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

Technical Appendix to "Smaller and Safer: A New Plan for Nuclear Postures," in Foreign Affairs, Volume 89, No. 5

Bruce Blair Ph.D., Col.-Gen. (Ret.) Victor Esin Ph.D., Matthew McKinzie Ph.D., Col. (Ret.) Valery Yarynich Ph.D., and Maj.-Gen. (Ret.) Pavel Zolotarev Ph.D.

A GLOBAL ZERO WORKING PAPER: VERSION 09/02/2010

Note: A Russian version of this document can be accessed at:
http://www.globalzero.org/files/FA_appendix_RussianLanguageVersion.pdf

OBJECTIVE, METHOD AND CONTENT

The aim of this study is to assess the effects on mutual deterrence of making deep cuts in the nuclear arsenals of the United States and Russia (and later of all nuclear-armed countries) while reducing their combat readiness and accommodating a limited deployment of missile defense systems. The study designs and tests smaller and safer force postures that provide for stable mutual nuclear deterrence.

The methods used in this study involve statistical modeling of scenarios of sudden nuclear war between the United States and Russia. As a baseline scenario, the nuclear forces of both sides are, during peacetime, in a reduced operational status (i.e., de-alerted). We postulate that the United States possesses a highly-capable missile defense system even though this is not a particularly credible assumption at this time.

The model estimates the risk to the attacker of conducting a first strike: the United States against Russia, and vice versa. This risk can be measured with the help of two calculated quantities: the scale of a nuclear retaliation in response to a first strike (number of nuclear explosions on the attacker's territory) and the corresponding probability of this event. Because the nuclear arsenals of the United States and Russia are well matched, 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 (orchestrated) nuclear war between the United States and Russia is unrealistic.

A hypothetical nuclear war relates to a complicated process with many different events, where chance and uncertainty play a significant role. 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). Any single run may represent the actual outcome of a nuclear war. 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 was more probable.

The implications of each next step on the path to reducing nuclear arsenals must be grounded on open, quantitative analyses. Information pertinent to estimating the stability of deterrence should not be classified. Such openness allows progress in devising mutually beneficial measures by American and Russian experts, both on official and on an independent basis. Our specifications of nuclear forces, command, control and communications networks, and missile defense systems for this work are taken from public unclassified sources.

The contents of this Technical Appendix are as follows:

1) INTRODUCTION;
2) NUCLEAR EXCHANGE MODELING;
3) MODELING THE FIRST ECHELON;
4) NUCLEAR STRIKES AGAINST THE NATIONAL COMMAND AUTHORITY;
5) MISSILE DEFENSES;
6) MODELING THE SECOND ECHELON;
7) CONCLUSIONS AND BIBLIOGRAPHY

1) INTRODUCTION

The nuclear command, communications and weapons systems of the United States and Russia today remain capable of launch on warning – a mass firing of missile forces *before* the arrival of attacking enemy missiles which have a flight time of half an hour or less. 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. Both the United States and Russia are 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.

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. Verifiable, workable means to extend the time needed to fire U.S. and Russian nuclear forces – by hours, days, weeks, months, and even years – have been developed. And 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.

But can taking nuclear forces off alert make deterrence less stable? A necessary step in achieving the de-alerting of US 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.

Two fundamental criticisms of nuclear de-alerting have been put forward: strategic nuclear forces off alert are vulnerable to a disarming first strike, and a future crisis between the United States and Russia would grow more dangerous as missile forces race to return to launch-ready status. De-alerting should not create exploitable advantages from breaking out and re-alerting.

A stable nuclear deterrent is a situation where both the United States and Russia would not rationally choose to strike first with nuclear weapons, because doing so could cause unacceptable death and destruction from nuclear retaliation. In a stable nuclear deterrent situation, neither the United States nor Russia could easily attain nuclear dominance. Deterrence falters if either the United States or Russia has a credible nuclear attack capability (an ability to attack without fear of reprisal), which could also be used as a threat.

Deterrence in our view is the possibility of keeping a sufficient size of retaliation at a given probability. The specter of retaliation is the foundation of deterrence. Uncertainty is an important aspect of nuclear conflict that bolsters the fear of retaliation to attack. However, if we wish to reduce nuclear arms to low levels, this uncertainty must be specified well enough to impart knowledge of the possible outcome of a nuclear exchange.

The stability of deterrence depends strongly on the configuration and capabilities of forces on both sides. The current status of nuclear deterrence – including a significant launch on warning capability from a sizable portion of the nuclear arsenals <u>on alert</u> – is stable, in that neither the United States nor Russia could strike first without the risk of devastating retaliation: neither country could mount a disarming first strike. A solution to a stable nuclear deterrent with all forces <u>off alert</u>, put forward here, 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, a stable nuclear deterrent whole is constructed from more vulnerable, de-alerted parts.

It should be noted that maintaining nuclear weapons off alert is an aspect of the current nuclear deterrent relationship between the United States and Russia, where approximately one-third of today's forces are maintained on alert. With the ending of the Cold War, the relative danger of accidental launch or intentional interference with nuclear command and control systems have declined, but they now represent a greater danger than a surprise first strike.

In our formulation, the partitioning of nuclear forces into a First and Second Echelons serves as a barrier to nuclear war while maintaining a stable deterrent.

The First Echelon of de-alerted nuclear forces for the United States and Russia consists of equal numbers of US and Russian single-warhead, high-yield, silo-based intercontinental ballistic missiles (ICBMs) maintained off alert. First Echelon forces are vulnerable to a sudden strike, although not completely. The primary characteristic of this First Echelon is both a weak capability to threaten opposing nuclear forces, and a strong capability to threaten opposing economic and administrative sectors (i.e. urban-industrial centers), for deterrence. These First Echelon ICBMs have the least degree of de-alerting – it is postulated that these weapons can be brought to launch-ready status in a matter of hours (this rapid generation time, prevents additional attacks by conventional forces following a sudden nuclear strike). The primary role of First Echelons is to conduct peacetime day-to-day deterrence operations between the United States and Russia. They also deter nuclear (and non-nuclear) attack by other nuclear-armed states. In other words, the First Echelon is the "front line of deterrence."

The Second Echelon of de-alerted nuclear forces for the United States and Russia consists of a more diverse group of weapons, with roughly equal numbers of total warheads but with asymmetry in types of weapons. 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 highly vulnerable in their day-to-day, off-alert status. It is postulated that these Second Echelon forces have a much deeper degree of de-alerting than the First Echelon –these Second Echelon weapons can only be brought to launch-ready status over the course of weeks to months, and that mutually-verifiable de-alerting measures would insure a roughly symmetrical rate of re-alerting of Second Echelon forces. 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 in a crisis situation. One consideration in the modeling is that the victim of a sudden nuclear strike will have more difficult conditions for restoring Second Echelon forces than the aggressor.

In short, the First Echelon is likened to a small and relatively weak shield, or barrier to nuclear war, and the Second Echelon may be likened to a big and more reliable sword, or a reservoir of additional nuclear capability. The First Echelon shield provides a buffer time for the Second Echelon sword to be drawn, and so permits the de-alerting of all forces. Full symmetry between First Echelons ensures no temptation exists for a surprise first attack.

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. Russian and the Unites States currently maintain different patrol rates for their SSBNs. 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 US and Russia 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.

Uncertainty, incomplete knowledge and chance permeate nuclear deterrence as it continues to be carried out day-to-day between the United States and Russia. The title of this Technical Appendix speaks to the role of randomness in outcomes if deterrence fails and nuclear conflict begins. A nuclear war between the United States and Russia will surely only be fought only once, but computer modeling allows us to look at the outcome of one hundred nuclear wars, for example, and assess the probabilities of these outcomes. The modeling scenarios explore the Echelon concept for nuclear forces off alert for two types of targeting: strikes against opposing nuclear weapons, and retaliatory strikes against urban targets. In our scenarios, an Attacking State (AS) and a Victim State (VS) will have a different targeting policy. The targeting policy of the AS will be to fully eliminate the nuclear forces of the VS, in order to achieve dominance. The VS will have another targeting policy, targeting the cities of the AS in retaliation.

The VS is forced into a different strategy than the AS. In general, the VS and AS will have limited knowledge about the military forces and actions of the opposing side. In the conditions of a real nuclear war the VS has uncertain knowledge about AS nuclear forces. City targets do not require re-planning during a nuclear exchange. Therefore it is logical that the AS must assume that the VS will retaliate against cities. The AS must also take into account that the VS could delegate launch authority to duty crews in the aftermath of a sudden nuclear attack, which will likely mean that city targets are used because the National Command Authority cannot communicate information about the status of the AS to its launchers.

The stability of deterrence with nuclear forces having increased warning and decision time and arrayed in off-alert Echelons was analyzed using computer modeling of nuclear exchanges. Key aspects of the modeling were: the numbers of strategic missiles and the numbers of nuclear warheads they carry; the time required to bring a missile to launch-ready status (i.e., the depth of de-alerting); the probability that an attacked missile could survive a nuclear strike and launch in retaliation; and the effectiveness of missile defenses. The nuclear exchange modeling is presented in the form of scenarios of increasing complexity. Our modeling examined the stability of deterrence when nuclear forces are taken off alert, and for different nuclear arsenal sizes for the United States and Russia.

In the course of this modeling work, it was reasonable to ask: How low can the United States and Russia go in terms of numbers of strategic nuclear weapons? Could reliable mutual deterrence be confirmed even in the case of Russian and US nuclear arsenals a fraction of today's sizes? In addition the study examined related questions of deterrence stability: scenarios of targeting leadership and the added factor of missile defense, for de-alerted forces.

2) NUCLEAR EXCHANGE MODELING

Nuclear Exchange Models (NEMs), or computer calculations of the consequences of nuclear warfare, can be traced back to the 1960s in their US origins to Secretary of Defense Robert McNamara's call for a dynamic approach to US nuclear force planning which sought to examine nuclear force mission objectives using a common model among the military services and their contractors, rather than simple, static comparisons of US and Soviet weapons inventories for defense planning purposes. Despite the secrecy associated with nuclear weapons, an open literature exists on US NEMs, including legacy code listings. However we know of no analog in Russia.

Analytical, less detailed NEMs have been used in the United States to understand the deterrent capability of the US nuclear arsenal and understand the effects of new developments on the deterrence objectives for US nuclear forces. More detailed, complex NEMs are computer simulations used to construct operational plans in the event of nuclear conflict. The evolution of NEMs in the United States, taking advantage of increasing computing power, has focused on more interactive capabilities with the user, on assigning relative priorities to classes of target (including the avoidance of some classes of targets), improvements to assigning "optimal" allocation of weapons to targets to achieve specified levels of damage in war, and incorporating increasingly complex weapon and target databases.

Two NEMs which have been of substantial significance for the United States, and for which information has been published in the open literature from the 1960s until the 1990s, are CODE 50 and the Arsenal Exchange Model.

CODE 50 (1960s-1970s): A once widely-used computer program for solving a two-sided nuclear war game developed by the Lambda Corporation. In CODE 50 the Soviet Union strikes first against US strategic offensive forces, and then the maximum damage that surviving US forces could do against Soviet urban-industrial targets measured the "deterrence capability" of US forces. A third strike by the Soviet Union could also be calculated. The code optimized the Soviet strike on US nuclear forces. CODE 50 assigned values to the Soviet urban industrial targets according to population, industrial capacity or a combination of the two. Reportedly, the model allowed for 48 types of targets, took into account defenses, and contained bomber sub-models.

ARSENAL EXCHANGE MODEL – AEM (1960s-1990s): Originally built in 1964 by the Martin Marietta Corporation, the AEM became one of the most widely-used NEMs for the US defense community throughout the 1980s and into the 1990s. AEM was designed to address problems pertaining to: strategic nuclear policy and arms control; the management of nuclear forces; intelligence support for nuclear war planning; and strategic calculations generally. AEM has been described as going beyond the "assured destruction-only approach" of CODE 50, including such scenarios as limited nuclear war and outcomes that favored the ability of the United States to recover more rapidly from a nuclear war than could the Soviet Union. In the AEM value targets could include leadership as well as economic targets. The AEM allowed the user to determine the importance of any given target class (e.g., silos), and specific that all members be targeted or excluded.

There are several modeling concepts pertinent to most NEMs: Damage Expectancy, Force Optimization, Target Optimization and Hedge. The Damage Expectancy is the likely probability that a weapon will arrive on target, detonate, and cause a certain level of damage. The Force Optimization is the NEM's determination of the appropriate force structure to accomplish a set of specified goals subject to constraints like total available attacking nuclear forces. Target Optimization is how the NEM allocates weapons against targets in the most effective and economic way, usually the computer code's attempt to maximize the damage achieved to a set of targets. Finally a Hedge is an input rule or constraint that allows the user of the NEM to specify additional, side goals in the nuclear conflict in addition to the primary goal or objective (for example, holding some forces in reserve after conducting primary strikes).

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. 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 the what reserve forces could persist.

In our work we did not construct a single NEM, but built several related NEMs that explored different aspects of the stability of deterrence. 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 do not explicitly calculate the value damage, equating the size of the retaliation to the number of "hostage cities" for deterrence purposes.

A key aspect of our modeling was the use of Monte Carlo methods. 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 (a product of the Lumina Decision Systems corporation, www.lumina.com) 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.

The workspace in *Analytica* consists of a Diagram Window depicting the model objects which are referred to as Nodes. The arrows in the Diagram Window between the Nodes show the influences between the Nodes in the model. One Node in an *Analytica* model influences a second Node if the value of the second Node depends on the value of the first Node through a mathematical relationship. An example of an *Analytica* Diagram Window showing the Nodes and influence arrows is given in Figure 2.1, below. For this work four types of *Analytica* Nodes were used: Constants; Index Variables; Chance Variables; and General Variables.

