peacetime circumstances as well as during a crisis period in which restraint may break down. It is assumed that the certainty of retaliation is more important to deterrence than is the timing of retaliation, and that stable deterrence would not be adversely affected by some delays in retaliation.

Given these calculated assured retaliations, and a requirement that the capability to threaten 10 cities is sufficient for deterrence, First Echelon force sizes on the order of 100 launchers would be adequate for a stable nuclear deterrent, even given our calculations that Russian ICBMs are less survivable than U.S. ICBMs.

A nuclear war between the United States and Russia would be fought only once. An analysis that considers only the average number of launchers surviving a strike discounts the less likely—but possible—outcome of larger numbers of surviving, retaliating ICBMs. In this study we posit that both mean and outlier modeling results are important for deterrence.

MISSILE DEFENSES AND THE FIRST ECHELON

In order for deterrence to be robustly stable with nuclear forces off alert, First Echelons must themselves be stable. The AS cannot expect to eliminate the VS First Echelon though a combination of surprise offensive strike and successful defense against the surviving VS First Echelon retaliation. Our calculations will examine the expected retaliation from the Russian First Echelon at various force sizes under the conservative estimate of a highly capable U.S. missile defense shield capable of intercepting on the order of several hundred incoming targets—warheads or heavy warhead decoys—even though this is not a particularly credible assumption at this time.

Our *Analytica*-based analysis that we applied to our conceptual First Echelon nuclear forces follows closely the missile defense model of Dean Wilkening, who treated interceptor-based missile defense as a Bernoulli trial problem.[14] The approach taken by Wilkening was to develop a simple model of missile defense effectiveness that did not require "a detailed understanding of the sensors and interceptors that make up the defense, as well as a detailed characterization of the targets the defense is attempting to shoot down."

Variables in this model of missile defense effectiveness pertaining to attacking warheads, decoys, and the missile defense system's discrimination between them are as follows:

W—the actual number of warheads in an attack (our model takes as this variable the output calculation from the surviving First Echelon warheads, launched in retaliation);

D—the actual number of decoys in an attack, taken as the number of decoys per warhead on a given nuclear force launcher, multiplied by the number of surviving warheads launched in retaliation;

Pww—the probability that the missile defense system has correctly identified a warhead as a warhead, and not a decoy;

Pdd—the probability that the missile defense system has correctly identified a decoy as a decoy, and not a warhead.

It follows then that Pwd, the probability that a warhead is mistakenly identified as a decoy, is given by:

$$\mathrm{Pwd} = 1 - \mathrm{Pww} \tag{4}$$

And Pdw, the probability that a decoy is mistakenly identified as a warhead, is given by:

$$\mathrm{Pdw} = 1 - \mathrm{Pdd} \tag{5}$$

Therefore the apparent size of an attack, or the number of targets for the missile defense system to contend with, T, is given by:

$$\mathrm{T} = \mathrm{Pww} \times \mathrm{W} + \mathrm{Pdw} \times \mathrm{D} \tag{6}$$

Warheads leak through the defense and reach their targets either because the warhead was misidentified as a decoy, or because the warhead was not intercepted once correctly identified as an attacking warhead. Misidentifying decoys as warheads increases the burden on the missile defense system from the attack. Pwd, the probability that a warhead is misidentified by the missile defense system as a decoy, is an example of a common mode failure which affects all attempts by the system to thwart the attack. Another example of a common mode failure would be an inability of the missile defense command and control system to communicate properly with the interceptor missile launchers during an attack. The importance of separately considering common mode failures is that such problems cannot be improved by increasing the number of missile defense interceptors, but instead reflects overall technical shortcomings of the system.

We define the variable k as the probability that the missile defense system shoots down a warhead which the system has correctly identified as a warhead on one try. Considering the case where multiple shots (a number, N, of separate kill attempts) can be taken by the missile defense system against an incoming target, and then assuming that the probability of success of these shots is statistically independent, then the combined probability from multiple kill attempts, K, is given by:

$$K = 1 - (1 - k)^\wedge N \tag{7}$$

And therefore the probability that warheads leak through the defense, or the probability of the retaliation by the VS in the face of missile defense, Pretal, is given by:

$$\mathrm{Pretal} = [\mathrm{Pwd} + \mathrm{Pww} \times (1 - K)]. \tag{8}$$

This probability of the retaliation by a given warhead in the presence of missile defenses can also be written as:

