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BALLISTIC MISSILE GUIDANCE AND TECHNICAL UNCERTAINTIES OF COUNTERSILO ATTACKS

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Preface

For the past several years, the U.S. Congress, press, and public have been told that the the land-based intercontinental missiles of the United States were extremely vulnerable to a surprise attack by the Soviet Union. This idea has been put forward by a variety of military leaders and civilian analysts, and has become one of the central tenets of strategic debate in this country.

In general, these assessments are based on simplified mathematical models of the outcome of strategic exchanges. This Report examines some of the technical and operational difficulties that would obtain in any real attack, in order to provide a more rigorous assessment of ICBM vulnerability and clarify some of the extremely complex issues that have been raised in this regard.

The research for this Report commenced two years ago, and was conducted by Matthew Bunn under my direction. All of the information contained in this Report is from unclassified sources, freely available to the public. Earlier drafts have been read and commented on by a number of scientists in and out of the Government. Many of their comments and criticisms of these earlier drafts have been incorporated in this Report.

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CONTENTS

INTRODUCTION

Stable deterrence requires that nuclear forces not be vulnerable to preemptive attack. For decades, strategic planners in both the United States and the Soviet Union have been concerned about the possibility of a disarming nuclear first-strike by the other side, which would leave the victim of the strike unable to retaliate in kind.

In the early post-war years, each side's nuclear weapons were carried by intercontinental bombers; since bombers required hours to reach their targets, the possibility of a disarming preemptive strike was remote, as long as a portion of the bomber force was kept on alert. However, with the development of long-range ballistic missiles, with their very short flight times, the possibility of an entire bomber force being wiped out by a preemptive attack became very real; as a result, the U.S. began maintaining its bombers in very high states of alert, sometimes airborne.

By the early 1960's, the United States, while maintaining its bomber force, was moving a substantial portion of its nuclear force into submarine-launched ballistic missiles (SLBMs), and land-based intercontinental ballistic missiles (ICBMs). The ICBMs were placed in concrete structures known as "silos," which were hardened against nuclear blasts. Thus was created the "triad" of strategic forces; with the U.S. strategic nuclear force distributed between bombers, submarines, and ICBMs, the potential importance of a Soviet technical advance threatening to any one of the three systems was reduced.

The Soviet Union was making similar efforts, but their early ICBMs were not based in hardened silos, and their early submarine-launched missiles had extremely short ranges, making them much less effective weapons. It was not until the mid-to-late 1960's that the Soviet Union developed a truly survivable nuclear force. The Soviet Union never developed a "triad" in the same sense that the United States did; it put the bulk of its nuclear force in land-based ICBMs. Even today, the Soviet Union has three-quarters of its nuclear force in ICBMs, although it has expanded its submarine force considerably in recent years. This compares to roughly one-quarter of the U.S. forces. The Soviet Union does not have an appreciable strategic bomber force.

For a time, it seemed that the problem of vulnerability had been permanently solved. Submarines at sea were essentially impossible to find; while it was clear that anti-aircraft technology would improve, bombers could easily penetrate then-current air defenses. ICBMs in hardened silos were very difficult to destroy, and in any case, since each missile carried only one warhead, any attack would expend at least as many missiles as it would destroy. As long as a rough parity of forces existed, such an attack would be pointless.

Then the United States developed missiles that carried several warheads, each capable of striking a separate target; these were dubbed MIRVs, for multiple independently-targetable reentry vehicles. This changed the situation dramatically; if both powers had several warheads on each of their land-based missiles, an attacker with perfect missiles could theoretically destroy several times as many warheads as he expended in the attack. This would have the destabilizing effect of giving a large advantage to the side that struck first.

Despite considerable pressure from Congress, the Nixon Administration did not seriously attempt to negotiate a ban on MIRVs in SALT I, as the United States had a substantial lead in this technology. Continued American efforts on MIRVs were justified as a method of overwhelming possible future Soviet anti-ballistic missile (ABM) defenses, but severe limits on ABMs were negotiated as part of SALT I, thereby obviating the need for further deployment of MIRVs as an ABM countermeasure.

When the Soviet Union began deploying MIRVed weapons, in the mid-1970's, it became clear that the American avoidance of a MIRV ban had been a major error; since the Soviet Union had traditionally deployed much larger ICBMs than the United States, with much greater throw-weight (the weight of the payload that can be delivered to a target at a given range), they could conceivably put a very large number of warheads on each missile, once they had matched U.S. technology. Not surprisingly, the Soviet Union rejected several of the U.S. MIRV-limiting proposals in SALT II, although that treaty does contain very substantial limits on potential Soviet capabilities. Although SALT II was never ratified, both sides are still observing its provisions.

It became clear to strategic planners in the United States that if the Soviet Union were in fact to deploy a large number of warheads, and if those warheads were also accurate, powerful, and reliable, they could theoretically destroy most of the U.S. land-based missile force in its silos. Thus was born the "window of vulnerability."