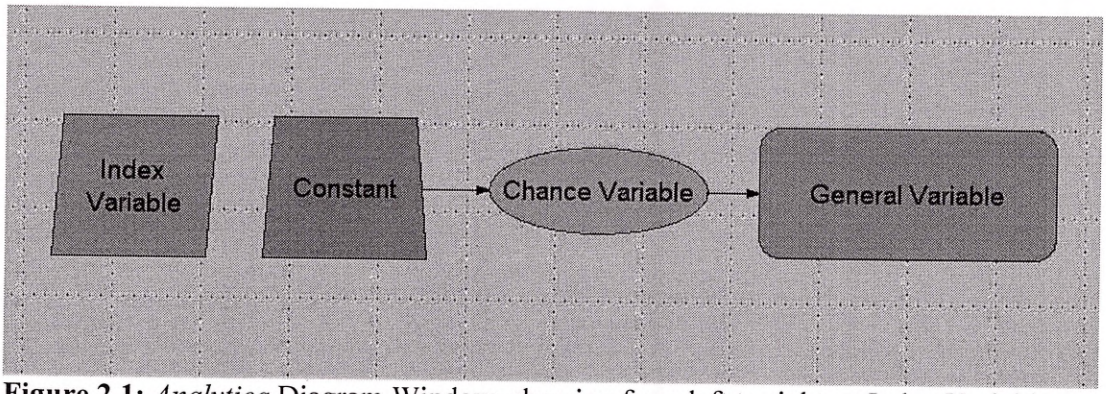


Figure 2.1: *Analytica* Diagram Window, showing from left to right an Index Variable Node, Constant Node, Chance Variable Node and General Variable Node. The Influence Arrows indicate that the Constant Node is included in the calculation of the Chance Variable Node, which in turn is included in the calculation of the General Variable Node. The presence of the Index Variable indicates that the model calculations are performed on a list of items.

An Index Variable is a Node used to define the dimension of an array, or ordered list of items. Model calculations are performed for each element of an array. An example of an Index Variable in this modeling work is a list of nuclear force launchers. Index Variables are depicted in the Diagram Window as purple parallelograms.

A Constant in the model is a Node whose value is fixed and is not dependant on other variables. An example of a constant in this modeling work is the probability that communication channels between the national leadership and deployed missile forces functions in the environment of a nuclear war. Constant Nodes are depicted in the model diagrams as orange trapezoids.

Monte Carlo methods enter into the *Analytica* models in this work with the use of Chance Variable Nodes. A Chance Variable Node is an uncertain quantity whose definition contains a probability distribution. An example of a chance variable in this modeling work is the Node determining whether or not the missile defense system misidentifies an attacking warhead as a decoy. Chance variables are depicted in the Diagram window as light blue ovals.

Two probability distributions for chance variable Nodes were used in this work: a uniform probability distribution and a Bernoulli probability distribution. A uniform probability distribution, defined in *Analytica* as:

Uniform(min, max, Integer: True/False)

returns a number at random between the numbers "min" and "max." If "Integer: True" is set to *True*, then the number returned at random will be an integer between the numbers "min" and "max." If "Integer: True" is set to *False*, then the number returned at random will be a real number between the numbers "min" and "max."

A Bernoulli probability distribution, defined in *Analytica* as:

Bernoulli (p)

returns a value of 1 with probability "p" and a value of 0 with probability 1 – "p" producing a sample of ones and zeros. A "Bernoulli trial" is an experiment whose result is random and can be one of two potential outcomes, for example the toss of a coin.

Finally a General Variable is a Node that represents an all-purpose calculated result from the model and are depicted in the *Analytica* Diagram Window as a dark blue rounded shape. General variables can be uncertain as they may depend on one or more Chance Variables, and may represent the results of a model calculation for all the objects in an array or list defined by an Index Variable. An example of a general variable in this modeling work is the VS retaliation following an AS sudden attack.

Thus a model is so constructed in *Analytica* from Nodes and Influence Arrows, building up to a calculation which in this work is the Monte Carlo simulation of the outcome of a nuclear war between the United States and Russia.

The "Result" window in *Analytica* displays the model calculation output in either table or chart format. Since the model outputs for this work depend on one or more Chance Variables, the results have uncertain or probabilistic values, which *Analytica* terms "prob" values. As a way to understand a prob value, the *Analytica* Result window allows the user to select a "Mid" output value or six uncertainty views: Mean; Statistics; Probability bands; Probability density; Probability mass function; Cumulative probability; and Sample. In this work the Statistics, Probability density and Sample *Analytica* Results were most often used to evaluate the implications of a model.

The Mid value is computed by using the median instead of any input probability distribution and does not use Monte Carlo simulation – the purpose of the *Analytica* Mid value is a quick check that the model appears to be well constructed. For the Statistics Result window, *Analytica* produces a table including the minimum, median, mean, maximum and standard deviation, estimated from the Monte Carlo sample. The Probability mass function is a bar graph with the height of each bar indicating the probability of that output value. An *Analytica* Sample is an array of the random values from the distribution generated by the Monte Carlo sampling process.

Recall that the mean value of the output is simply the average value over the Monte Carlo runs, whereas half of the Monte Carlo runs produce an output greater than the median and half less than the median. A large standard deviation indicates that model results are frequently far from the mean and a small standard deviation indicates that model results are clustered more tightly around the mean. It should be noted that the precision of statistical estimates of model output depends on the sample size. A larger sample size gives higher precision and takes more time and memory for *Analytica* to compute. The maximum number of Monte Carlo runs in *Analytica* was found to be limited to 30,000 runs. The title of the report "One Hundred Nuclear Wars" is a reference to a model output generated by a sample size of 100 Monte Carlo runs, which was used in the following calculations to illustrate the role of chance in the outcome of a nuclear war.

3) MODELING 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. 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. Later in this Technical Appendix, in Chapter 6, we show the role of the Second Echelon to further contribute to the total retaliation of the VS, and threfore to the stability of deterrence.

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 US and Russian silo-based ICBMs using open-source information.

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:

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

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:

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

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:

$$\text{Pdestroyed} = \text{SSKP x OAR}$$

The table below presents ranges of values based on open-source literature for US and Russian silo-based ICBM systems. For the US, 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 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 the table. Various values of

OAR are cited in Congressional testimony or Russian statements and a range was chosen based on these.

Table 3.1: 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%

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 US missile destroying a Russian silo, and a Russian missile destroying a US silo.

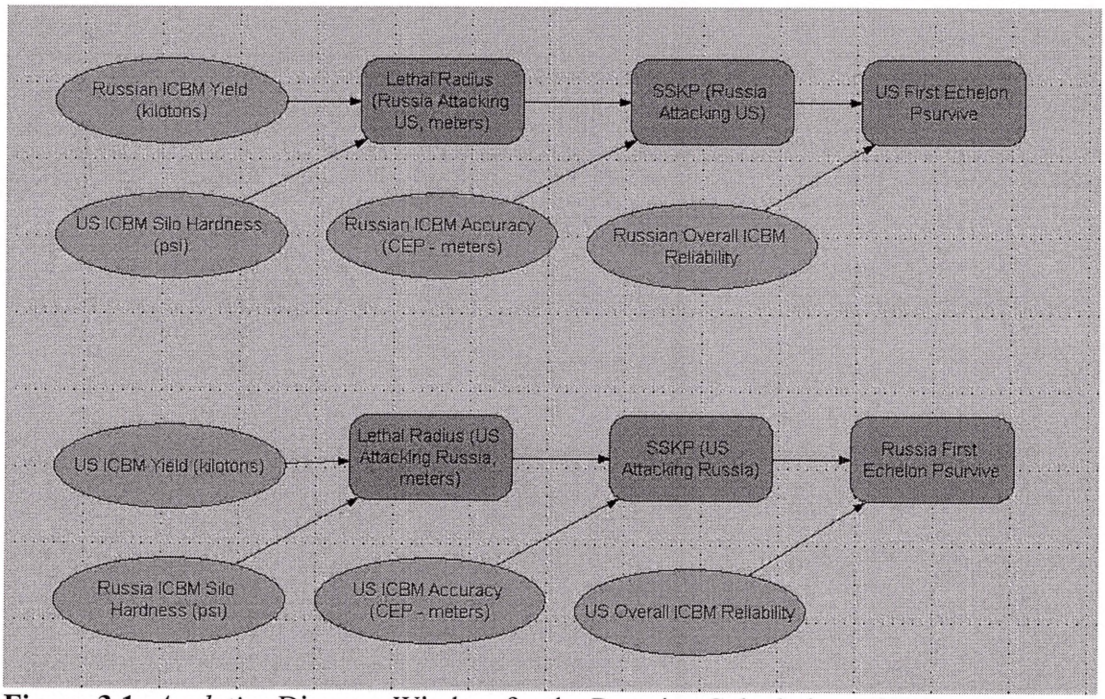


Figure 3.1: *Analytica* Diagram Window for the Psurvive Calculation, First Echelon Forces Attacking First Echelon Forces, where Psurvive means the survivability of one silo launcher only, but not the survivability of the First Echelon as a whole.

In the SSKP calculations, the higher yield range of the Russian warhead is offset by the smaller CEP of the US missile systems, and so the mean US 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 US 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 3.2 shows the Monte Carlo calculations of Psurvive for US missiles (above) and for Russian missiles (below).

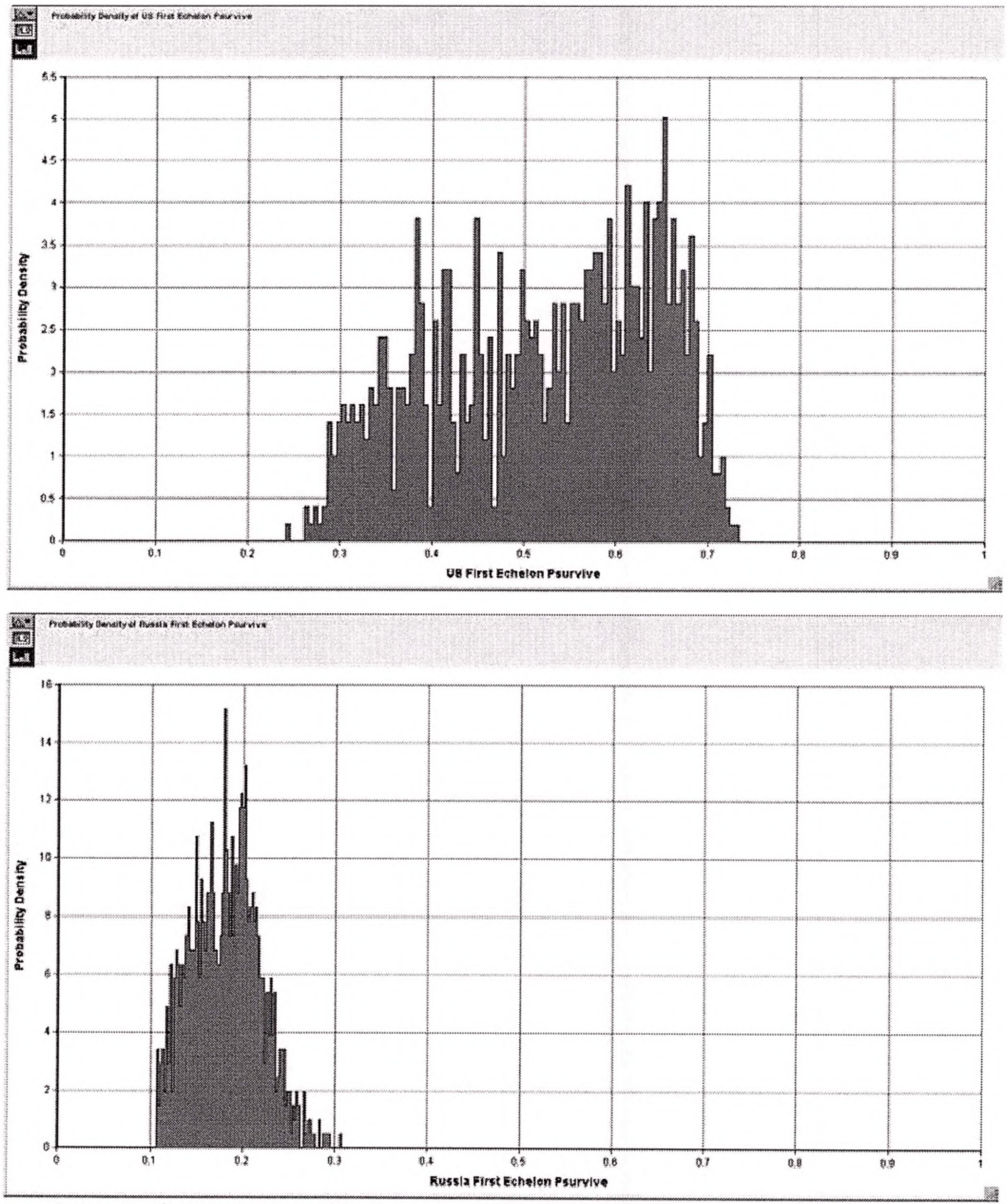


Figure 3.2: *Analytica* Result Windows (probability densities) for calculations of Psurvive for US (above) and Russian (below) First Echelons – single-warhead, silo-based ICBMs – over 1,000 Monte Carlo runs.

Note the clustering of Russian values of Psurvive around the mean, and note the broader spread of US values of Psurvive. Interestingly, the values of Psurvive for such attacks are very different for the United States and Russia, for today's ICBMs, if the input data ranges are accurate. The mean value of Psurvive for US 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 will determine below how these values of Psurvive impact the stability of deterrence for different First Echelon force sizes.

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 "Victim State" (VS) is struck by the entire First Echelon nuclear force of single-warhead ICBMS of the "Attacking State" (AS). Recall that the First Echelon is the subset of the total nuclear forces of each state that are maintained at a higher state of readiness than the rest of the de-alerted forces. In this scenario the AS does not attack the VS command, control and communication targets (which is explored in the following chapter), or other nuclear forces (i.e., the Second Echelon) or nuclear weapons infrastructure, and the VS has no missile defense capabilities. The attack is one-to-one, AS missile against VS launcher, and synchronous in time. After the first strike by the AS on the VS, the VS retaliates with all surviving launchers. The model was run 100 times – the horizontal axis in Figure 3.3 shows the Monte Carlo run, or nuclear war, numbering 1 to 100, and the vertical axis shows the number of surviving Russian First Echelon launchers that can retaliate.