$$\mathrm{Pretal} = \mathrm{Pww} \times K. \tag{9}$$

Using a Monte Carlo approach to the modeling, we create an array of incoming warheads, assign a number of heavy decoys for each warhead, and follow the fate of each warhead and decoy through the discrimination process and interception event, summing the total retaliation for each Monte Carlo run. Specifically, we consider the case where the U.S. missile defense system possesses: a warhead discrimination capability (Pww) of 80%; a heavy decoy discrimination capability (Pdd) of 10%; and a single missile defense interceptor kill probability (k) of 80%. We model missile defense interceptor limits of up to 300 defensive missiles. These parameters were chosen as an upper limit with respect to Russian assessments of future U.S. missile defense capabilities against Russian strategic warheads: a "worst-case scenario" for defense planners. The number of heavy decoys that can be installed on a specific Russian missile launcher depends on the type of missile, but we looked at the cases of zero to five heavy decoys installed with a nuclear warhead. We are particularly interested in the situation where the number of targets, T (both warheads and decoys misidentified as warheads) overwhelms the number of interceptors fielded by the missile defense system, termed Ninterceptors.

Now, combining the calculations of attack, discrimination and interception, summary results over 100 Monte Carlo model runs for a Russian First Echelon size of 150 single-warhead ICBMs is given in Table 4. Based on the Psurvive calculation, the mean initial Russian retaliation from its surviving First Echelon, prior to encountering the U.S. missile defense shield, would be 21 attacking warheads. For the lower case of 10 missile defense interceptors, the mean Russian retaliation is reduced by about seven warheads without the Russian use of heavy decoys, reflecting the assumed U.S. interceptor kill probability against the 10 possible targets it can attempt to kill. As more heavy decoys are added to each Russian launcher the U.S. missile defense system must divert interceptors where it misidentifies these decoys as warheads, and so the mean Russian retaliation is not as reduced. In the cases of three or five heavy

Table 4: *Analytica* statistical results for a U.S. missile defense system intercepting the retaliation from a Russian First Echelon of 150 single-warhead ICBM launchers

VS (Russia) First Echelon size	Number of AS (United States) missile defense interceptors	Decoys per VS (Russia) warhead	Min retal.	Mean retal.	Max retal.	Std dev
150	10	0	0	13.9	37	8.4
150	50	0	0	4.6	16	3.0
150	100	0	0	4.1	12	2.7
150	200	0	0	4.1	12	2.7
150	300	0	0	4.1	12	2.7
150	10	1	0	17.8	28	8.6
150	50	1	0	6.7	31	5.4
150	100	1	0	4.5	15	3.1
150	200	1	0	4.1	12	2.7
150	300	1	0	4.1	12	2.7
150	10	3	0	19.5	46	8.9
150	50	3	0	12.6	34	8.2
150	100	3	0	7.1	33	5.8
150	200	3	0	4.5	13	3.1
150	300	3	0	4.3	12	3.0
150	10	5	2	20.3	47	8.7
150	50	5	0	15.5	42	8.8
150	**100**	**5**	**0**	**10.7**	**36**	**7.9**
150	200	5	0	5.6	27	4.2
150	300	5	0	4.6	17	3.2

decoys per warhead, and 10 missile interceptors, the U.S. missile shield is so overwhelmed by targets—decoys misidentified as warheads—that the attack is not significantly reduced by the defenses.

As the number of missile defense interceptors is increased beyond the initial number of attacking Russian warheads (greater than on average 21 missile defense interceptors), more of the Russian First Echelon retaliation is successfully defended against by the U.S. shield. When the numbers of missile defense interceptors are far in excess of the initial mean Russian retaliation, at 300 interceptors for example, the only Russian warheads which penetrate the U.S. missile defense shield are those that have been misidentified as decoys (about four warheads on average are misidentified as decoys based on our choice of Pww). Therefore in the case of 300 missile defense interceptors against much fewer targets, a better U.S. operational strategy for its shield would be to attack all warheads and decoys to compensate for common mode failures.

Highlighted in Table 4 is the case of 100 U.S. missile defense interceptors contending with five heavy decoys per Russian warhead. From our perspective this model run illustrates a reasonable missile defense interceptor limit at a First Echelon size of 150 launchers. We postulate that deterrence today would remain stable even if retaliation against only 10 cities were assured. Note that