In 1977-78, the worst fears of U.S. strategic planners were realized: the Soviets began testing a new-generation guidance system that was much more accurate than their previous systems. This guidance system was tested on two missile systems, the SS-18 Mod (for modification) 4, and the SS-19 Mod 3. Simplified calculations indicated that by the early 1980's, when the Soviets were predicted to have deployed these systems extensively, they could destroy nearly 90% of the U.S. ICBMs in a first-strike. This premise has dominated American strategic thinking for several years now, and has been the primary justification for the development of a new generation of U.S. nuclear missiles, including the MX and the D5 Trident II missiles.

However, there are considerable technical uncertainties involved in planning such a strike that are not considered in these simplified calculations. Because tests of operational missiles are not extremely frequent, there will be some uncertainty as to the precision of any weapon (usually measured by the Circular Error Probable (CEP), the radius from the average point of impact within which half of the incoming warheads will fall). This is especially true in the Soviet case, as most of their tests take place on a range substantially shorter than that necessary for a strike on U.S. silos (usually called a "counterforce" strike, as opposed to a strike on urban-industrial targets, which is referred to as a "countervalue" strike). Since the accuracy of a weapon varies with range, the observed test performance of Soviet ICBMs over these shorter ranges will not be duplicated during operational launches, and calculating the appropriate adjustment factors is a complex and uncertain process.

Moreover, these calculations assume that there will be no systematic error, that is, that the average point of impact, from which the CEP is measured, will be coincident with the target; in fact, it is often true that the average point of impact is offset by a systematic bias. If the bias is large, it can have a significant effect on the outcome of a countersilo attack. Unpredictable changes in both the CEP and the bias sometimes occur when new missiles are tested, or old systems are tested over a different range. These changes are caused by a variety of factors, including variations in the earth's atmosphere and gravitational field, as well as errors in the guidance systems themselves.

Other uncertain factors include the yield of the warhead, the reliability of the missile, the response of silos to nuclear effects, the coordination and timing of the attack, and the interference between the many warheads used in the attack, referred to as "fratricide." Many of these factors have never been tested, and can never be tested. Political factors add to the technical uncertainties. Thus, the level of destruction the planner of an attack could <u>have confidence</u> in achieving is much lower than that idealized calculations would predict; since <u>any</u> use of nuclear weapons represents an enormous gamble, such uncertainty will serve as a powerful deterrent to an attack.

This paper is divided into two distinct but interrelated parts. In the first, we describe the functioning of modern ICBM guidance systems, describing in a general way the major sources of the errors that contribute to CEP and bias. We hope that this will provide the reader with a good understanding of the workings of modern ICBMs, providing a useful background for the second portion of the paper. There, we discuss in detail how calculations of the outcome of counterforce strikes are made, and more fully describe the technical uncertainties mentioned above. We conclude by providing a rough order-of-magnitude quantification of the effect of these uncertainties both in the current situation, and an extrapolation into the future. An appendix discusses some of the political difficulties involved in large-scale counterforce attacks, and another reviews current procedures for the testing of ICBMs.

This paper is intended for readers familiar with elementary calculus and physics; a somewhat simplified version is forthcoming.

PART ONE: THE GUIDANCE OF ICBMS

1.1 BALLISTIC MISSILE GUIDANCE

Because of the extreme destructive power of nuclear weapons, most of the possible missions of a nuclear missile do not require great accuracy. A weapon with a yield of one megaton (that is, one with the explosive power of one million tons of TNT) could destroy most residential buildings, industrial sites, and military bases even if it detonated more than a kilometer away from them.

However, there are a small number of targets, such as missile silos, nuclear weapon storage sites, and command bunkers, which are "hardened" against the effects of nuclear blasts. Rather than collapsing under a shockwave of some 5-10 pounds per square inch (psi), as an ordinary brick building does, these structures are designed to withstand shock waves of many hundreds or thousands of psi. As we will discuss in detail in the second half of this paper, the destruction of these targets requires great accuracy; to destroy a U.S. Minuteman missile silo, a one-megaton weapon would have to detonate less than 400 meters from its target, after flying some 10,000 kilometers from its launch site. Indeed, the accuracy of the weapon is the single most important factor in an attack on hardened targets (Gu1).

In the following sections, we describe how these levels of accuracy are achieved in modern inertially guided ballistic missiles (Gu2).