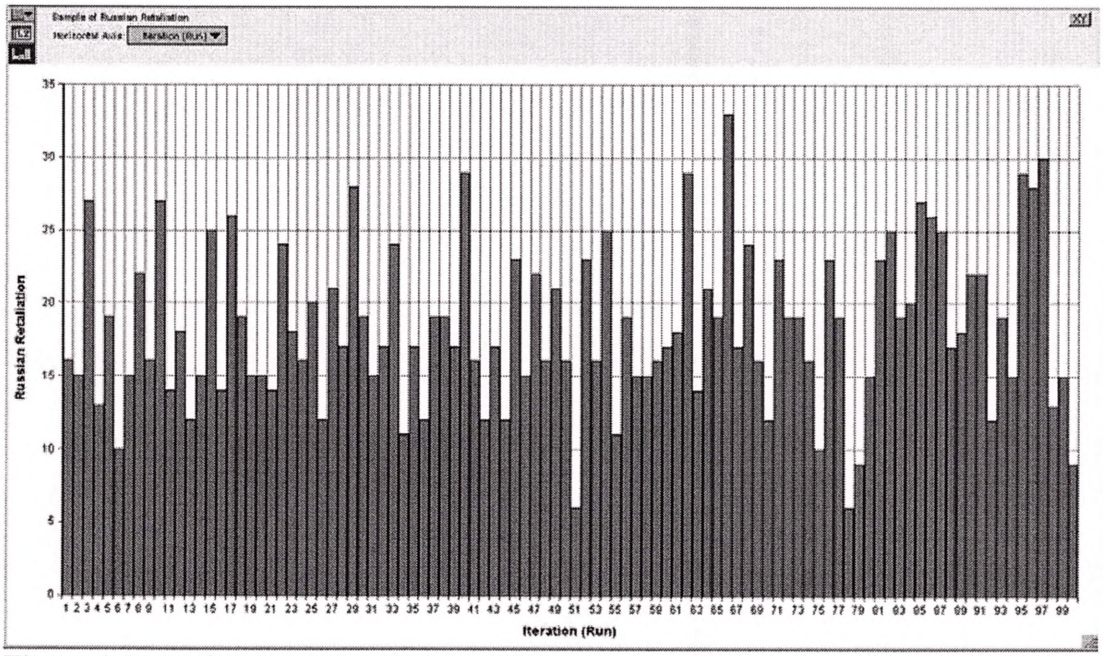


Figure 3.3: *Analytica* Result Window showing the Russian retaliation from a US First Echelon strike on the Russian First Echelon for a First Echelon size of 100 launchers.

Out of one hundred nuclear first strikes, given our range of probability of survival of the Russian struck silos from the Psurvive calculations above, with a mean value of 0.18, the mean number of surviving silos is then 18. Of course, if we increased the number of model Monte Carlo runs we would see outlier results more distant from the mean. For example, increasing the number of model runs to 1,000, we find a result where only six Russian silo missiles survive to retaliate, and a result where 36 missiles survive to retaliate.

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? If one side in a nuclear war could achieve an advantage by striking first, run 51 would imply the attacked state was almost completely disarmed, whereas run 66 would imply that the attacked state could respond with an overwhelming retaliation against more than thirty cities. Tables 3.2 and 3.3, below present results for surviving First Echelon retaliation at various First Echelon force sizes.

Table 3.2: Statistical results for Russian First Echelon retaliation following a US 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

Table 3.3: Statistical results for US First Echelon retaliation following a Russian First Echelon strike, for a given First Echelon size (100 Monte Carlo runs).

Number of Initial First Echelon Launchers	US Min. Retaliation	US Mean Retaliation	US 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

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.

In the table above we see that for a First Echelon size of ten single-warhead ICBMs, Monte Carlo runs occurred where there was no retaliation by the VS after a first strike by the AS. Given the mean survivability of Russian First Echelon forces of 0.18, the chance that a strike by ten US ICBM warheads could thereby disarm Russia is 14 percent. Similarly, given the mean survivability of US First Echelon forces of 0.52, the chance that a strike by ten 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 away from launch ready status. De-alerting should not create exploitable advantages from breaking out 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 far more important to deterrence than is the timing of retaliation, and that stable deterrence would not be adversely affected by delays in retaliation.

Given these calculated assured retaliations, and a requirement that the capability to threaten ten 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 US ICBMs. In the following chapters we will explore the additional effects of targeting command and communications aspects of nuclear forces, the effects of the Second Echelon, and the effects of missile defense on this basic structure of nuclear forces so partitioned into a First and Second Echelon, maintained off alert.

4) NUCLEAR STRIKES AGAINST THE NATIONAL COMMAND AUTHORITY

Nuclear strikes against the National Command Authority (NCA) are so-called "decapitation strikes," that is, an attack on leadership (the president and the secretary of defense) and its means to communicate with nuclear launchers, most likely mounted by ballistic missile submarines operating close to territorial waters. In the course of this modeling work we considered the additional uncertainty in assessing the stability of deterrence with reduced US and Russian strategic nuclear forces off alert: the possibility that NCA targets would also be initially struck and its implications.

The NCA for Russia or the United States is represented in the models as multiple NCA nodes, and multiple communication channels which link those nodes to the individual strategic nuclear force launchers. An NCA node represents a specific facility, such as Site "R" for the United States or Yamantau Mountain for Russia. Reflecting open source knowledge of NCA systems, we assign a relatively high probability of survival for one of the NCA nodes being struck (the Primary NCA node), and a relatively lower probability of survival of the other NCA nodes (the Secondary NCA nodes). While we do not postulate that the many communication channels linking these NCA nodes to strategic nuclear force launchers are individually struck by attacking nuclear weapons or conventional forces, we do assume that, in the environment of a nuclear war, there is a probability that a given communication channel may not function. A communication channel may fail to function due to the nuclear explosive effect of the Electromagnetic Pulse (EMP), for example. In that case launch orders would not be transmitted from a surviving NCA node to a surviving strategic nuclear force launcher.

In our models a communication channel between an NCA and a launcher is really a group of communication routes – cables, radio transmission, satellites, etc. The models have in them an overall probability that a communication channel will function between an NCA and a launcher: this should be viewed as an overall probability that one of a group of means of communication will function during a nuclear exchange when subject to the EMP, electronic countermeasures or other interference (for example events that can occur in the intermediate stages of a nuclear conflict when conventional means are used by the AS against the VS).

For this modeling work we varied the number and probability of survival of the NCA nodes and the probability that the individual communication channels between these NCA nodes and the strategic nuclear force launchers function in the environment of a nuclear war. Should launch delegation be in effect, however, isolated, surviving strategic nuclear force launchers may still participate in a retaliatory strike. In that case retaliation would be based on pre-assigned targeting and not at the wartime direction of the NCA. Figure 4.1, below, shows the *Analytica* Diagram Window for the NCA models, which used a Russian First Echelon size of 500 launchers – the maximum First Echelon size considered in the previous chapter. This model introduces several new variables and calculations: the Probability that the Primary NCA Node Survives; the Probability that Secondary NCA Nodes Survive, and the Probability that Communications Channels Function.

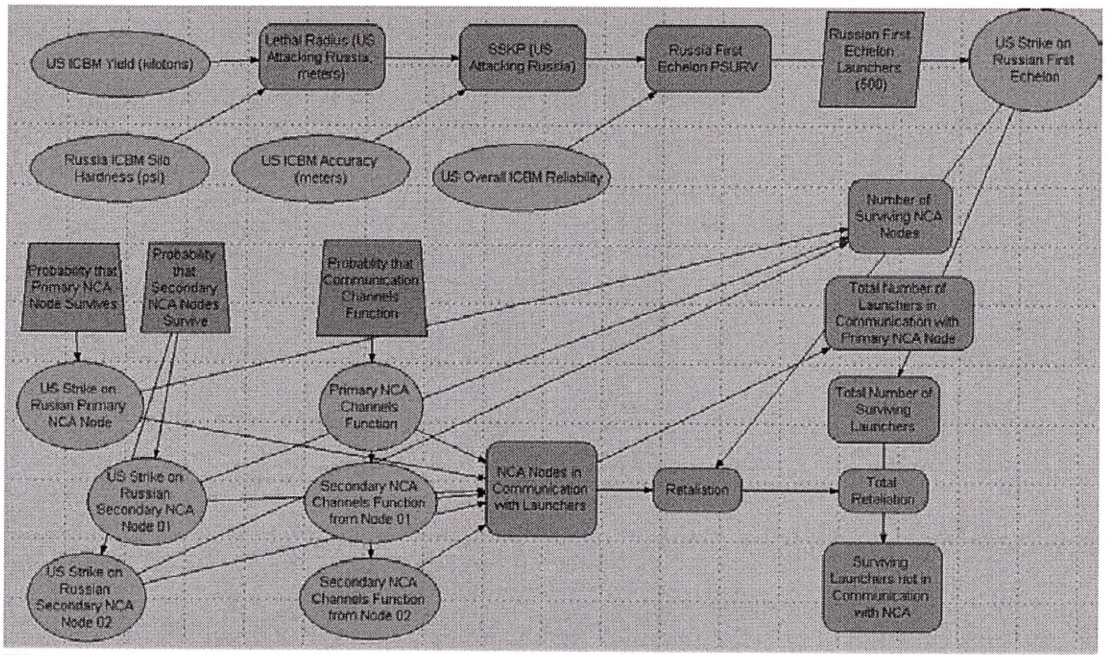


Figure 4.1: *Analytica* Diagram Window for an NCA Calculation, AS First Echelon Forces Striking VS NCA Nodes and VS First Echelon.

Now we consider the impacts of these variables in our model by following the Monte Carlo calculation Result Windows step by step through Nodes in the *Analytica* Diagram Window. In Figure 4.2, below, the number of surviving NCA nodes is shown for each of 100 Monte Carlo runs of the model, where the probability of survival of the Primary NCA Node was set to 0.3, and the probability of survival of the Secondary NCA Nodes was set to 0.1. For a sizable number of nuclear wars, decapitation occurs – no NCA nodes survive to issue launch orders to nuclear forces. In a fewer number of nuclear wars at least one NCA node survives, and in a still smaller number of nuclear wars multiple NCA nodes survive.

Figure 4.3 shows the number of functioning communication channels in contact with surviving NCA nodes for a given Monte Carlo model run, where the Probability that communications channels Function in the environment of a nuclear war was set to 0.8. The same gaps in this *Analytica* Result Window are evident for decapitation strikes. Where only one NCA node has survived, the number of communication channels that can function are reduced by on average 80 percent from the total number of 500 channels. Where three NCA nodes have survived, in Monte Carlo run #12, the redundancy of the NCA nodes completely compensates for the possibility that communication channels may not function, and for this Monte Carlo run all launchers are in communication with national leadership.

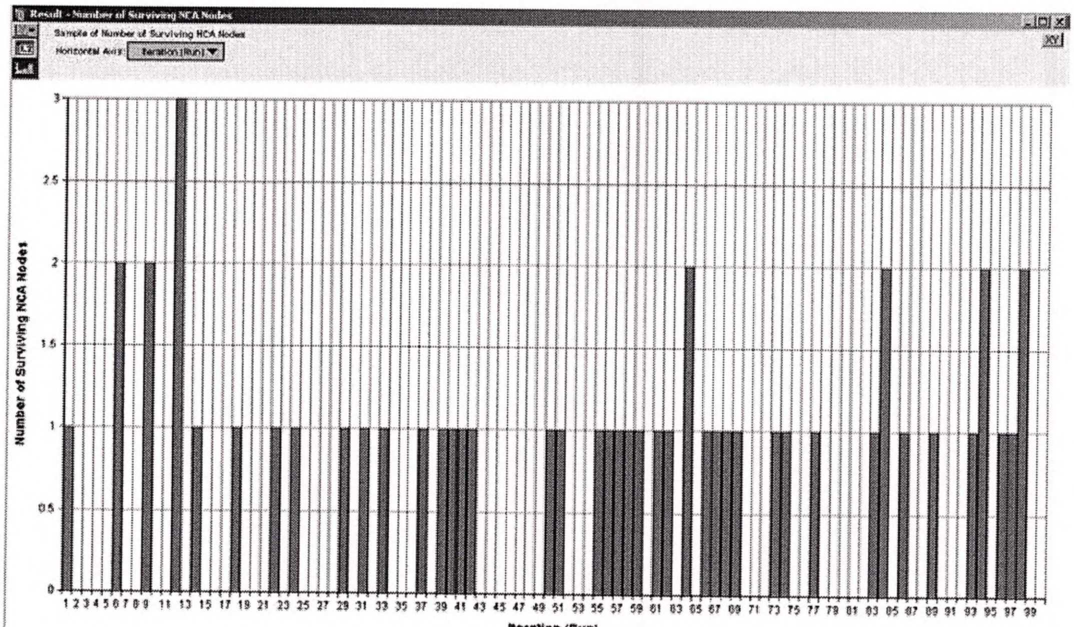


Figure 4.2: *Analytica* Result Window displaying the number of surviving NCA Nodes for each of 100 model runs. In this calculation, the Probability that the Primary NCA Node Survives was set to 0.3 and the Probability that Secondary NCA Nodes Survive was set to 0.1.