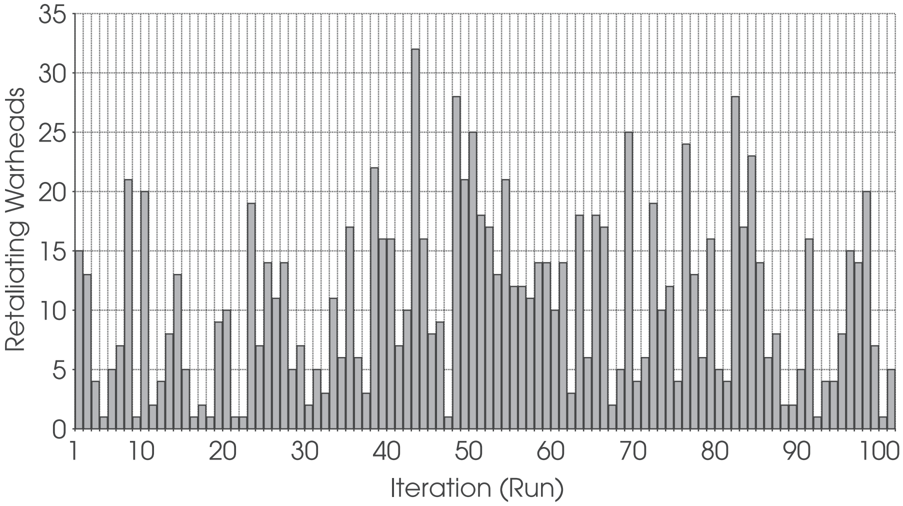

Figure 2: *Analytica* Result Window displaying the number of Russian First Echelon warheads out of an initial 150 warheads that survive a U.S. strike and penetrate a highly capable U.S. missile defense system, for 100 missile defense interceptors and five heavy decoys per Russian warhead.

these can be any 10 U.S. cities—the specific VS retaliatory targeting unknown to the AS—and in this sense all major metropolitan centers would be "hostage" cities for deterrence purposes.

However it is not just the mean retaliation that is important, but also what would be the worst case for the AS (here the U.S.) among possible nuclear wars, which is the maximum retaliation. Figure 2 shows the surviving Russian First Echelon warheads (out of initially 150 warheads) which penetrate the U.S. missile defense shield in the case of 100 missile interceptors and five heavy decoys per warhead, for 100 Monte Carlo runs of the model. The maximum retaliation is a strong function of the number of missile interceptors, as the maximum retaliation depends more on the interception and less on the discrimination aspect to the missile defense system. And of course the discrimination capabilities of a missile defense system could not reasonably be the subject of negotiated limits in future arms control treaties between the United States and Russia, but limits on the number of interceptors could be negotiated and verified. As the AS missile defense interception and warhead discrimination probabilities decrease, the VS retaliation rises to the level of surviving VS forces, thus increasing the stability of deterrence with respect to the First Echelon force structure. Note that two Monte Carlo runs were found in which the missile defense shield completely defended against the Russian First Echelon retaliation. Judgments about the stability of deterrence also need to take into account lower-probability events favoring the AS.

In this work we also examined the cases of 100 Russian First Echelon launchers and 50 Russian First Echelon launchers with respect to our missile

Table 5: *Analytica* statistical results for a U.S. missile defense system intercepting the retaliation from a Russian First Echelon of 100 single-warhead ICBM launchers (the proposed 500 warhead limit)

VS (Russia) First Echelon size	Number of AS (United States) missile defense interceptors	Decoys per VS (Russia) warhead	Min retal.	Mean retal.	Max retal.	Std dev
100	10	0	0	7.0	19	5.0
100	25	0	0	2.84	8	2.0
100	50	0	0	2.8	8	2.0
100	75	0	0	2.8	8	2.0
100	100	0	0	2.8	8	2.0
100	10	1	0	10.2	23	6.0
100	25	1	0	5.6	16	4.2
100	50	1	0	3.5	10	2.7
100	75	1	0	3.0	8	2.2
100	100	1	0	2.9	8	2.0
100	10	3	1	12.1	25	6.0
100	25	3	0	9.5	26	5.9
100	50	3	0	5.9	19	4.7
100	75	3	0	4.3	14	3.5
100	100	3	0	3.6	10	2.5
100	10	5	1	12.6	26	5.8
100	**25**	**5**	**0**	**11**	**26**	**5.9**
100	50	5	0	8.0	21	5.6
100	75	5	0	5.8	19	4.6
100	100	5	0	4.6	15	3.7

defense model, in order to similarly gauge missile defense interceptor limits as a component of future arms control discussions. Tables 5 and 6 provide similar statistical results of the model at these lower Russian First Echelon sizes.

These proposed missile defense interceptor limits provide assurance that, at a given warhead limit, sufficient forces survive a surprise nuclear attack, and retaliating warheads penetrate a missile defense shield to potentially explode over an attacker's cities. The modeling has displayed the significance of countermeasure to a missile defense shield. With the presence of additional, more deeply de-alerted nuclear forces in the Second Echelon, missile defense systems would have to cope with follow-on retaliatory strikes in the form of salvos.