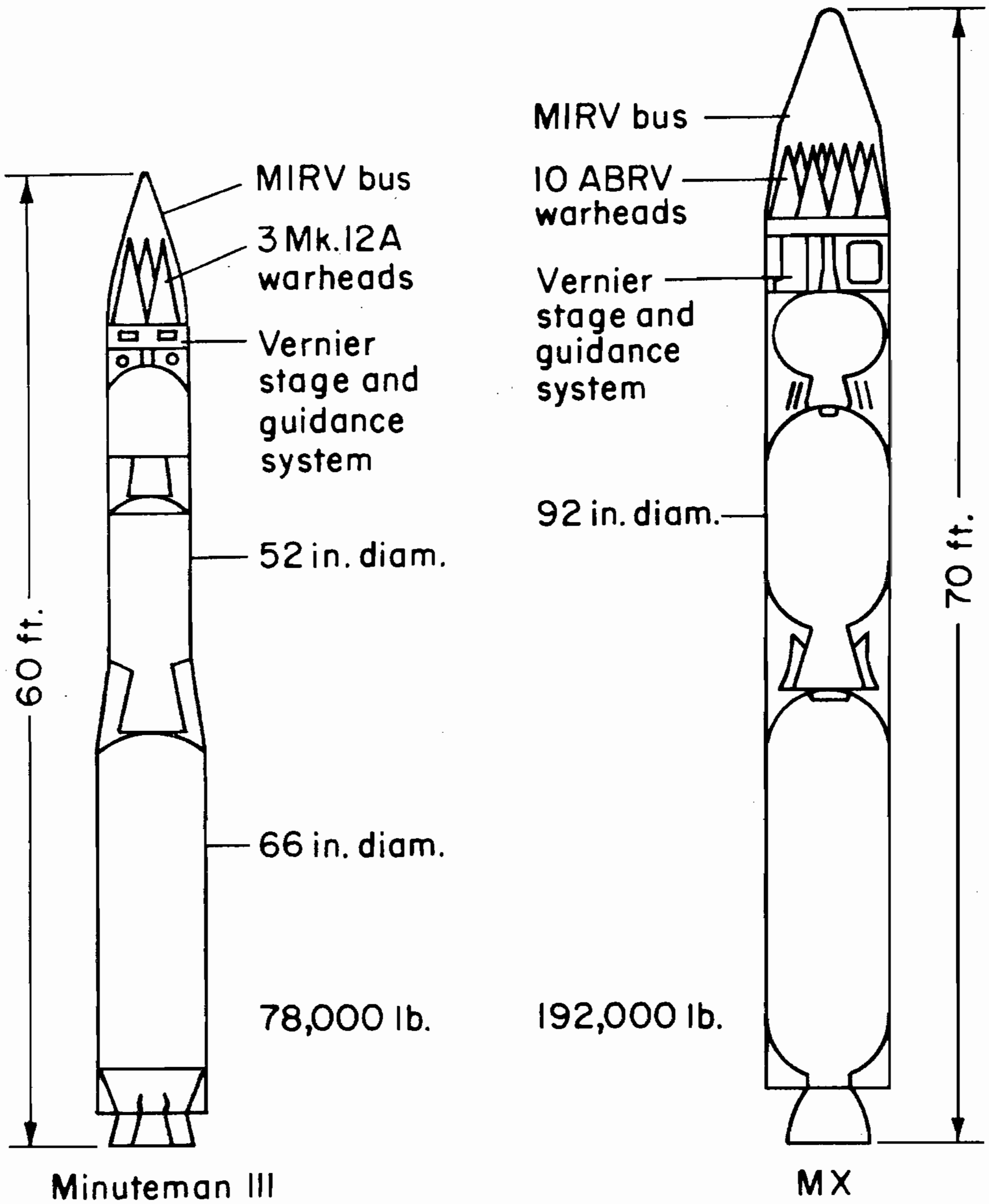
A modern intercontinental ballistic missile consists of three main parts: a rocket, which may consist of several stages, a guidance system to direct the rocket, and the payload, which generally consists of one or more reentry vehicles armed with thermonuclear warheads. See Figure 1.1.1..

An ICBM requires roughly 30 minutes to travel distances comparable to those between the United States and the Soviet Union. The word "ballistic" refers to the fact that for most of its flight, an ICBM is falling freely, much like an artillery shell. The rocket and guidance system only function for the first 3-7 minutes of the flight; the warheads are then detached from the rest of the system, and fall freely, influenced mainly by the earth's gravity field, unpowered and unguided. At the end of its flight, the warhead reenters the atmosphere, and detonates over the target. Thus, it is convenient to divide the trajectory into three parts: the boost phase, free flight, and reentry.

There are several possible guidance methods available. For instance, the missile could be guided by radio commands from ground stations; this could be done with extreme accuracy. Early Soviet ICBMs used this method, but the vulnerability of the tracking stations and the susceptibility to jamming of the guidance signal led the Soviet Union to a less vulnerable technique known as inertial guidance, which was already in use on U.S. ICBMs. While

Fig. 1.1.1

Two Modern ICBMs



the problems of early radio guidance systems could now largely be solved, both superpowers continue to rely on inertial guidance for the guidance of their ICBMs. Inertial guidance systems are completely self-contained, and do not rely on any sensing of radiation from the outside world. Thus, they cannot be prevented from functioning short of tampering with the missile itself.

A. INERTIAL GUIDANCE

Inertial guidance systems are so called because they rely on Newton's law of inertia, F=ma, to determine the path of the missile. In essence, what an inertial guidance system does is to measure the acceleration of the missile, in order to determine its position and velocity; it then calculates the velocity the missile will need to reach its target, using a model of the forces the missile will experience after thrust termination, and directs the rocket thrust to match that velocity. When the current velocity of the missile is equal to that required to hit the target, the rocket is shut off, and the missile enters the free-flight phase of its trajectory.