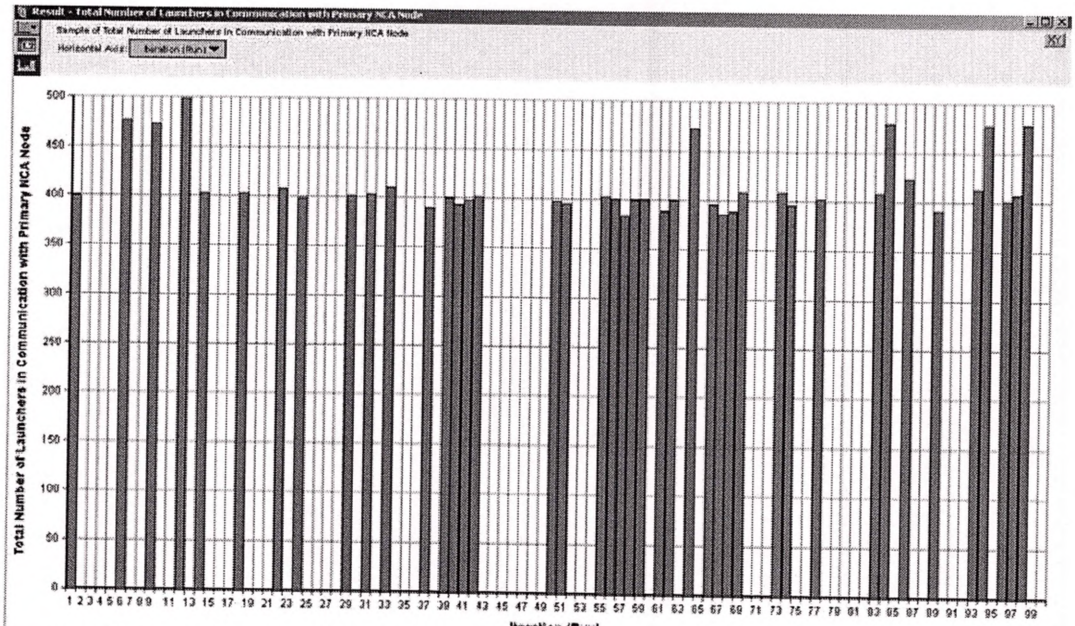


Figure 4.3: *Analytica* Result Window displaying the number of launchers in communication with NCA nodes for each of 100 model runs for a First Echelon size of 500 launchers. In this calculation, the Probability that Communications Channels Function in the environment of a nuclear war was set to 0.8.

This model contains within it the First Echelon Psurvive calculation from the previous chapter. Figure 4.4, below shows the *Analytica* Result Window displaying the number of Russian First Echelon launchers out of an initial 500 launchers that survive a US strike, for each of 100 Monte Carlo model runs, with a mean value of 71 surviving First Echelon launchers as given in Table 3.2.

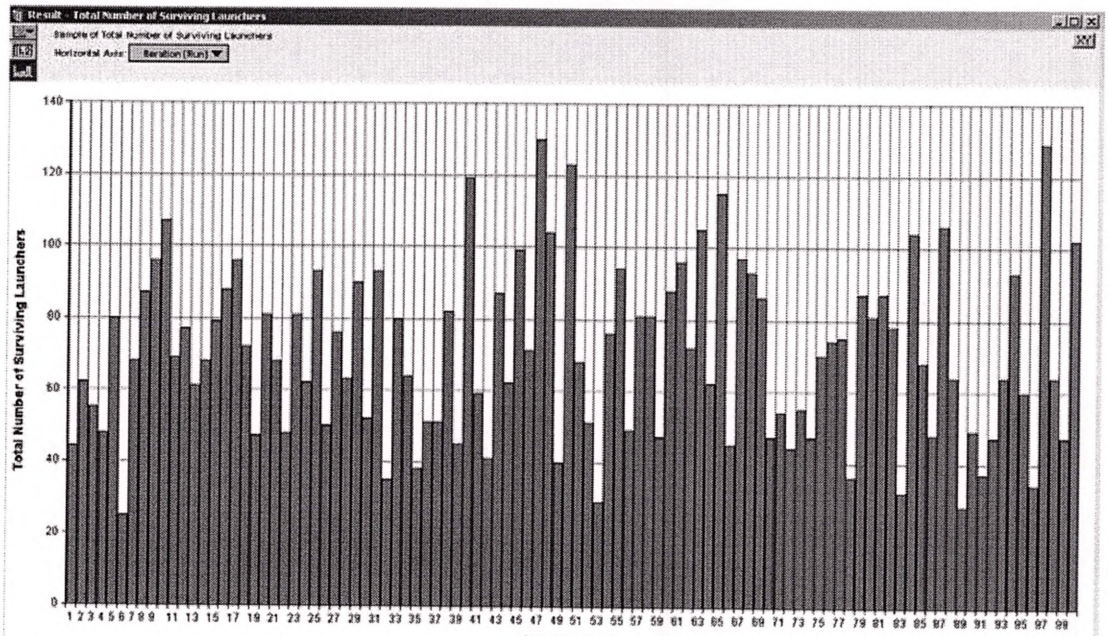
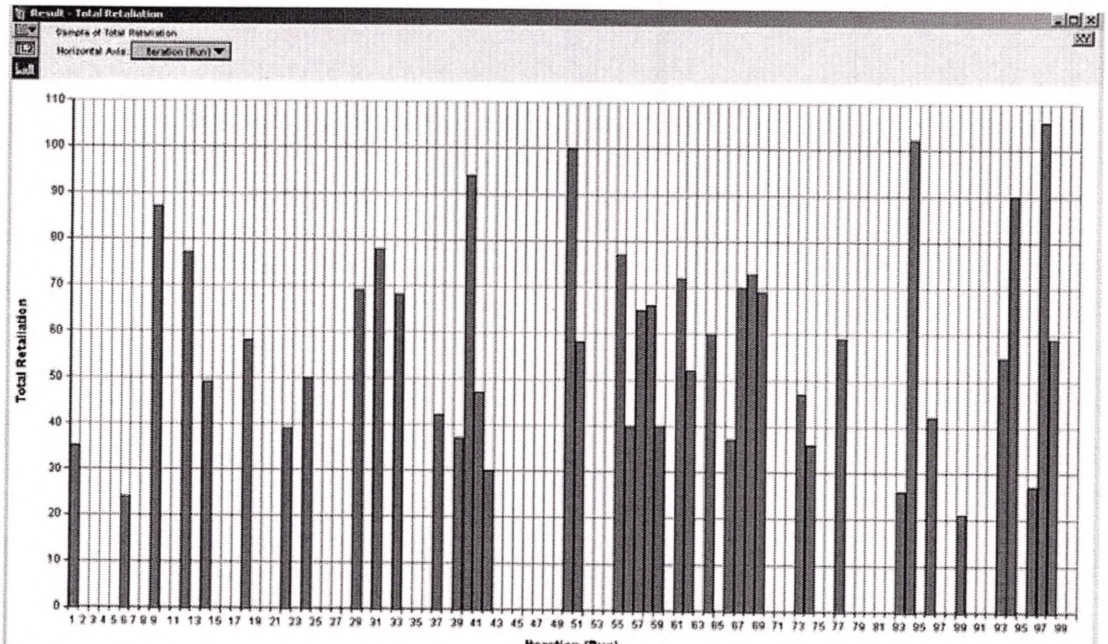


Figure 4.4: *Analytica* Result Window displaying the number of First Echelon launchers out of an initial 500 launchers that survive a strike, for each of 100 Monte Carlo model runs. Psurvive was taken for Russia as analyzed in the previous chapter (mean 0.14).

Therefore taking strikes against NCA nodes into account, and the necessity that communication channels between NCA nodes and launchers operate, the probability that a given launcher in an attacked state can retaliate is modified by:

P(Launch in Retaliation, Attacked Launcher I) = [Sum over NCA Nodes, J] of P(Survive, NCA Node J) x P(Function, Communication Channel from NCA Node J to Launcher I) x P (Survive, Launcher I)

Figure 4.5 then shows the full calculation of the size of the Russian retaliation, for an initial First Echelon force of 500 launchers, given attacks on both leadership and forces, the possibility that communication channels between the leadership and deployed forces may not function during the exchange, and the requirement that retaliation must be authorized by the NCA. Evident are those nuclear wars – Monte Carlo runs – where decapitation has occurred, and those nuclear wars where launch orders cannot be transmitted to all surviving forces.



Sample of Total Retaliation

Horizontal Axis: Iteration (Run)

Figure 4.5: *Analytica* Result Window displaying the total calculated retaliation based on the initial 500 Russian launchers.

In Tables 4.1 through 4.5, below, we examined the implications of varying parameters in the model runs, looking at the impacts on the Russian retaliation. It was found that varying the probability that communication channels function during a nuclear war influences both the mean and the maximum calculated retaliation, whereas varying the survivability of the NCA nodes influences the mean and not the maximum retaliation (see Tables 4.1 and 4.2). In other words, the maximum retaliation always results when one or more NCA nodes survive, whereas a vulnerable leadership will reduce the retaliation averaged over wars were decapitation does or does not occur.

Table 4.1: Statistical results for Russian First Echelon retaliation based on First Echelon sizes of 500 launchers, where Russian NCA Nodes are intact during the nuclear exchange.

Probability that Communication Channels Function during Nuclear War	Min. Retaliation	Mean Retaliation	Max. Retaliation	Std. Dev.
1.0	26	69.6	129	23.8
0.9	23	62.4	116	21.7
0.8	18	55.6	101	19.1
0.7	17	48.5	89	17.6
0.6	16	42.0	76	15.6
0.5	8	34.6	65	12.3

Table 4.2: Statistical results for a Russian First Echelon retaliation based on First Echelon sizes of 500 launchers, where the Russian NCA Nodes have a survivability of 30 percent for a Primary NCA Node, and a survivability of 10 percent for two Secondary NCA Nodes.

Probablity that Communication Channels Function during Nuclear War	Min. Retaliation	Mean Retaliation	Max. Retaliation	Std. Dev.
1.0	0	29.7	128	38.2
0.9	0	27.3	115	34.8
0.8	0	24.5	102	31.3
0.7	0	21.5	90	27.8
0.6	0	18.7	76	24.0
0.5	0	16.0	73	20.5

The effects of redundancy of NCA Nodes is shown in Tables 4.3 and 4.4, where introducing even highly vulnerable, additional NCA Nodes increases both the mean and maximum calculated Russian retaliations.

Table 4.3: Statistical results for a Russian First Echelon retaliation based on First Echelon sizes of 500 launchers, where the Russian communication channels function with a probability of 80 percent in the environment of nuclear war, and the NCA Node survivability was varied.

Probability that NCA Nodes Survive during Nuclear War (Primary Node, Secondary Node, Secondary Node)	Min. Retaliation	Mean Retaliation	Max. Retaliation	Std. Dev.
NCA Survivability(0.9/0.0/0.0)	0	51.0	106	25.2
NCA Survivability (0.7/0.0/0.0)	0	38.7	106	30.7
NCA Survivability (0.5/0.0/0.0)	0	29.7	106	32.3
NCA Survivability (0.3/0.0/0.0)	0	16.1	86	26.3
NCA Survivability (0.1/0.0/0.0)	0	6.8	106	21.6

Table 4.4: Statistical results for a Russian First Echelon retaliation based on First Echelon sizes of 500 launchers, where the Russian communication channels function with a probability of 80 percent in the environment of nuclear war, the Primary NCA Node survivability was varied and the Secondary NCA Node survivability was set to 10 percent.

Probability that NCA Nodes Survive during Nuclear War (Primary Node, Secondary Node, Secondary Node)	Min. Retaliation	Mean Retaliation	Max. Retaliation	Std. Dev.
NCA Survivability (0.9/0.1/0.1)	0	52.7	122	26.7
NCA Survivability (0.7/0.1/0.1)	0	45.7	110	30.7
NCA Survivability (0.5/0.1/0.1)	0	23.8	110	32.1
NCA Survivability (0.3/0.1/0.1)	0	24.5	102	31.3
NCA Survivability (0.1/0.1/0.1)	0	15.1	110	27.4

Finally, we looked at our base case of three NCA Nodes, with probabilities of survival of 0.3, 0.1 and 0.1, and the probability that communication channels function during nuclear war of 0.8, and varied the size of the Russian First Echelon forces as in the previous chapter. These results shown in Table 4.5 can be compared with those of Table 3.2. It was found that introducing the risk of decapitation strikes destabilizes deterrence from the perspective of the greater number of possible nuclear wars where no retaliation occurs, due to the failure of the national leadership to issue launch orders to deployed forces, and because of the strong reduction in the mean retaliation. However attacking the NCA does not appreciably reduce the maximum retaliation, which we suggest is a more rational measure of the stability of deterrence.

Table 4.5: Statistical results for a Russian First Echelon retaliation for decreasing First Echelon sizes, where the Russian communication channels function with a probability of 80 percent in the environment of nuclear war, and where the Russian NCA Nodes have a survivability of 30 percent for a Primary NCA Node, and a survivability of 10 percent for two Secondary NCA Nodes (base case)

Number of Initial First Echelon Launchers	Min. Retaliation	Mean Retaliation	Max. Retaliation	Std. Dev.
500	0	25.2	108	31.5
400	0	20.0	73	24.23
300	0	13.8	71	17.9
200	0	9.1	34	11.7
100	0	5.1	23	6.6
50	0	2.6	12	3.4
25	0	1.3	9	2.0
10	0	0.5	5	0.9

Now, it is interesting to consider the manner in which retaliation could occur following a first strike, given a delegation of launch authority which circumvents the problem of decapitating strikes. For example, if ten Russian ICBMs survived a US strike, could the United States anticipate retaliation against ten cities, or could those ten retaliating Russian ICBMs all target Los Angeles, for example, because coordination from the national leadership is absent (and thus present a lesser deterrent)? In practice each Russian nuclear warhead has in peacetime several possible targets, and during a war it can be launched only to one of them. The duty crew of at the lowest C3 level is not able to plan the warhead to any target. The result of an American attack against Russian nuclear forces may be different, and we cannot say in advance what the missiles will survive, and what does not. Survived Russian missiles will be launched to targets from a list. So the idea of a full re-planning during the war is not so obvious. Of course, NCA may, in principle, to do so, but such a procedure in emergency conditions is quite complicated. However, this concept of the Russian planning retaliation, by contrast, is more advantageous for deterrence, because all the major cities of America are in these plans for missiles, and they all are hostages. And how exactly will the list of destroyed cities - it is a matter of chance. Here deterrence is much stronger.