THE ROLE OF THE SECOND ECHELON

The intent of our work was to first construct plausible First and Second Echelon forces for the United States and Russia, based on open-source information about strategic and tactical weaponry, and second to evaluate the contribution of the Second Echelons to assured retaliation, or the Second Echelon's

Table 6: *Analytica* statistical results for a U.S. missile defense system intercepting the retaliation from a Russian First Echelon of 50 single-warhead ICBM launchers (the proposed 100 warhead limit)

VS (Russia) First Echelon size	Number of AS (United States) missile defense interceptors	Decoys per VS (Russia) warhead	Min retal.	Mean retal.	Max retal.	Std. dev.
50	5	0	0	3.6	16	3.0
50	10	0	0	2.2	8	1.9
50	15	0	0	1.7	8	1.6
50	20	0	0	1.5	6	1.5
50	25	0	0	1.5	5	1.4
50	5	1	0	5.3	15	3.5
50	10	1	0	3.8	16	3.1
50	15	1	0	2.7	15	2.7
50	20	1	0	2.2	11	2.0
50	25	1	0	1.9	10	1.8
50	5	3	0	6.3	16	3.6
50	10	3	0	5.5	17	3.6
50	15	3	0	4.6	18	3.6
50	20	3	0	3.9	15	3.4
50	25	3	0	3.4	14	2.9
50	**5**	**5**	**0**	**6.6**	**18**	**3.5**
50	10	5	0	5.9	18	3.6
50	15	5	0	5.3	15	3.4
50	20	5	0	4.8	16	3.4
50	25	5	0	4.4	15	3.4

contribution to the stability of deterrence. The Second Echelon of nuclear forces we posit are more deeply de-alerted than the First Echelon—brought to launch ready status over a lengthy period of time from days to weeks. Indeed, the Second Echelon can be thought of as the whole reservoir of a state's nuclear weapons capability. Of course the First and Second Echelons together constitute the nuclear deterrent, but in our formulation the main barrier to nuclear war between the United States and Russia lies in the expected retaliation from the First Echelon alone.

This Second Echelon of de-alerted nuclear forces consists of a more diverse set of nuclear weapons, providing for equal numbers of warheads on each side, but with asymmetry in the types of weapons. Our model assigns multiple-warhead silo ICBM launchers to a Second Echelon because a subset of these weapon systems would have the capability to destroy a First Echelon, compromising assured retaliation. And our model assigns SSBN and road-mobile launchers to a Second Echelon because of variations in the tempo of operational deployments and the vulnerability to non-nuclear attack, as discussed above.

Because of the role of the First Echelon single-warhead ICBMs to pose a main barrier to nuclear war, the Second Echelons have a greater flexibility in terms of differences in composition between the United States and Russia, for example including tactical nuclear weaponry as determined by the separate security assessments of the United States and Russia. Even though we considered a First Echelon force size of 500 silo-based ICBMs, it is implausible that Russia could maintain these numbers of silo launchers into the near future. However recall that a First Echelon size of roughly 100 launchers provides a stable barrier to nuclear war.

In this article we propose First and Second Echelon nuclear forces for the United States and Russia at total warhead limits of 1,000, 500, and 100 warheads, including tactical weaponry. These force mixes take into account the fact that Russian SS-18, SS-19 and SS-25 systems are approaching the end of the service lives and will be replaced by the SS-27 systems at lower total force levels. We also assume that SSBNs will remain central to the U.S. force mix and that road-mobile ICBMs will remain central to the Russian nuclear force mix. As the warhead limits decrease from 1,000 to 100 weapons, we propose that the fraction of weapons in the First Echelon increases from 15 percent to 50 percent.

The events in the Second Echelon scenario models unfold as follows:

- An attack on the First Echelon ICBM silo launchers of the VS is conducted by the AS, where each VS First Echelon launcher has a given probability of survival as evaluated in our Monte Carlo manner;
- Surviving VS First Echelon ICBM silo launchers retaliate against cities of the AS;
- As Second Echelon forces of the AS are generated, follow-on strikes by these generated AS Second Echelon forces strike the generating VS Second Echelon forces;
- If a VS Second Echelon launcher is brought to combat readiness before it is struck by the AS Second Echelon, then it retaliates against AS cities.
- If a VS Second Echelon launcher is struck before it is brought to combat readiness, but survives, it then retaliates against AS cities.

In this modeling work we introduced a new random variable, termed Pbefore, which is the (small) probability that a Second Echelon launcher can be bought to launch-ready status and deployed (for example, SSBNs to sea, road-mobile ICBMs to forest) before it is struck by the opposing side's Second Echelon forces, or possibly by conventional military means. Furthermore, we do not at this stage of the work explicitly calculate Psurvive for Second Echelon forces, nor consider attrition by missile defense, instead examining the model results for aggregate low, mid, and high values of Psurvive for silo-based ICBMs, road-mobile ICBMs, and SSBNs coming under attack. For silo-based launchers, Psurvive was modeled as: 0.03 (low), 0.04 (mid), and 0.05 (high). For road-mobile launchers, Psurvive was modeled as: 0.02 (low), 0.06 (mid), and 0.10 (high). For SSBNs Psurvive was modeled as: 0.01 (low), 0.02 (mid), and 0.03 (high).