The acceleration of a missile in the earth's gravity field can be described by the following equation:

$$a = \frac{f_a}{m} + g \qquad (1.1.1)$$

In order for equation 1.1.1 to hold, the reference frame of the guidance system must be non-rotating and inertial. Often, the coordinate frame that is used is a non-rotating frame with its origin at the center of the earth. The first term is the specific force per unit mass acting on the missile, and g is the acceleration of gravity. The specific force is the vector sum of all forces acting on the missile except the force of gravity; it includes such forces as rocket thrust and aerodynamic drag. It can be measured directly by instruments known as <u>accelerometers</u>.

In each accelerometer, there is a test mass, and the specific force is measured from the forces required to support the test mass. In one conceptually simple configuration, the test mass would rest on calibrated beams with strain gauges. The strain gauges would measure the components of the support force on the test mass, which would then become the output of the accelerometer. It is essentially impossible to achieve the required linearity and dynamic range with such a configuration; a more common configuration is the pendulous integrating gyroscopic accelerometer (PIGA), in which a single-degree-of-freedom integrating gyroscope is arranged so that a force along the measurement axis will cause a precession proportional to the force; the measurement of the gyro precession then becomes the output of the accelerometer.

If the missile is rigid and not rotating, the forces measured will be the same, no matter where the accelerometers are located within the missile. In practical applications, the missile is usually not completely rigid, and may be rotating; for this reason, the accelerometers are usually mounted on the rotational axis, and as close to the warheads as possible, so that the forces measured will be identical, for all intents and purposes, to those experienced by the warheads themselves.

Since the missile will be accelerating in three dimensions, three accelerometers, mounted orthogonally, are required to measure the three components of the specific force. In order to maintain the initial orientation of the accelerometers' coordinate frame, the accelerometers are mounted on a gimballed platform stabilized by

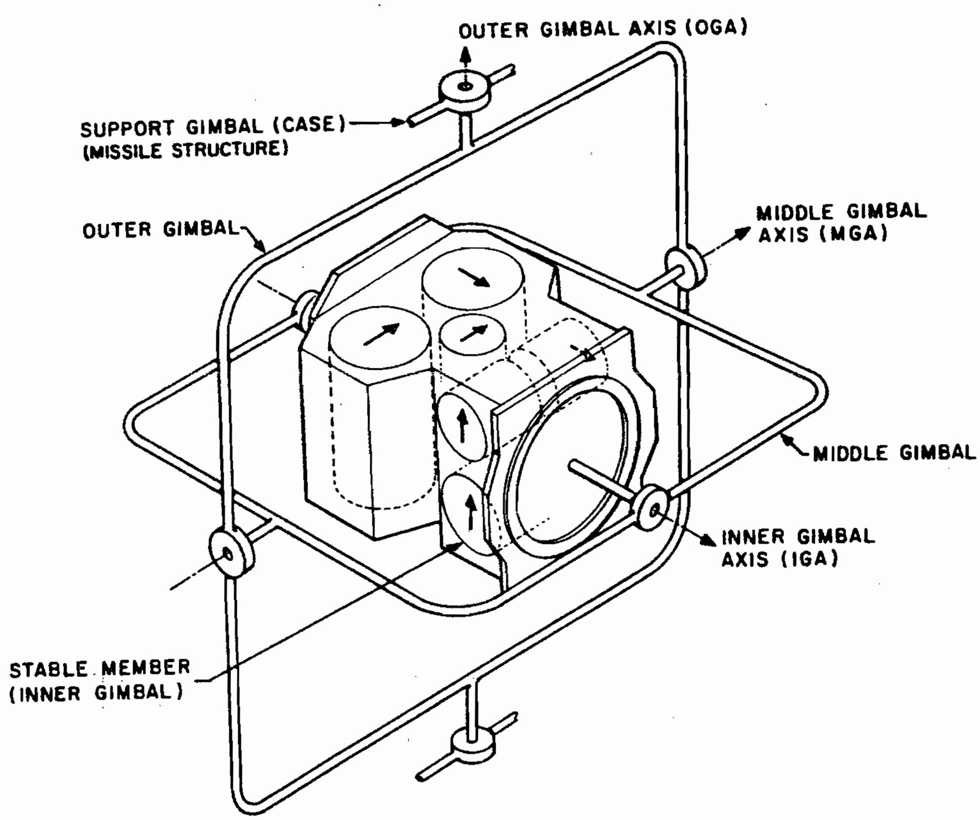


Figure 1.1.2 - Simplified Diagram of Stable Platform

three orthogonal gyroscopes. See Figure 1.1.2 (Gu3). Conceptually, each gyroscope is a self-contained rapidly spinning wheel; the conservation of angular momentum causes it to resist changes in its angular orientation. This resistance can be translated into angular error signals; these signals can be used to control electronic servomechanisms, which apply torques to maintain the initial orientation of the guidance system. In single-degree-of-freedom gyroscopes, such as those used in the hypothetical guidance system we describe in subsequent sections, the instrument is constrained to precess about one axis; since the output of the gyroscope is the precession about this axis, it