The construction of de-alerted nuclear forces into Echelons as we have described allows us to estimate the role of nuclear *command, control and communication systems* (C^3 systems) in a new fashion: we find some unexpected conclusions about C^3. First, if all the missiles of an AS First Echelon are used in an attack against a VS FE (recall from the previous chapter that for First Echelons, each VS silo launcher is struck with at most one AS warhead), then there are no additional nuclear weapons available to strike the C^3 system of the VS. In any case, in peacetime, both sides can readily provide very high redundancy and readiness of C^3 that allows it survive attack even by practically all missiles of an AS First Echelon. And second, what is more, from the point of view of the AS, there is no sense to attack the VS C^3 with strategic missiles even when nuclear war has begun. The reason is the following: a potential AS (if it is a "reasonable planner") is obliged again to wait for a worst outcome for itself. It must believe that a VS NCA in conditions of a real nuclear war will delegate, "without fail" and as quickly as possible, its nuclear authority to all lower C^3 levels, including launchers themselves. In other words, the VS C^3 behaves as if it has "disappeared," and therefore for the AS it's more expedient to use its strategic missiles against other targets, mainly VS SE launchers. Of course, the VS C^3 command posts and channels will be subjected to the impacts of all other offensive AS weapons, but that is another matter which we have modeled. These arguments increase the role of C^3 systems in providing reliable deterrence.

5) MISSILE DEFENSES

We now consider the impact on strategic stability of a future, hypothetical US missile defense system posited as highly capable of intercepting on the order of several hundred incoming targets: warheads or heavy warhead decoys. The *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. 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."

To begin, initial 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:

$$Pwd = 1 - Pww.$$

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

$$Pdw = 1 - Pdd.$$

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

$$T = Pww \text{ x } W + Pdw \text{ x } D$$

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 the assuming that the probability of success of these shots are statistically independent, then the combined probability from multiple kill attempts, K, is given by:

$$K = 1 - (1-k)^N$$

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, Pr, is given by:

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

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

$$\text{Pretal} = \text{Pww} \times K.$$

(Note that Pretal still depends on Pdd through K, as discussed below.) The *Analytica* Diagram Window for the missile defense model is shown in Figure 5.1. 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.

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. To include this case, we conditionally define K as:

> When ($\text{Ninterceptors}/T > 1$), $K = 1 - (1-k)^{(\text{Ninterceptors}/T)}$: a Monte Carlo run where the number of missile defense interceptors outnumbers the targets resulting in multiple kill attempts;
>
> When $\text{Ninterceptors}/T = 1$, $K = k$: a Monte Carlo run where the number of interceptors is equal to the number of targets, and so the single-shot kill probability for one interceptor against one target is used; and

When Ninterceptors/T < 1, K = Bernoulli(Ninterceptors/T) x k: a Monte Carlo run where the number of targets outnumbers the missile defense interceptors thus kill attempts cannot be made against all targets.

The use of the expression 1 – (1-k)^(Ninterceptors/T) results in a higher probability of target interception when the number of missile defense interceptors is larger than the number of targets, which is still a good approximation when Ninterceptors/T is non-integer. For example if Ninterceptors/T = 1.5, then half of the targets can have two kill attempts and half of the targets can only have one kill attempt and here the interception probability used for all targets is 1-(1-k)^1.5, rather than applying an interception probability of 1-(1-k)^2 to half of the targets selected at random and k to the other half of the targets selected at random.

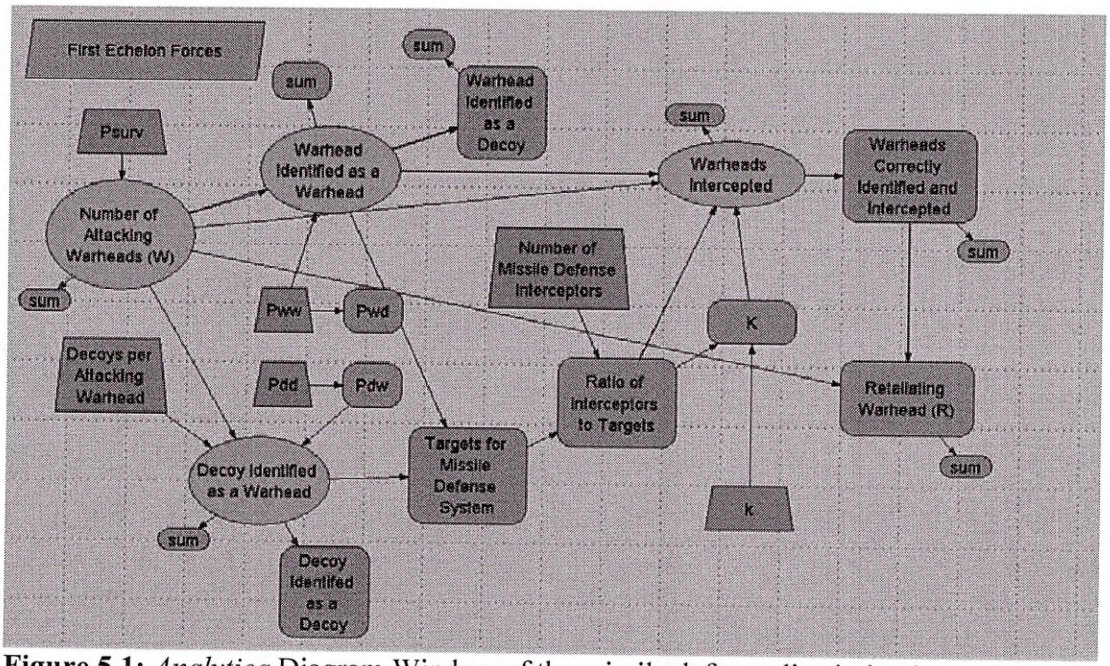


Figure 5.1: *Analytica* Diagram Window of the missile defense discrimination and interception model as a Bernoulli trial.

The presence of the Bernoulli(Ninterceptors/T) expression for the case when the number of missile defense interceptors is less than the number of targets is equivalent to randomly setting whether or not a target for the missile defense system is attacked based on the fraction of available interceptors per target as a Bernoulli trial. Thus if 10 interceptors are available to strike 20 targets, Bernoulli (0.5) will be used to determine if a given target has been chosen for a kill attempt, independently of whether the kill attempt is successful.

Now we consider the impacts of these variables in our missile defense model by following the Monte Carlo calculation Result Windows step by step through Nodes in the *Analytica* Diagram Window. For clarity of reproduction of the Analytica Result Windows we set the number of Monte Carlo runs to be equal to 25.

Figure 5.2 shows the number of warheads in the attack by Monte Carlo from VS launchers surviving an initial strike by the AS with probability Psurvive. The warheads result from an initial VS force size of 100 single-warhead ICBM launches with a probability of survival, Psurvive, of 0.2. The mean value of the number of warheads in the VS retaliation prior to reaching the missile defense system is therefore 20.

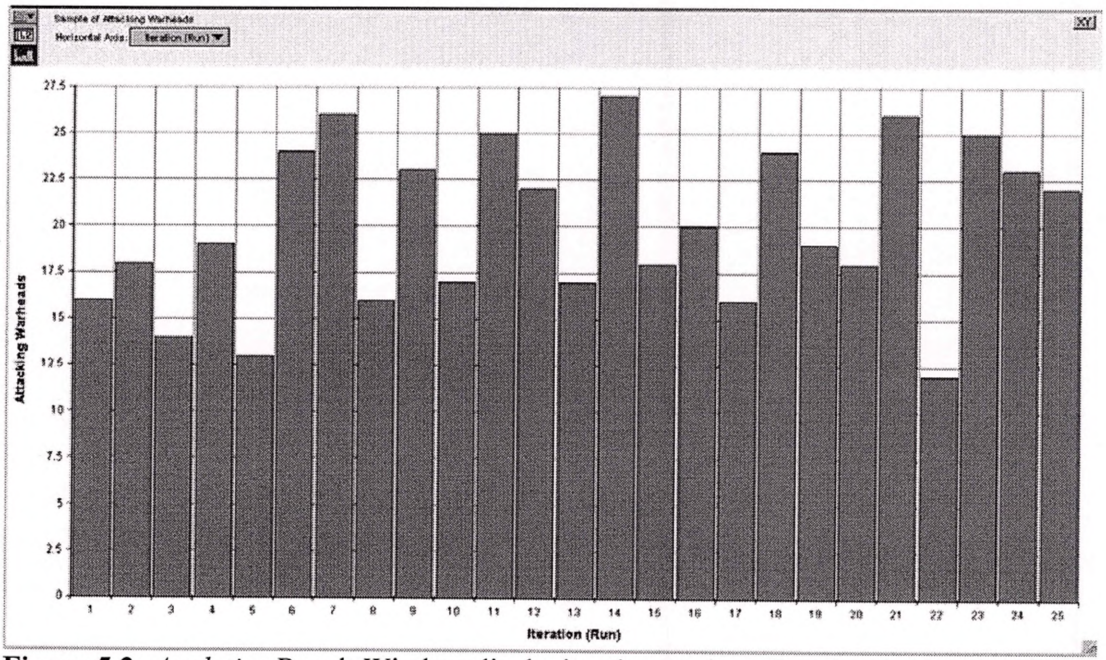


Figure 5.2: *Analytica* Result Window displaying the number of warheads in an attack for each of 25 Monte Carlo runs of the model.

The value of Pww, the probability that the missile defense system has correctly identified a warhead as a warhead, and not a decoy, was set to 0.9 for these model runs – we posit that the missile defense system is highly capable of determining what is or is not an attacking warhead. The mean number of attacking warheads correctly identified as warheads by the missile defense system would therefore be equal to 18. Figure 5.3 displays the number of warheads correctly identified as warheads in the attack for a given Monte Carlo run, which should be compared with Figure 5.2. In Monte Carlo run #1 of the model, only one warhead was not correctly identified as a warhead by the missile defense system, which functioned well in this attack. In Monte Carlo run #10 just 11 out of 17 warheads were correctly identified as warheads – a statistically-expected, poor performance of the missile defense system for this particular attack.

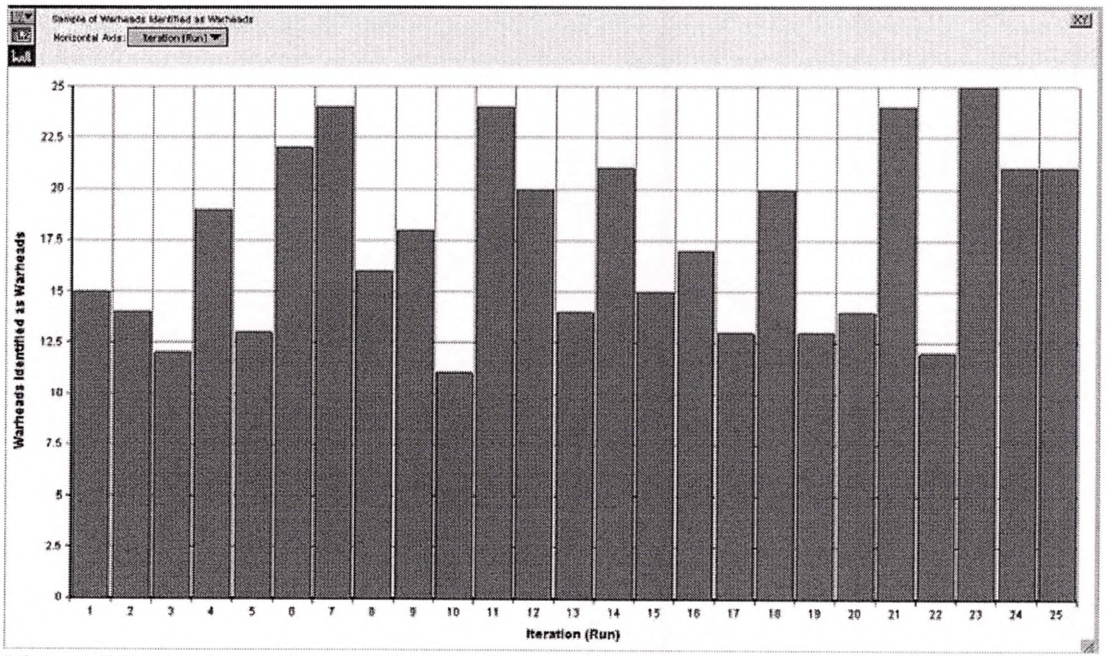
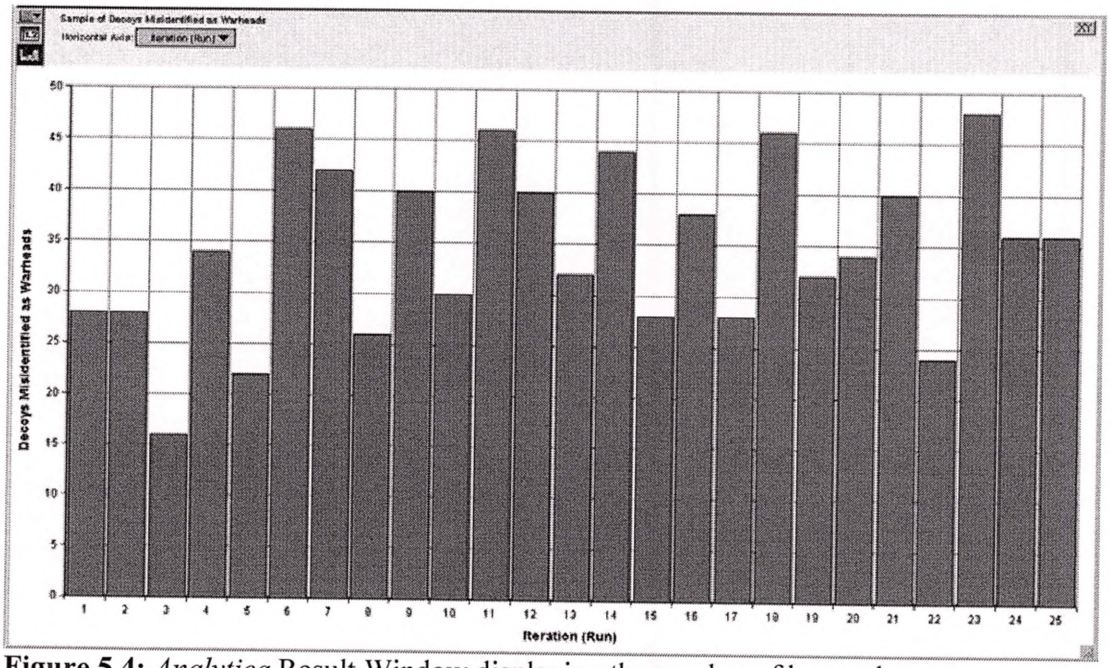


Figure 5.3: *Analytica* Result Window showing the number of attacking warheads correctly identified as warheads by the missile defense system in a given Monte Carlo model run.