For each of these model runs we have used the First and Second Echelon forces from Tables A1 through A3 (see Appendix)—our proposed force structures for steps in the arms control process following implementation of New START. The Tables A4 through A6 (see Appendix) examine, for a range of generation and survivability of Second Echelon forces, their contribution to assured retaliation in addition to the assured retaliation from the First Echelon. In these calculations we do not consider attrition of AS warheads from VS missile defenses. What we find is that the Second Echelon's contribution to the stability of deterrence bolsters the First Echelon, particularly at low numbers and for the computed maximum retaliation. In addition the Pbefore factor, i.e., the probability some Second Echelon missiles are re-alerted and fired before being struck, also plays an important role in the value of retaliation. The size of this factor is random, and it depends on many extreme conditions occurring in the course of nuclear war. In order to strengthen deterrence it would be useful to study a possibility to assign (to fix) technically this uncertainty in the required framework, and therefore really manage the deterrence effectiveness.

CONCLUSIONS

In this study we examined the effects of reducing the force size and changing the launch posture of U.S. and Russian strategic forces on the stability of deterrence. We partitioned U.S. and Russian forces into a First Echelon, consisting of single-warhead, silo-based ICBM launchers that can be generated in hours to launch-ready alert but are normally off alert, and into a Second Echelon of more diverse nuclear forces that take much longer (days to weeks) to become launch ready.

We found that, given reasonable estimates of weapons characteristics such as accuracy and hardness to nuclear blast, First Echelon nuclear forces can survive to retaliate in numbers that satisfy reasonable requirements of deterrence. In the event of a surprise strike with as few as 100 launchers in a First Echelon—on average 10 cities would be destroyed in retaliation. Moreover, the AS, if rational, would have to acknowledge that a much worse outcome could occur, further bolstering deterrence. In a cosmic roll of the dice, the aggressor might just as readily suffer the devastation of scores of its cities instead of "only" 10.

We then derived limitations on the numbers of missile defense interceptors that are consistent with stable deterrence between First Echelon forces, assuming a highly capable missile defense system (an unlikely technological feat for the foreseeable future). Finally, we introduced Second Echelon forces into the model and calculated their additional contribution to retaliatory capacity and thus to stability. We suggested specific forces within a First and Second Echelon framework that would strengthen strategic stability.

An important step on the path toward ridding the world of nuclear danger consists in de-alerting U.S. and Russian nuclear forces, providing increasing warning and decision times. Today a large share of American and Russian strategic nuclear missiles remain on "hair-trigger" alert poised for launch in minutes. This indefensible mutual posture runs a significant and constant risk of accidental or unauthorized nuclear missile launches, quite possibly leading to full-scale nuclear war, because of technical defect, duty personnel error, or terrorist sabotage which will likely increase during periods of rising international tensions. To reduce this serious peacetime and crisis danger it is necessary to lower the launch readiness of all nuclear forces—de-alerting.

At the present, a deep-seated Cold War mindset within the security establishments of both the United States and Russia opposes de-alerting. In the recent Nuclear Posture Review (NPR) the U.S. administration said: "The NPR considered the possibility of reducing alert rates for ICBMs and at-sea rates of SSBNs, and concluded that such steps could reduce crisis stability by giving an adversary the incentive to attack before 're-alerting' was complete." Our modeling results refute this view. By re-configuring each side's strategic forces into two echelons of varying launch readiness, there would be no incentive to initiate "re-alerting". Both sides' cities would remain vulnerable to second-strike retaliation by the other side under any scenario and therefore preemptive "re-alerting" would serve no rational purpose. Furthermore, these results are robust under a wide range of conditions that allow for capable missile defenses and force attrition resulting from conventional strikes.

This study demonstrates how stable deterrence based on the mutual vulnerability of U.S. and Russian urban centers can exist with relatively low numbers of strategic forces and without keeping them on launch-ready alert. There is ample opportunity to deeply reduce the size of the strategic arsenals and to lower their normal launch readiness in ways that reliably protect against mistaken launch on false warning or unauthorized launch.

Further research and modeling work is needed to define a stable path from the low numbers of nuclear forces assumed in this study down to very low numbers or zero forces. Our modeling results suggest that the echelon architecture of the forces will need to be further re-designed in order to ensure a stable transition to Global Zero. We also will need to take into account the strategic nuclear arsenals of the other nuclear-armed countries. The bi-polar nuclear balance analyzed in this study will have to be broadened into a multi-polar balance, the stability of which at very low numbers remains an open question.