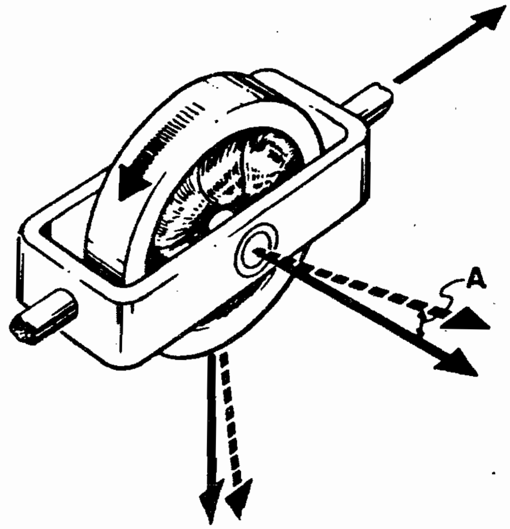


Figure 1.1.3 - A Single-Degree-of-Freedom Gyro

is referred to as the output axis. See Figure 1.1.3. Thus, accelerometers and gyroscopes are the fundamental instruments of inertial guidance; they allow the guidance system to measure the specific forces applied to the missile.

However, it should be noted that the accelerometers do not measure the force of gravity. A more precise way of expressing this is to say that the accelerometers cannot separate the effect of an actual acceleration from the effect of the presence of a gravitational field, as described by Einstein's Principle of Equivalence. An accelerometer in a free-falling elevator would register zero, as its real acceleration would be canceled by the effect of the earth's gravitational field.

Similarly, while the missile is in the silo, the accelerometers will register a force, that of the silo holding up the missile, even though the missile is not accelerating. While the missile is in free-fall, the accelerometers will read zero, even though the missile is accelerating under the force of gravity. Thus, for the guidance system to calculate the actual acceleration of the missile, the gravity vector, as a function of position, must be programmed into the missile's guidance computer before launch.

By combining the information concerning the specific force provided by the accelerometers and gyroscopes with the information concerning the gravity field provided by the missile's guidance program, the guidance computer can calculate the three-dimensional acceleration of the missile, using equation (1.1.1). The computer then integrates once to find the missile's current velocity, and again to find the missile's current position.

The portion of the guidance system's function which has been described so far is referred to as inertial navigation, and is used in many systems, both commercial and military, ranging from airplanes and cruise missiles to submarines. It is of enormous use whenever outside information concerning the position of the vehicle is unavailable or cannot be relied on. A block diagram

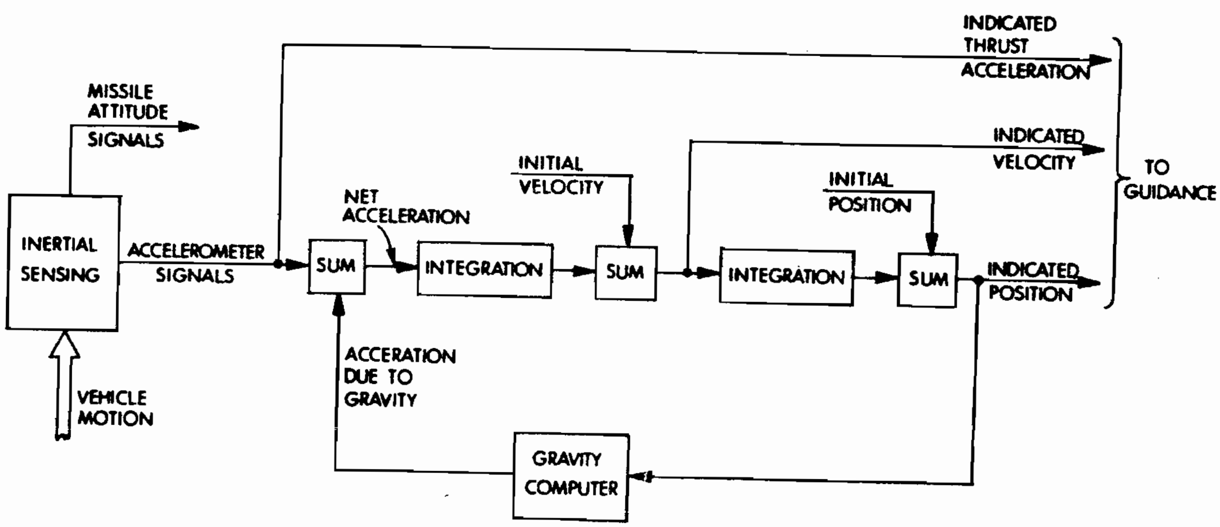


Figure 1.1.4 - Block Diagram of Inertial Navigation

of inertial navigation is given in Figure 1.1.4 (Gu4).

Once the guidance computer has calculated the missile's current position and velocity, the next step is to calculate the velocity needed to reach its target from its current position. The motion of the warhead after thrust termination, or "burnout", is predicted using a detailed mathematical model of the forces that will act on it during the rest of its flight, such as gravity and aerodynamic forces. Clearly, the accuracy of this model is as important as the measurement accuracy of the accelerometers and gyroscopes themselves. The guidance computer then takes the vector difference between the current velocity and the required velocity, and directs the rocket thrust parallel to that difference. If the rocket thrust is controlled properly, all three components of the velocity difference should then go smoothly and simultaneously toward zero. While the control of the rocket is a difficult problem in itself, the inertial guidance system can sense, and compensate for, any errors that build up as a result of the rocket not responding perfectly to guidance signals.