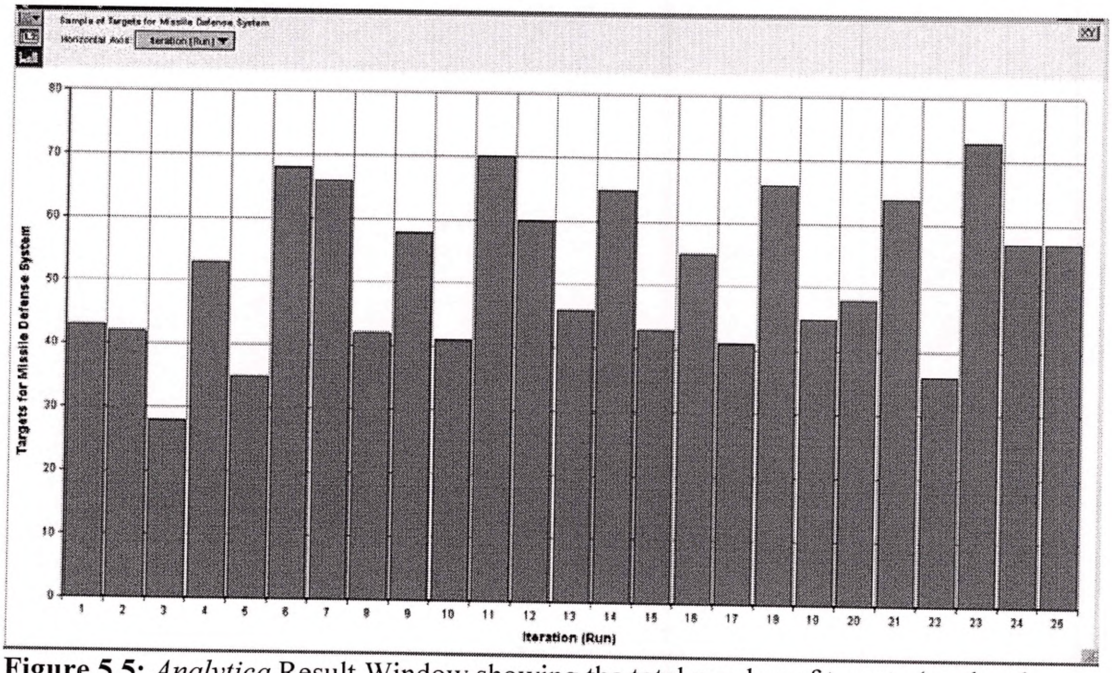
We set the number of heavy decoys per attacking warhead to be equal to two, and therefore the mean number of decoys for the model would be 40. A heavy decoy can be made difficult to distinguish from an actual warhead, therefore we explore the results of the calculation when we set Pdd, the probability that the missile defense system has correctly identified a decoy as a decoy, and not a warhead, to be 0.1. In Figure 5.4 the number of decoys incorrectly identified as warheads is shown for each Monte Carlo run. The mean number of decoys misidentified as warheads for the model would therefore be equal to 36. Figure 5.5 shows the apparent number of targets that the missile defense system must contend with – the sum of the warheads identified as warheads and the decoys misidentified as warheads. The mean number of targets, T, in the model would therefore be equal to 54 targets, the majority of which are decoys. As we can see from Figure 5.5, the total number of targets can range by over a factor of two. In Monte Carlo run #3 the system performed well distinguishing decoys from warheads, as expected statistically for some attacks, whereas in Monte Carlo run #23 nearly all decoys were misidentified as warheads as would also be anticipated for a small fraction of attacks.



Sample of Decoys Misidentified as Warheads

Horizontal Axis: Iteration (Run)

Figure 5.4: *Analytica* Result Window displaying the number of heavy decoys misidentified as warheads by the missile defense system for each Monte Carlo run.



Sample of Targets for Missile Defense System

Horizontal Axis: Iteration (Run)

Figure 5.5: *Analytica* Result Window showing the total number of targets (warheads correctly identified as warheads and decoys incorrectly identified as warheads) for the missile defense system for each Monte Carlo run.

In this model we set the number of missile defense interceptors to be equal to 100, with a single shot kill probability, k, of 0.8 – again, a highly-capable system. Based on the number of apparent targets for the system, in general more than one missile defense interceptor can be assigned to each target, as Figure 5.6 illustrates by a histogram of the ratio of missile defense interceptors to targets in each Monte Carlo run. The single-shot kill probability will be modified by this ratio to account for multiple kill attempts. In Monte Carlo run #3 about three kill attempts can be made against each missile defense target, whereas in Monte Carlo run #23 only about one kill attempt can be made per target.

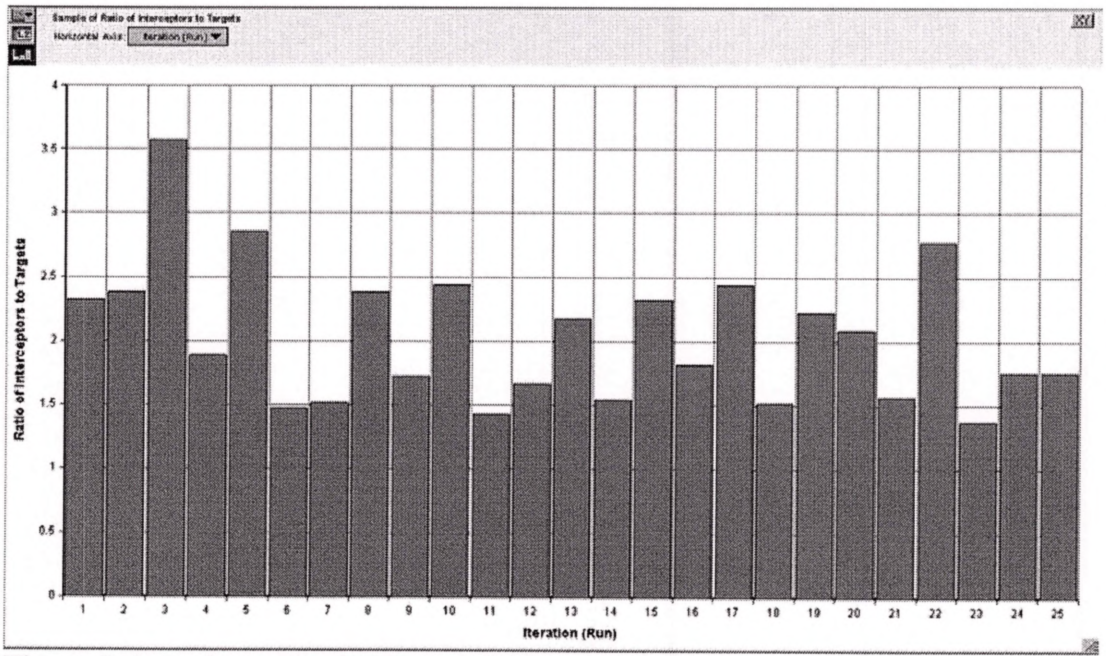


Figure 5.6: *Analytica* Result Window displaying the ratio of the number of missile defense interceptors to apparent targets for each Monte Carlo run.

Now, combining the calculations of attack, discrimination and interception, Figure 5.7 shows the total number of attacking warheads correctly identified as warheads and intercepted through multiple kill attempts by the missile defense system, taking into account the necessary allocation of missile defense interceptors to decoys misidentified as warheads. Figure 5.8 then shows the calculated VS retaliation, meaning the warheads from launchers surviving a strike by the AS which either leaked through the missile defense system because they were not correctly identified as warheads, or failed to be intercepted. A maximum retaliation over the 25 Monte Carlo runs can be seen for run #9, where 5 warheads were not correctly identified as warheads and 3 warheads failed to be intercepted on multiple kill attempts. In three out of the 25 Monte Carlo runs, the missile defense system was completely successfully in defending against the VS retaliation. The average retaliation over 25 Monte Carlo runs was computed to be 3.3 +/- 2.3 warheads, and, increasing the statistical sample, the average retaliation over 10,000 Monte Carlo runs was computed to be 3.1 +/- 1.9 warheads.

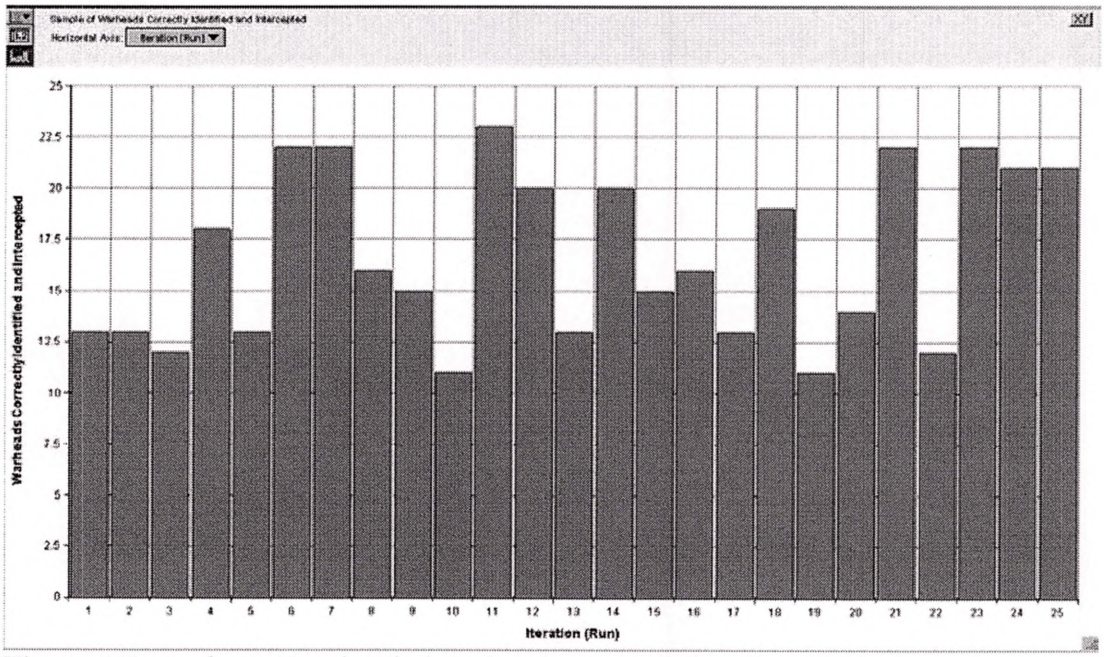


Figure 5.7: *Analytica* Result Window showing the number of warheads correctly identified as warheads and successfully intercepted by the missile defense system.

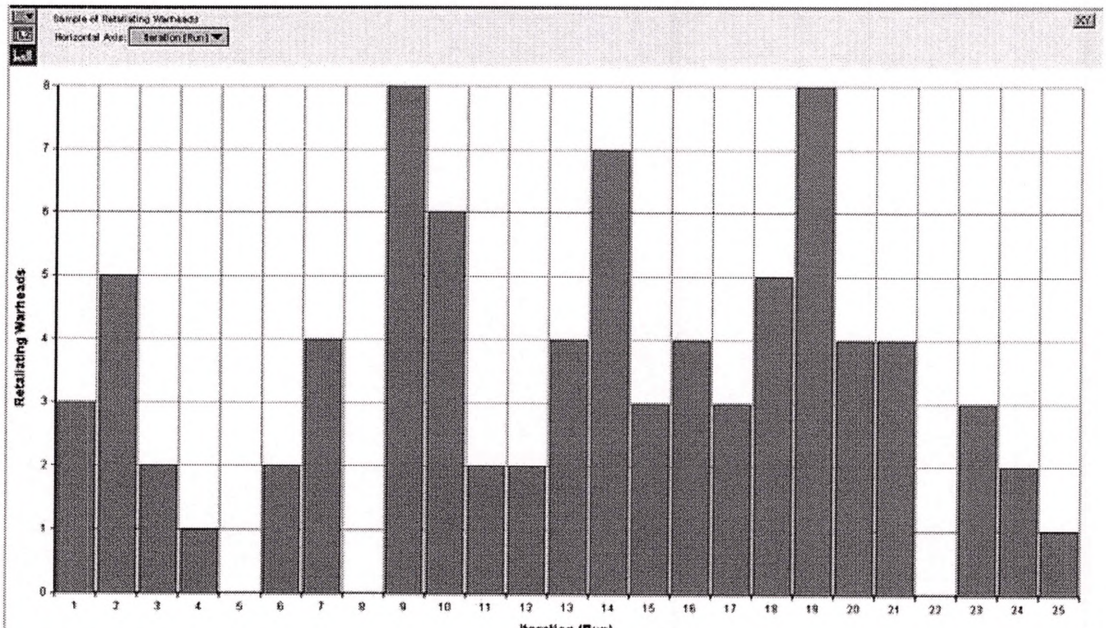


Figure 5.8: *Analytica* Result Window displaying the total retaliation by the VS, based initially on 100 launchers attacked by the AS and then defended against using a highly-capable missile defense system.