Whatever the results of such assessments, openness is the key to understanding the nuclear risks and opportunities ahead and to deriving sound implications for strategic policy. Transparency ensures informed public debate on the requirements of deterrence and on the existing and desired level of nuclear risk incurred. It fosters clarity, consensus, and cooperation on these issues between U.S. and Russian nuclear planners, and allows the widening of expert discourse to include stakeholders from other nations. The way forward to Global Zero is to establish an open and global forum on deterrence and alternative frameworks of mutual security. This collaborative U.S.-Russian study hopefully will encourage further openness and joint work in future strategic assessments.

NOTES AND REFERENCES

1. For a discussion of technical options for de-alerting nuclear forces, see: Bruce G. Blair, "De-Alerting Strategic Forces," in George P. Shultz, Sidney D. Drell, and James E. Goodby, editors, *Reykjavik Revisited: Steps Toward a World Free of Nuclear Weapons* (Stanford: Hoover Institution Press, 2008). See also: Victor Esin, "Nuclear Disarmament: State, Problems and Prospects,*" Russia and America in the XXI Century*, 3 (2010), and Pavel Zolotarev, "The Prospect of Universal Complete Nuclear Disarmament," James Martin Center for Nonproliferation Studies, Occasional Paper No.15 (April 2009).

2. Of the current operational U.S. warheads, we believe that nearly all of the silo-based ICBM strategic warheads are maintained in an alert posture, and additionally four U.S. ballistic missile submarines are on "Hard Alert" patrol at any given time in the Atlantic and Pacific Oceans. See Robert S. Norris and Hans M. Kristensen, "U.S. Nuclear Forces, 2010," *Bulletin of the Atomic Scientists* 66 (May/June 2010): 57–70 and Hans M. Kristensen, "U.S. Strategic Submarine Patrols Continue at Near Cold War Tempo," (http://www.fas.org/blog/ssp/2009/03/usssbn.php) (March 16, 2009). With respect to Russian strategic forces, we understand that 75–80 percent of SS-18, SS-19 and SS-27 silo-based ICBM warheads are maintained in an alert posture. A small fraction of road-mobile (SS-25 and SS-27) weapons are on alert patrol out of garrison at any given time, and Russia likely does not maintain a continuous patrol of its SSBNs currently. See Robert S. Norris and Hans M. Kristensen, "Nuclear Notebook: Russian Nuclear Forces, 2009," *Bulletin of the Atomic Scientists* 65 (May/June 2009): 59–69 and Hans M. Kristensen, "Russian Strategic Submarine Patrols Rebound," (http://www.fas.org/blog/ssp/2009/02/russia.php) (February 2009). See also Bruce G. Blair, "Global Zero Alert for Nuclear Forces," Brookings Occasional Papers (1995), and Blair, "De-alerting Strategic Forces," *op. cit*.

3. Our definition of the stability of nuclear deterrence focuses on what is also called "first-strike stability" between two nuclear-armed states, discussed famously in Thomas Shelling, *The Strategy of Conflict* (Cambridge: Harvard University Press, 1960). A more quantitative analysis can be found in Glenn A. Kent and David E. Thaler, "First-Strike Stability: A Methodology for Evaluating Strategic Forces," RAND R-3765-AF (August 1989).

4. The 2010 Nuclear Posture Review explicitly rejected de-alerting of U.S. strategic nuclear forces: "reducing alert rates for ICBMs and at-sea rates of SSBNs . . . could reduce crisis stability by giving an adversary the incentive to attack before "re-alerting" was complete." United States Department of Defense, "Nuclear Posture Review Report" (April 2010), 26.

5. See Blair, "De-alerting Strategic Forces," *op. cit*.

6. For an extended presentation of this approach to modeling deterrence, see Valery Yarynich, *C3*: *Nuclear Command, Control, and Cooperation* (Washington D.C.: Center for Defense Information, 2003).

7. See for example the chapter on Strategic Nuclear Exchange Models in: Francis P. Hoeber, *Military Applications of Modeling: Selected Case Studies*, (New York: Gordon and Breach, 1981), 154–180.

8. See for example: M. K. Paul and Neal H. Hillerman, "The Calculational Procedure of the CNA Version of the CODE 50 Nuclear Exchange Model," Center for Naval Analysis (April 1970) and Neal H. Hillerman, "The Theoretical Basis of the CODE 50 Nuclear Exchange Model," Center for Naval Analysis (March 1972).

9. One interesting non-official Russian NEM is described here: V.A. Gelovani, A.A. Piontkovsky and A.P. Skerokhodov, "Strategic Stability Analysis through Mathematical Modeling," *International Political Science Review*, 11 (1990): 243–260.

10. Robert E. Bunnell and Richard A. Takacs, "BRIK: An Interactive, Goal Programming Model for Nuclear Exchange Problems," *Thesis, Air Force Institute of Technology* (March 1984).