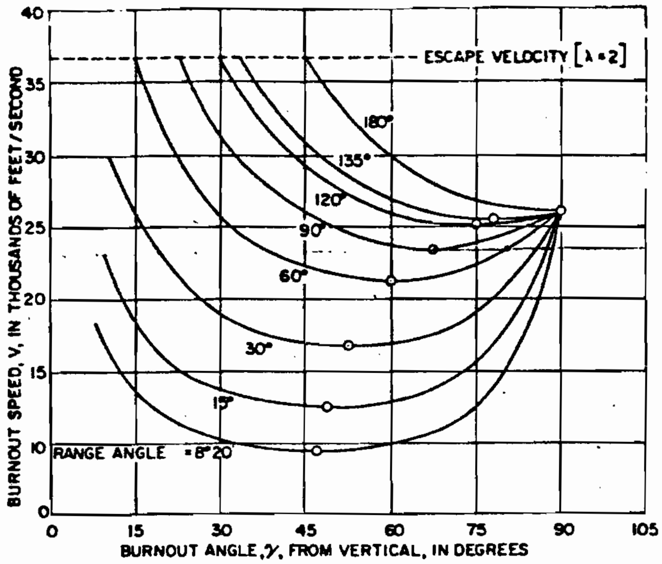
B. INTERCONTINENTAL BALLISTIC TRAJECTORIES

After thrust termination, an ICBM will follow an essentially Keplerian elliptical path, deformed slightly near the target by the effect of aerodynamic forces. The range between targets in the United States and the Soviet Union will vary somewhat, depending on the location of the launchers and the targets within the respective countries, but in general, an ICBM must travel through a range angle of slightly less than 90 degrees (that is, a quarter of the way around the earth), a distance of some 9-10,000 kilometers.

There are an infinite number of possible trajectories, but for any given distance, there is one trajectory that requires less fuel than any other, and is hence referred to as the "minimum energy trajectory." For a range of 10,000 kilometers, the minimum energy trajectory requires the missile to be traveling roughly 22 degrees from the horizontal at thrust termination, with a velocity of approximately 7,200 m/sec. Flight time is of the order of 30 minutes, and the apogee height (the distance from the earth at the highest point of the trajectory) is approximately 1300 km. A detailed derivation of the trajectory equations is given in Appendix B.

Figure 1.1.5 shows the required velocity versus the angle of motion at thrust termination, for several range angles (Gu5). Since the curves are nearly flat near the minimum-energy point, some variation from the minimum-energy trajectory is possible, providing operational flexibility. Another constraint on the trajectories that can be flown is the ability of the warhead to withstand heating; higher speed, more nearly vertical trajectories mean higher thermal loads during reentry, requiring better heat shielding for the warhead.

Two reasons can be advanced why such operational flexibility in trajectories might be desirable. First, a depressed trajectory will mean a shorter flight time, which might aid in surprising the opponent's forces; alternatively, a lofted trajectory, while requiring more time, will, in general, decrease both guidance errors and reentry errors. While it is probable that weapons are designed with some operational flexibility in mind, most missile tests on both sides have remained reasonably near the minimum-energy trajectory, and for the rest of this paper, we will assume that the minimum-energy trajectory is used.



Variation of required burnout speed with burnout angle γ and range angle ϕ for nonrotating spherical Earth ($h = 0$). Circles mark minimum speed points

Figure 1.1.5

C. THE EFFECT OF ERRORS AT THRUST TERMINATION

From the above discussion of inertial guidance, it can be seen that there are two broad types of possible errors in a ballistic missile system. First, errors can build up during the boost phase, as a result of pre-launch conditions, guidance system errors, thrust termination errors, or inadequate modeling of the earth's gravity field. These types of problems result in errors in the position and velocity of the warhead at thrust termination. The other broad class of errors are those that arise from the prediction of the forces that a missile will encounter after thrust termination. The most prominent errors in this class are those due to reentry through the earth's atmosphere and those that arise from the anomalies in the earth's gravity field.

From a mathematical description of the trajectory, it is possible to derive the impact errors at the target that will be caused by given errors in position and velocity at thrust termination. The results, for a 10,000 km minimum-energy trajectory, are given in Figure 1.1.6 (Gu6). These results are linearized approximations, but for modern guidance systems, the errors will be small enough for the approximations to be quite accurate. The figures are ap-