In our analysis we look at the case of the Russian First Echelon retaliation following a US attack as most pertinent to understanding the role of missile defense limitations in a future arms control process. The United States is currently more advanced than Russia in the area of kinetic, hit-to-kill missile defense technologies and operational experience. Furthermore, as derived above, the probability that a US ICBM would survive being struck by a Russian ICBM warhead is greater on average because of lower Russian missile accuracy and higher US missile survivability.

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 US missile defense shield. Specifically, we consider the case where the US 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. 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.

Summary results over 100 Monte Carlo model runs for a Russian First Echelon size of 150 single-warhead ICBMs (a component of the proposed 1,000 warhead limit) is given in table 5.1, below. Based on the Psurvive calculation, the mean initial Russian retaliation from its surviving First Echelon, prior to encountering the US 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 7 warheads without the Russian use of heavy decoys, reflecting the assumed US interceptor kill probability against the ten possible targets it can attempt to kill. As more heavy decoys are added to each Russian launcher the US 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 decoys per warhead, and ten missile interceptors, the US 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 US 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 US missile defense shield are those that have been misidentified as decoys (about 4 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 US operational strategy for its shield would be to attack all warheads and decoys to compensate for common mode failures.

Table 5.1: *Analytica* statistical results for a US missile defense system intercepting the retaliation from a Russian First Echelon of 150 single-warhead ICBM launchers (the proposed 1,000 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
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

Highlighted in Table 5.1 is the case of 100 US 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, which is a component of the proposed 1,000 total warhead limit. Deterrence today would remain stable even if retaliation against only ten cities were assured.

However it is not just the mean retaliation that is important, but also what would be the worst case for the AS (here the US) among possible nuclear wars, which is the maximum retaliation. Figure 5.9, below, shows the surviving Russian First Echelon warheads (out of initially 150 warheads) which penetrate the US missile defense shield in the case of 100 missile interceptors and 5 heavy decoys per warhead, for 100 Monte Carlo runs of the model. As noted in Table 5.1, the maximum calculated retaliation over the 100 Monte Carlo runs was computed to be 39 warheads reaching their city targets, for run #66. In this particular Monte Carlo run, 48 Russian First Echelon launchers survive a US strike, 37 were correctly identified as warheads by the US missile defense system, but only 9 warheads were intercepted, in large part due to the presence of a cloud of 240 heavy decoys, most of which were misidentified as warheads.

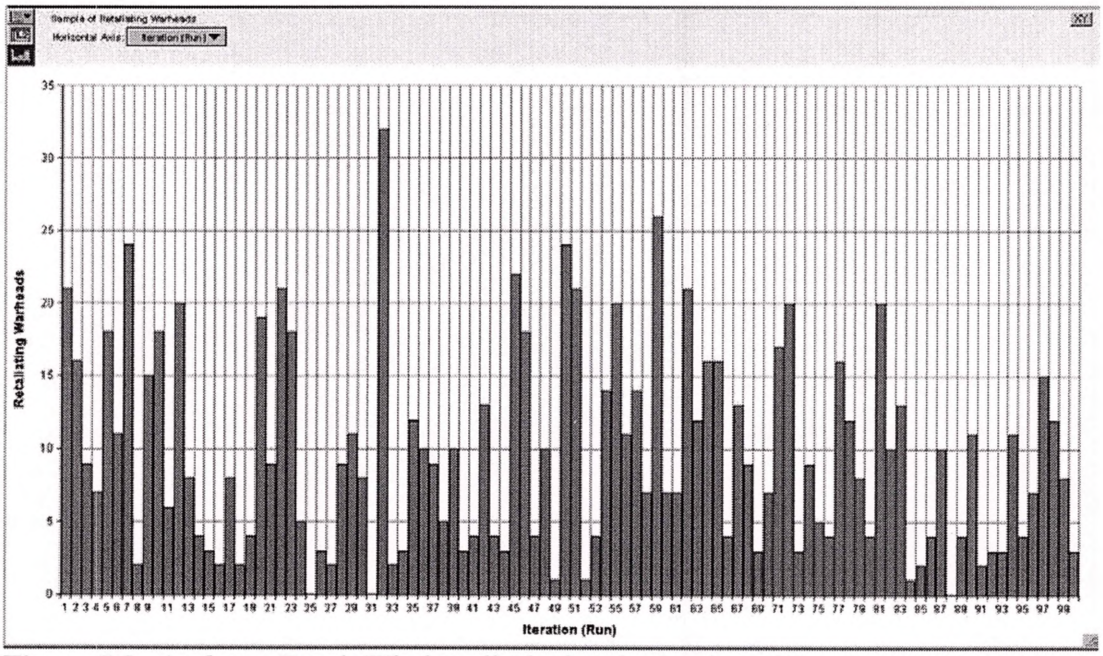


Figure 5.9: *Analytica* Result Window displaying the number of Russian First Echelon warheads out of an initial 150 warheads that survive a US strike and penetrate a highly-capable US missile defense system, for 100 missile defense interceptors and five heavy decoys per Russian warhead.

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. Note that two Monte Carlo runs were found in which the missile defense shield completely defended against the Russian First Echelon retaliation. In Monte Carlo run #36, only 3 Russian First Echelon launchers survived a US strike, and all 3 warheads were subsequently identified as warheads and successfully intercepted in the model, despite the 15 heavy decoys. 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 (a component of the proposed 500 warhead limit) and 50 Russian First Echelon launchers (a component of the proposed 100 warhead limit) with respect to our missile defense model, in order to similarly gauge missile defense interceptor limits as a component of future arms control discussions. Tables 5.2 and 5.3 provide similar statistical results of the model at these lower Russian First Echelon sizes.

Table 5.2: *Analytica* statistical results for a US 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

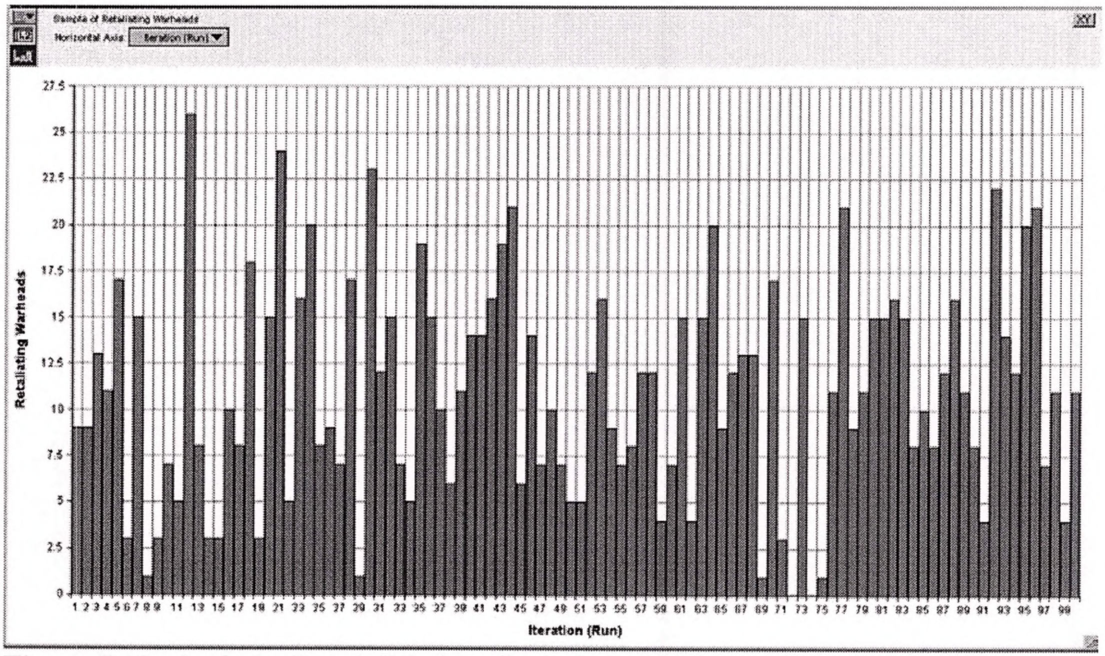
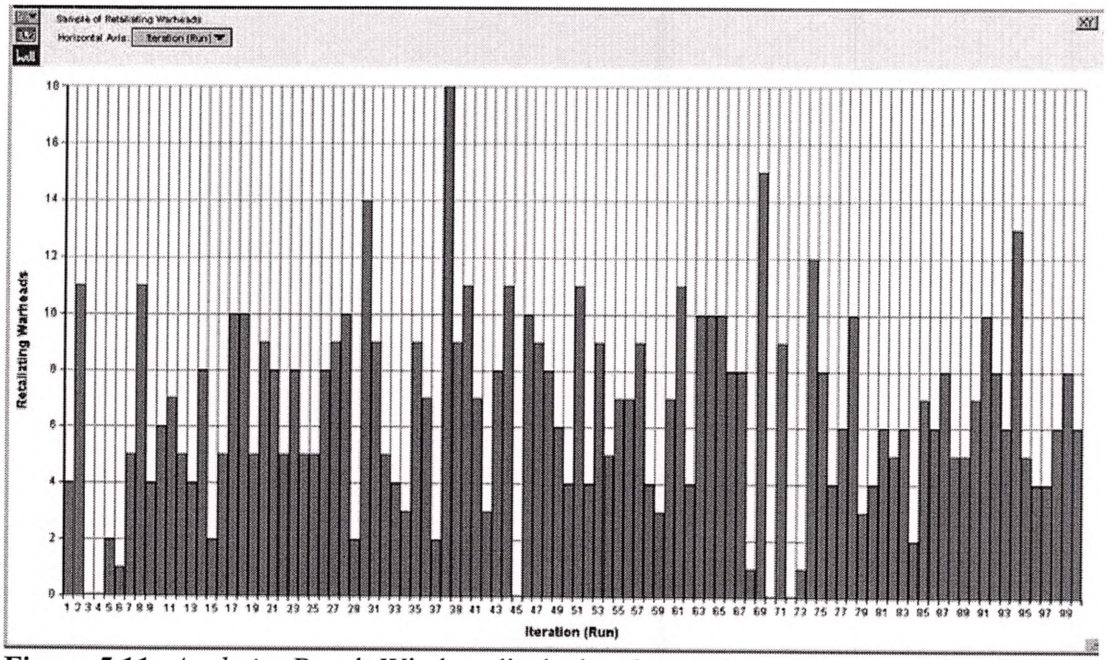


Figure 5.10: *Analytica* Result Window displaying the number of Russian First Echelon warheads out of an initial 100 warheads that survive a US strike and penetrate a highly-capable US missile defense system, for 25 missile defense interceptors and five heavy decoys per Russian warhead.

Table 5.3: *Analytica* statistical results for a US 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


Sample of Retaliating Warheads

Horizontal Axis: Iteration (Run)

Figure 5.11: *Analytica* Result Window displaying the number of Russian First Echelon warheads out of an initial 50 warheads that survive a US strike and penetrate a highly-capable US missile defense system, for five missile defense interceptors and five heavy decoys per Russian warhead.

These proposed missile defense interceptor limits, for example a limit of 100 missile defense interceptors for nuclear force limits of 1,000 total warheads with First Echelons consisting of 150 single-warhead, silo-based ICBMs, 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. Both suggested missile defense interceptor limits are based on models showing high attrition of nuclear forces off alert in an attack, but mitigated by the structure of the U.S. and Russian deterrent forces into the *Echelons*. 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. With this modeling, we have derived suggested limits on the numbers of missile defense interceptors as a function of strategic warhead limits of 1,000, 500 and 100 warheads, partitioned into a First and Second Echelon, and consistent with a stable deterrent so defined.

6) MODELING THE SECOND ECHELON

Recall that we propose to partition the nuclear forces of the United States and Russia into two groups: a First and Second Echelon. In the previous two chapters the modeling work examined the survivability of one First Echelon coming under attack by another First Echelon, and the importance of the survivability and proper functioning of nuclear command and control for the stability of deterrence. The models in this chapter introduce another important aspect of our study: the role of this additional, Second Echelon of nuclear forces which we posit are more deeply de-alerted than the First Echelon – these Second Echelon forces can only be brought to launch ready status over a lengthy period of time from weeks to months. 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 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 operational deployments and the vulnerability to non-nuclear attack, as discussed in Chapter 1.

The intent of this chapter is to first of all construct plausible First and Second Echelon forces for the United States and Russia, based on open-source information, and secondly to evaluate the contribution of the Second Echelons to assured retaliation, or the Second Echelon's contribution to the stability of deterrence.

Because of the role of the First Echelon single-warhead ICBMs to pose a 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 in Chapter 4, it is implausible that Russia could maintain these numbers of silo launchers. But recall that in Chapter 3 we derived a First Echelon size of roughly 100 launchers providing a stable barrier to nuclear war.

Tables 6.1 through 6.3 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 US 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 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.
- If a VS Second Echelon launcher is struck before it is brought to combat readiness, but survives, it then retaliates against AS cities.

Table 6.1: Hypothetical First and Second Echelon Nuclear Forces for the United States and Russia under a 1,000 warhead limit, including tactical nuclear weaponry.

Hypothetical Nuclear Forces of Russia under a 1,000 Warhead Limit				
Echelon	Launcher	Number of Launchers	Warheads per Launcher	Total Warheads
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				
Echelon	Launcher	Number of Launchers	Warheads per Launcher	Total Warheads
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 6.2: Hypothetical First and Second Echelon Nuclear Forces for the United States and Russia under a 500 warhead limit, including tactical nuclear weaponry for Russia.

Hypothetical Nuclear Forces of Russia under a 500 Warhead Limit				
Echelon	Launcher	Number of Launchers	Warheads per Launcher	Total Warheads
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				
Echelon	Launcher	Number of Launchers	Warheads per Launcher	Total Warheads
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 6.3: Hypothetical First and Second Echelon Nuclear Forces for the United States and Russia under a 100 warhead limit, without tactical nuclear weaponry.