11. Analytica, Release 4.0.0.68, is a product of the Lumina Decision Systems Corporation, (www.lumina.com).

12. Lynn Etheridge Davis and Warner R. Schilling, "All You Ever Wanted To Know About MIRV and ICBM Calculations but Were Not Cleared to Ask," *Journal of Conflict Resolution*, 17 (1973): 207–242.

13. Pavel Podvig, "The Window of Vulnerability that Wasn't: Soviet Military Buildup in the 1970s," *International Security*, 33 (2008): 118–138.

14. Dean A. Wilkening, "A Simple Model for Calculating Ballistic Missile Defense Effectiveness," Working Paper, Center for International Security and Cooperation, Stanford University, August 1998 (modified April 2002).

APPENDIX: FIRST AND SECOND ECHELON FORCES AND MODELING RESULTS

Table A1: Hypothetical First and Second Echelon nuclear forces for the United States and Russia under a 1,000 warhead limit, including tactical nuclear weaponry

Echelon	Launcher	Number of launchers	Warheads per launcher	Total warheads
Hypothetical nuclear forces of Russia under a 1,000 warhead limit				
First Echelon	SS-18	20	1	20
First Echelon	SS-19	70	1	70
First Echelon	SS-27 (silo)	60	1	60
Total First Echelon		150		150
Second Echelon	SS-25 (mobile)	120	1	120
Second Echelon	SS-27 (mobile)	10	1	10
Second Echelon	SS-18	30	10	300
Second Echelon	4 SSBN, 16 SLBM per SSBN	64	2	128
Total Strategic Second Echelon		224		558
Tactical Nuclear Weapons				292
Total		374		1,000
Hypothetical nuclear forces of the United States under a 1,000 warhead limit				
First Echelon	Minuteman-III	150	1	150
Total First Echelon		150		150
Second Echelon	Minuteman-III	120	2	240
Second Echelon	8 SSBN, 16 SLBM per SSBN	128	4	512
Total Strategic Second Echelon		248		752
Tactical Nuclear Weapons				98
Total		398		1,000

Table A2: Hypothetical First and Second Echelon nuclear forces for the United States and Russia under a 500 warhead limit, including tactical nuclear weaponry for Russia

Echelon	Launcher	Number of launchers	Warheads per launcher	Total warheads
Hypothetical nuclear forces of Russia under a 500 warhead limit				
First Echelon	SS-18	20	1	20
First Echelon	SS-27 (silo)	80	1	80
Total First Echelon		100		100
Second Echelon	SS-25 (mobile)	36	1	36
Second Echelon	SS-27 (mobile)	40	1	40
Second Echelon	SS-27 (multiple warheads)	40	4	160
Second Echelon	2 SSBN, 16 SLBM per SSBN	32	2	64
Total Strategic Second Echelon		148		300
Tactical Nuclear Weapons				100
Total		248		500
Hypothetical nuclear forces of the United States under a 500 warhead limit				
First Echelon	Minuteman-III	100	1	100
Total First Echelon		100		100
Second Echelon	Minuteman-III	72	2	144
Second Echelon	4 SSBN, 16 SLBM per SSBN	64	4	256
Total Strategic Second Echelon		136		400
Tactical Nuclear Weapons				0
Total		236		500

Table A3: Hypothetical First and Second Echelon nuclear forces for the United States and Russia under a 100 warhead limit, without tactical nuclear weaponry

Echelon	Launcher	Number of launchers	Warheads per launcher	Total warheads
Hypothetical nuclear forces of Russia under a 100 warhead limit				
First Echelon	SS-27 (silo)	50	1	50
Total First Echelon		50		50
Second Echelon	SS-27 (mobile)	50	1	50
Total Strategic Second Echelon		50		50
Tactical Nuclear Weapons				0
Total		100		100
Hypothetical nuclear forces of the United States under a 100 warhead limit				
First Echelon	Minuteman-III	50	1	50
Total First Echelon		50		50
Second Echelon	2 SSBN, 16 SLBM per SSBN	32	1 to 2	50
Total Strategic Second Echelon		32		50
Tactical Nuclear Weapons				0
Total		*82*		100

Table A4: Modeled Russian and U.S. deterrent retaliation under the proposed 1,000 warhead limit with forces partitioned into off alert First and Second Echelons