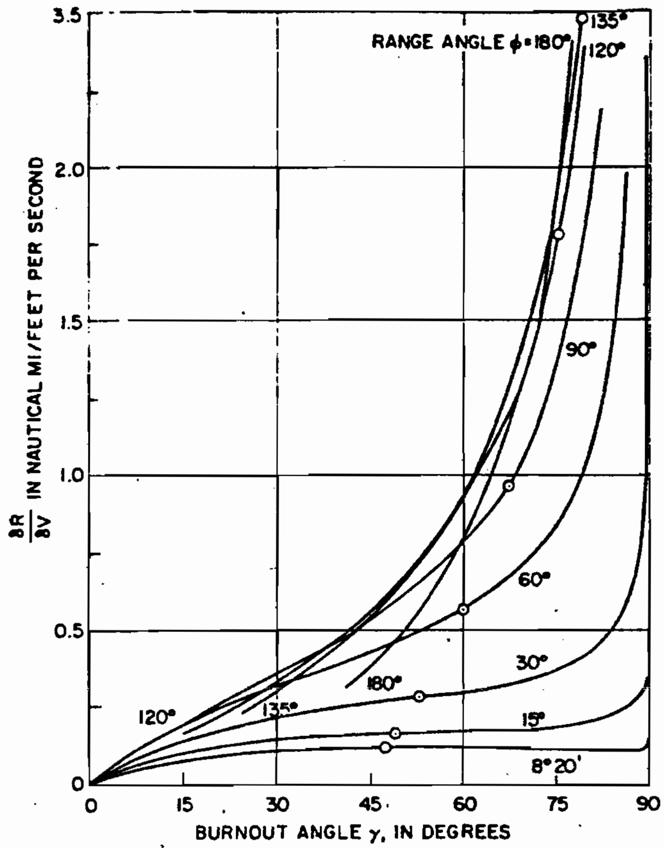
Fig. 1.1.6 - Effect of Errors at Thrust Termination

Error at Burnout	Target Miss, 90° minimum-energy trajectory: Range	Track
Vertical Velocity	2,300 m/m/sec	0
Vertical Position	5.8 m/m	0
Horizontal Velocity (in-plane)	5,600 m/m/sec	0
Horizontal Position (in-plane)	1 m/m	0
Horizontal Velocity (out-of-plane)	0	960 m/m/sec
Horizontal Position (out-of-plane)	0	0

proximate, as they were derived for an impulsive launch from the surface of a spherical, non-rotating earth with no atmosphere; however, they represent the actual relationships with reasonable accuracy. They are derived in Appendix B.

Not shown on this chart are errors caused by the earth's rotation; several of the errors listed cause variations in the flight time, with corresponding changes in the position of the target due to the earth's rotation. Because of the relative geography of the United States and the Soviet Union, ICBMs will in general be approaching the target from the north, and these errors would be crossrange errors rather than downrange errors. However, these components of target miss are small compared to those given in the chart; we will therefore neglect them.

It should be noted that most of these errors can be reduced by sending the missile on a trajectory higher than the minimum-energy trajectory. Figure 1.1.7 shows the error at the target as a result of errors in the magnitude of the velocity, compared to the angle of travel at thrust termination, measured from the vertical (Gu7). Other error sources behave somewhat differently, but in general, the trend is toward increased accuracy on higher trajectories, i.e. smaller burnout angles (measured from the vertical).



Velocity miss coefficient vs. burnout angle for various range angles

Figure 1.1.7

1.2 A HYPOTHETICAL ICBM

In the next several sections, we offer a rudimentary description of the functioning of modern ICBM inertial guidance systems. In order to facilitate our discussion, we have chosen to describe the types of error sources encountered in the guidance system of a hypothetical ICBM. The sections are arranged in chronological order, beginning with errors that occur before launch, and ending with errors attributable to reentry and fusing. For each error source, we provide a rough estimate of the magnitude of the error, with the corresponding error at warhead release point and impact error at the target. Specific data about weapon system component performance is, of course, classified; our estimates of the magnitude of error sources are no more than educated guesses, and do not represent actual data for any specific weapon system. They are by no means intended to be definitive, but merely illustrative of the types of problems encountered in the guidance of ballistic missiles. It should also be noted that actual errors will be greatly dependent on the specific configuration of the guidance system and the specifics of the boost phase trajectory.

We will treat all of the error sources as uncorrelated statistical standard deviations, and will make the further approximation that all errors behave in a linear fashion; the combined effect of any two errors is then the square root of the sum of their squares.

A. BOOST PHASE TRAJECTORIES

In order to calculate the effect at thrust termination of a given time-dependent or acceleration-dependent error in a gyroscope or accelerometer, it is necessary to approximate the boost phase trajectory of the missile.

The specific trajectory an ICBM flies during the boost phase is quite variable, depending on a number of design and operational parameters; no general solution for the trajectory during the boost phase is possible. However, it is possible to make some important generalizations. A modern ICBM generally has three main stages, in addition to the vernier stage. To operate efficiently, the rocket of each stage must operate at nearly constant thrust. Thus, the acceleration will be increasing, slowly at first, and quite rapidly toward the end of the boost phase, as the mass of the fuel is left behind. Peak accelerations will be of the order of 100 meters/second^2, and the flight time from launch to thrust termination is of the order of 200 seconds. Since the accelerometers do not measure the effect of gravity, which acts to slow the missile down, the accelerometer-sensed final velocity will be of the order of 8000 meters/second, as opposed to the actual velocity of 7,200 meters per second, and will be several degrees closer to the vertical than the actual velocity. Initially, the ICBM will be rising vertically out of its silo. During the burning of the first stage, the missile is usually not actively steered; the thrust is parallel to the direction of motion, which is slowly turned toward the horizontal by the effect of gravity. Once the missile leaves the atmosphere, the second stage will generally ignite, and active steering will begin. In order to calculate rough estimates of possible guidance errors, we have used a very rough approximation to the boost-phase trajectory, which is described in Appendix B.