Hypothetical Nuclear Forces of Russia under a 100 Warhead Limit				
Echelon	Launcher	Number of Launchers	Warheads per Launcher	Total Warheads
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				
Echelon	Launcher	Number of Launchers	Warheads per Launcher	Total Warheads
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

We introduce a new random variable, termed P_b, 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, 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). An *Analytica* Diagram Window of these Second Echelon models is presented in Figure 6.1.

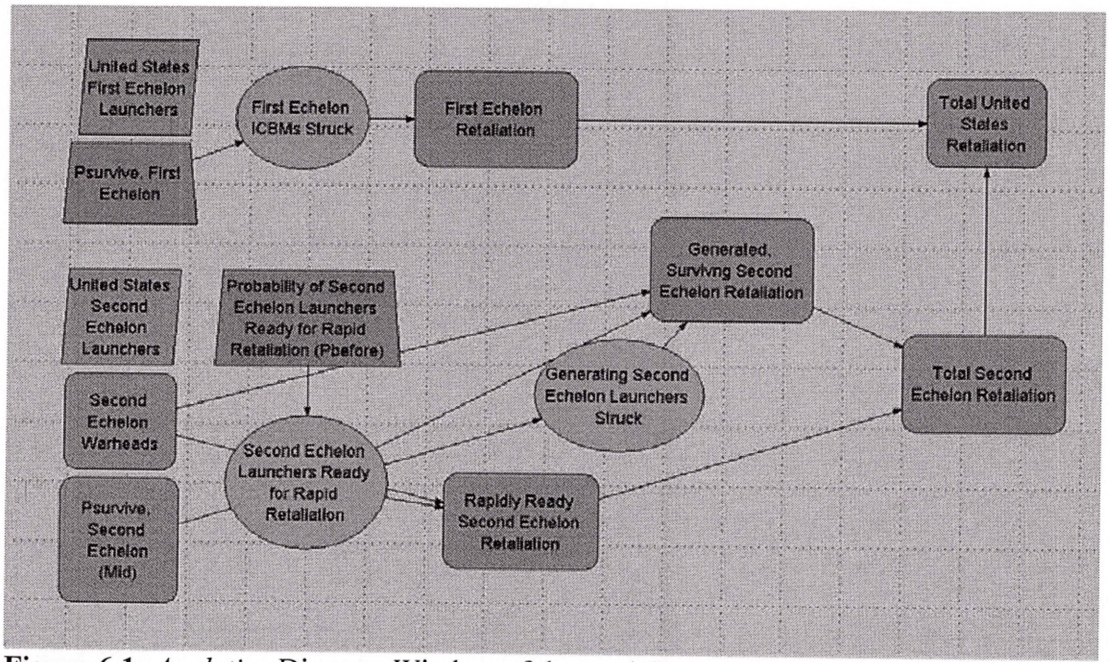


Figure 6.1: *Analytica* Diagram Window of the model examining the contribution of the Second Echelon to retaliation, in this case retaliation by the United States by surviving First Echelon forces, rapidly-generated Second Echelon forces, and surviving, generated Second Echelon forces.

Tables 6.4 through 6.6, below, show the model results for the United States as AS and Russia as VS. Tables 6.7 through 6.9, below, show the model results for Russia as AS and the United States as VS. For each of these model runs we have used the First and Second Echelon forces from Tables 6.1 through 6.3 – our proposed force structures for steps in the arms control process following implementation of New START. The tables 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. 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.

Table 6.4: Modeled Russian Retaliation, for the United States as AS and Russia as VS under the Proposed 1,000 Warhead Limit with Forces Partitioned into Off Alert First and Second Echelons.

$P_b = 0.0$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	14	33.7	85	12.8	12.7	66
Psurvive, Second Echelon, Mid	21	43.4	82	14.1	22.4	64
Psurvive, Second Echelon, High	24	52.8	100	17.5	31.8	74
$P_b = 0.02$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	18	44.7	90	15.6	23.7	74
Psurvive, Second Echelon, Mid	23	53.8	108	19	32.8	88
Psurvive, Second Echelon, High	30	63.4	126	20.2	42.4	107
$P_b = 0.05$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	29	60.9	111	21.7	39.9	95
Psurvive, Second Echelon, Mid	33	70.2	130	21.8	49.2	109
Psurvive, Second Echelon, High	30	79.1	151	23.7	58.1	133
$P_b = 0.10$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	35	87.8	165	29.5	66.8	29.7
Psurvive, Second Echelon, Mid	39	97	196	27.6	75.9	174
Psurvive, Second Echelon, High	40	105.6	175	28.8	84.6	160

Table 6.5: Modeled Russian Retaliation, for the United States as AS and Russia as VS under the Proposed 500 Warhead Limit with Forces Partitioned into Off Alert First and Second Echelons.

$P_b = 0.0$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	9	21	56	7.3	7	38
Psurvive, Second Echelon, Mid	12	26.2	72	9.4	12.2	56
Psurvive, Second Echelon, High	13	31.5	71	10.5	17.5	9.3
$P_b = 0.02$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	13	27	64	10.3	13	50
Psurvive, Second Echelon, Mid	15	32.1	77	12.5	18.1	61
Psurvive, Second Echelon, High	18	37.3	73	12.3	23.3	62
$P_b = 0.05$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	11	35.6	88	13.2	21.6	79
Psurvive, Second Echelon, Mid	14	40.8	78	13.5	26.8	62
Psurvive, Second Echelon, High	23	45.7	112	14.5	31.7	102
$P_b = 0.10$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	25	50.1	85	16	36.1	73
Psurvive, Second Echelon, Mid	28	55.3	127	20.3	41.3	109
Psurvive, Second Echelon, High	32	59.7	112	16.7	45.7	100

Table 6.6: Modeled Russian Retaliation, for the United States as AS and Russia as VS under the Proposed 100 Warhead Limit with Forces Partitioned into Off Alert First and Second Echelons.

$P_b = 0.0$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	3	8	18	2.7	1	6
Psurvive, Second Echelon, Mid	3	10	18	3.1	3	7
Psurvive, Second Echelon, High	5	12	19	2.9	5	10
$P_b = 0.02$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	3	8.9	20	2.9	2	7
Psurvive, Second Echelon, Mid	3	10.9	19	3.2	3.9	10
Psurvive, Second Echelon, High	5	13.5	21	3.2	5.9	12
$P_b = 0.05$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	4	10.5	23	3.2	3.5	9
Psurvive, Second Echelon, Mid	4	12.3	20	3.3	5.3	11
Psurvive, Second Echelon, High	6	14.2	21	3.4	7.2	14
$P_b = 0.10$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	5	12.9	22	3.6	5.9	12
Psurvive, Second Echelon, Mid	6	14.7	26	3.7	7.7	15
Psurvive, Second Echelon, High	7	16.6	25	3.6	9.6	16

Table 6.7: Modeled US Retaliation, for Russia as AS and the United States as VS under the Proposed 1,000 Warhead Limit with Forces Partitioned into Off Alert First and Second Echelons.

$P_b = 0.0$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	54	78.3	143	18.6	12.3	74
Psurvive, Second Echelon, Mid	49	85.8	213	29.2	19.8	142
Psurvive, Second Echelon, High	58	93.4	206	32.1	27.4	140
$P_b = 0.02$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	61	93.2	160	27.7	27.2	92
Psurvive, Second Echelon, Mid	51	100.1	217	35.5	34.1	146
Psurvive, Second Echelon, High	65	107.6	287	42.4	41.6	214
$P_b = 0.05$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	60	115.6	293	50	49.6	224
Psurvive, Second Echelon, Mid	59	122.3	281	49.6	56.3	208
Psurvive, Second Echelon, High	65	128.5	279	62.1	62.5	214
$P_b = 0.10$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	76	153	371	57.2	87	302
Psurvive, Second Echelon, Mid	79	160	361	65.8	94	288
Psurvive, Second Echelon, High	83	165.4	382	65.1	99.4	302

Table 6.8: Modeled US Retaliation, for Russia as AS and the United States as VS under the Proposed 500 Warhead Limit with Forces Partitioned into Off Alert First and Second Echelons.

$P_b = 0.0$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	37	50.9	177	16.3	6.9	130
Psurvive, Second Echelon, Mid	35	54.9	175	20.1	10.9	130
Psurvive, Second Echelon, High	37	58.9	120	21.7	14.9	74
$P_b = 0.02$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	41	58.8	243	27	14.8	196
Psurvive, Second Echelon, Mid	39	62.1	177	25.5	18.1	132
Psurvive, Second Echelon, High	39	66.9	126	26.6	22.9	78
$P_b = 0.05$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	43	70.6	187	31.9	26.6	148
Psurvive, Second Echelon, Mid	41	73.3	189	33.6	29.3	144
Psurvive, Second Echelon, High	45	78.5	192	33.7	34.5	148
$P_b = 0.10$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	52	89.7	202	39.3	45.7	152
Psurvive, Second Echelon, Mid	47	93.5	270	42.4	49.5	214
Psurvive, Second Echelon, High	49	98.3	212	41.4	54.3	162

Table 6.9: Modeled US Retaliation, for Russia as AS and the United States as VS under the Proposed 100 Warhead Limit with Forces Partitioned into Off Alert First and Second Echelons.

$P_b = 0.0$	Min. Retal.	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	15	22.5	49	4.9	0.5	25
Psurvive, Second Echelon, Mid	15	23	49	6.1	1	25
Psurvive, Second Echelon, High	15	23.5	54	7.2	1.5	25
$P_b = 0.02$	Min. Retal	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	15	23.5	54	7.2	1.5	25
Psurvive, Second Echelon, Mid	15	24	57	8	2	25
Psurvive, Second Echelon, High	15	24.5	54	8.4	2.5	25
$P_b = 0.05$	Min. Retal	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	15	25	57	8.7	3	25
Psurvive, Second Echelon, Mid	16	25.5	51	9	3.5	25
Psurvive, Second Echelon, High	15	25.5	79	10.5	3.5	50
$P_b = 0.10$	Min. Retal	Mean Retal.	Max Retal.	Std. Dev.	Contribution to Mean Retal. from Second Echelon	Contribution to Max Retal. from Second Echelon
Psurvive, Second Echelon, Low	15	27.3	78	12.3	5.3	50
Psurvive, Second Echelon, Mid	15	28	75	12.3	6	50
Psurvive, Second Echelon, High	15	28.5	72	12.3	6.5	50

We see that P_{before} factor, i.e. the probability some Second Echelon missiles are re-alerted and fired before be struck, 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 be able to assign (fix) this uncertainty in the required framework, and therefore really manage the deterrence effectiveness.

7) CONCLUSIONS AND BIBLIOGRAPHY

In this study we examined the effects on the stability of deterrence of partitioning US and Russian nuclear 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 a Second Echelon of more diverse nuclear forces that cannot be rapidly generated in a crisis. We found that, given reasonable estimates of weapons characteristics, sufficient surviving First Echelon nuclear forces can retaliate 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 but statistically a much worse outcome for the AS could occur,further bolstering deterrence.

We modeled the importance of retaining robust, redundant nuclear command, control and communications. The role of the Second Echelon to bolster assured retaliation, while maintaining force flexibility for deeply de-alerted forces was explored through hypothetical construction of the First and Second Echelons at force sizes reduced from today's numbers to 1,000, 500 and 100 total warheads. Finally we derived limitations on the numbers of missile defense interceptors for First Echelons that are consistent with a stable nuclear deterrent, assuming a highly-capable missile defense system.

An important step on the path of making the world free of nuclear danger consists in de-alerting US 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 creates constant threat of unauthorized nuclear war because of technical defect, duty personnel error, or terrorist sabotage which will be more probable in periods of sharp international crises. To reduce this serious danger it is necessary to reduce the combat readiness of ALL nuclear forces.

At the present, a persistent Cold War mindset within the military and political establishment in both U.S. and Russia opposes de-alerting. To overcome the mindset we have proved that the stable of deterrence can exist with forces off alert. Further research and modeling works are needed to define a stable path from very low numbers of nuclear forces down to zero forces – Global Zero. Our modeling results indicate that the forces will need to be re-configured through re-designed echelons and other measures in order to ensure a stable transition to Global Zero.

BIBLIOGRAPHY

Bruce Blair, "De-Alerting Strategic Forces," in *Reykjavik Revisited: Steps Toward a World Free of Nuclear Weapons*, George P. Shultz, Sidney D. Drell, and James E. Goodby, eds., (Stanford, CA: Hoover Institution Press, 2008), **http://www.hoover.org/publications/books/8143.**

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

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, 1973, Vol. 17, pp. 207-242.

V.A. Gelovani, A.A. Piontkovsky and A.P. Skerokhodov, "Strategic Stability Analysis through Mathematical Modeling," International Political Science Review 1990; Vol. 11; pp. 243-260.

Jeffrey H. Grotte, "Measuring Strategic Stability with Two-Strike Nuclear Exchange Models," Journal of Conflict Resolution, Vol. 24 No. 2, June 1980 213-239.

Neal H. Hillerman, "The Theoretical Basis of the CODE 50 Nuclear Exchange Model," Center for Naval Analysis, March 1972.

Francis P. Hoeber, "Military Applications of Modeling: Selected Case Studies," Military Operations Research, A Series of Monographs and Texts, Vol. 1, Gordon and Breach, 1981.

Glenn A. Kent and David E. Thaler, "First-Strike Stability: A Methodology for Evaluating Strategic Forces," RAND, R-3765-AF, August 1989.

Robert S. Norris and Hans M. Kristensen, "Nuclear Notebook: Russian Nuclear Forces, 2009," Bulletin of the Atomic Scientists, May/June 2009.

Robert S. Norris and Hans M. Kristensen, "U.S. Nuclear Forces, 2010," Bulletin of the Atomic Scientists, May/June 2010.

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.

Pavel Podvig, "The Window of Vulnerability that Wasn't: Soviet Military Buildup in the 1970s," International Security, Summer 2008, Vol. 33, No. 1: 118-138.

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