	Russian minimum retaliation	Russian mean retaliation	Russian maximum retaliation	Second Echelon contribution to Russian mean retaliation	Second Echelon contribution to Russian maximum retaliation	U.S. minimum retaliation	U.S. mean retaliation	U.S. maximum retaliation	Second Echelon contribution to U.S. mean retaliation	Second Echelon contribution to U.S. maximum retaliation
Pbefore = 0.0; Psurvive, Second Echelon = Low	14	33.7	85	12.7	66	54	78.3	143	12.3	74
Pbefore = 0.0; Psurvive, Second Echelon = Mid	21	43.4	82	22.4	64	49	85.8	213	19.8	142
Pbefore = 0.0; Psurvive, Second Echelon = High	24	52.8	100	31.8	74	58	93.4	206	27.4	140
Pbefore = 0.05; Psurvive, Second Echelon = Low	29	60.9	111	39.9	95	60	115.6	293	49.6	224
Pbefore = 0.05; Psurvive, Second Echelon = Mid	33	70.2	130	49.2	109	59	122.3	281	56.3	208
Pbefore = 0.05; Psurvive, Second Echelon = High	30	79.1	151	58.1	133	65	128.5	279	62.5	214
Pbefore = 0.10; Psurvive, Second Echelon = Low	35	87.8	165	66.8	29.7	76	153	371	87	302
Pbefore = 0.10; Psurvive, Second Echelon = Mid	39	97	196	75.9	174	79	160	361	94	288
Pbefore = 0.10; Psurvive, Second Echelon = High	40	105.6	175	84.6	160	83	165.4	382	99.4	302

Table A5: Modeled Russian and U.S. deterrent retaliation under the proposed 500 warhead limit with forces partitioned into off alert First and Second Echelons

	Russian minimum retaliation	Russian mean retaliation	Russian maximum retaliation	Second Echelon contribution to Russian mean retaliation	Second Echelon contribution to Russian maximum retaliation	U.S. minimum retaliation	U.S. mean retaliation	U.S. maximum retaliation	Second Echelon contribution to U.S. mean retaliation	Second Echelon contribution to U.S. maximum retaliation
Pbefore = 0.0; Psurvive, Second Echelon = Low	9	21	56	7	38	37	50.9	177	6.9	130
Pbefore = 0.0; Psurvive, Second Echelon = Mid	12	26.2	72	12.2	56	35	54.9	175	10.9	130
Pbefore = 0.0; Psurvive, Second Echelon = High	13	31.5	71	17.5	9.3	37	58.9	120	14.9	74
Pbefore = 0.05; Psurvive, Second Echelon = Low	11	35.6	88	21.6	79	43	70.6	187	26.6	148
Pbefore = 0.05; Psurvive, Second Echelon = Mid	14	40.8	78	26.8	62	41	73.3	189	29.3	144
Pbefore = 0.05; Psurvive, Second Echelon = High	23	45.7	112	31.7	102	45	78.5	192	34.5	148
Pbefore = 0.10; Psurvive, Second Echelon = Low	25	50.1	85	36.1	73	52	89.7	202	45.7	152
Pbefore = 0.10; Psurvive, Second Echelon = Mid	28	55.3	127	41.3	109	47	93.5	270	49.5	214
Pbefore = 0.10; Psurvive, Second Echelon = High	32	59.7	112	45.7	100	49	98.3	212	54.3	162

Table A6: Modeled Russian and U.S. deterrent retaliation under the proposed 100 warhead limit with forces partitioned into off alert First and Second Echelons

	Russian minimum retaliation	Russian mean retaliation	Russian maximum retaliation	Second Echelon contribution to Russian mean retaliation	Second Echelon contribution to Russian maximum retaliation	U.S. minimum retaliation	U.S. mean retaliation	U.S. maximum retaliation	Second Echelon contribution to U.S. mean retaliation	Second Echelon contribution to U.S. maximum retaliation
Pbefore = 0.0; Psurvive, Second Echelon = Low	3	8	18	1	6	15	22.5	49	0.5	25
Pbefore = 0.0; Psurvive, Second Echelon = Mid	3	10	18	3	7	15	23	49	1	25
Pbefore = 0.0; Psurvive, Second Echelon = High	5	12	19	5	10	15	23.5	54	1.5	25
Pbefore = 0.05; Psurvive, Second Echelon = Low	4	10.5	23	3.5	9	15	25	57	3	25
Pbefore = 0.05; Psurvive, Second Echelon = Mid	4	12.3	20	5.3	11	16	25.5	51	3.5	25
Pbefore = 0.05; Psurvive, Second Echelon = High	6	14.2	21	7.2	14	15	25.5	79	3.5	50
Pbefore = 0.10; Psurvive, Second Echelon = Low	5	12.9	22	5.9	12	15	27.3	78	5.3	50
Pbefore = 0.10; Psurvive, Second Echelon = Mid	6	14.7	26	7.7	15	15	28	75	6	50
Pbefore = 0.10; Psurvive, Second Echelon = High	7	16.6	25	9.6	16	15	28.5	72	6.5	50