1.3 PRE-LAUNCH ERRORS

The guidance system functions by measuring the acceleration of the missile. Thus, it can measure only the change in velocity and position since launch; the initial velocity and position of the launch site must be programmed into the guidance computer before launch. In addition, the alignment of each of the accelerometers with respect to the reference coordinate system must be precisely determined.

A. INITIAL VELOCITY

For a launcher such as an ICBM silo, which is stationary with respect to the earth's surface, the initial velocity of the launcher will depend only on the rotation of the earth at that latitude. Errors in determining this initial velocity should be completely negligible, and we will assume no error from this source.

For a submarine or other moving launcher, the problem is much more difficult. Submarines use inertial navigation systems to determine their position and velocity through time. These navigation systems are subject to substantial errors. Inertial measurement errors will be substantially larger in the submarine navigation system than in the ICBM guidance system, because of the very long time periods involved. Gravitational errors will also be much more significant in the submarine system, both because the submarine remains on the surface of the earth, where gravity anomalies are more noticeable, and because less detailed gravity models are available for submarine patrol areas than for ICBM launch fields.

These errors, however, can be damped considerably with Kalman filters, utilizing outside information concerning velocity, such as measurements of the water flow around the submarine, sensing of the ocean's surface below, or radio contact with outside sources. Even with damping, however, the errors in initial conditions for submarine-launched ballistic missiles (SLBMs) have in the past made these missiles too inaccurate for attacking anything other than soft targets. For missiles launched from a single submarine over a relatively short period of time, these errors will amount to a systematic bias; however, they will be random from submarine to submarine (For a detailed discussion of the distinction between random and systematic errors, see section 2.3).

The next generation of U.S. SLBMs, the D5 Trident II missile, is expected to achieve accuracies comparable to those of current land-based missiles; initial velocity errors will be minimized utilzing a system which measures the submarine's velocity with respect to the ocean floor, and remaining velocity and postiion errors will be reduced still farther by means of a method known as stellar-inertial guidance (SIG), in which position and velocity in reference to the stars is measured toward the end of the boost phase. Current U.S. and Soviet SLBMs already employ more primitive SIG systems.

B. INITIAL POSITION AND TARGETING

In addition to its initial velocity, the missile must be provided with information concerning its initial position, and the position of the target. Errors in the determination of the position of the launch site with respect to the missile's coordinate frame should be relatively small. However, errors in the determination of the location of the target with respect to the launch point cannot be completely ignored. Initial position errors will be essentially the same for all missiles launched from a given field; targeting errors will be essentially the same for all targets in a given area. Thus, both will be a source of systematic bias, rather than random error.

If a cooperative station is available at each point, the relative position of two widely separated points can be determined with extreme accuracy, using such techniques as very-long-baseline interferometry. Indeed, the state of the art is such that even the tiny movements of continental drift can now be directly measured, with considerable accuracy.

However, such cooperative stations are not available for ICBM targeting. It is necessary to utilize satellite ranging techniques to develop targeting maps. A satellite passing over the target can measure the direction of the target with respect to the satellite with accuracy limited by the accuracy of the angular measurement the satellite can make. Estimating the position of the satellite at the time the measurement was taken requires accurate clocks on board the satellite and an accurate model of the satellite's orbit. Orbit models are developed by long observation of satellites, utilizing models of the gravitational, drag, and other forces acting on the satellite.

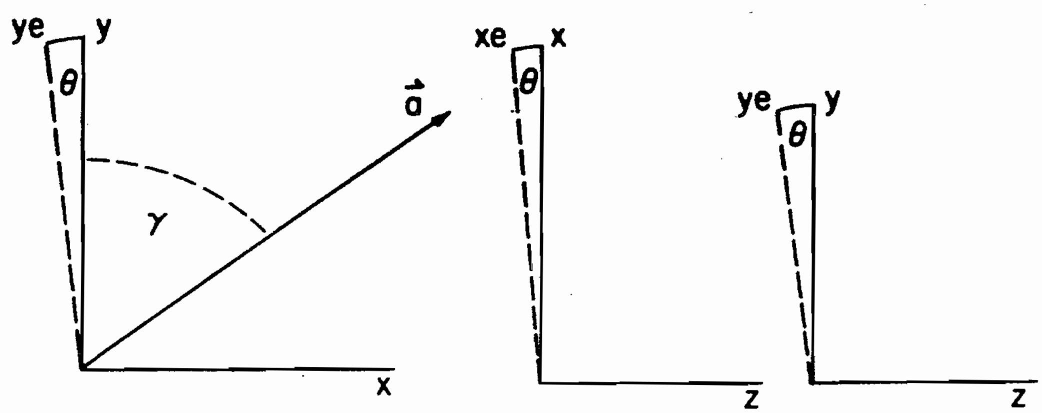
For our hypothetical system, we will assume targeting errors of 20 meters about each axis (Gu8).

C. INITIAL ALIGNMENT

By far the most significant initial condition error is the initial orientation of the guidance system. For the accelerometers to accurately measure the acceleration, their alignment with respect to the reference coordinate frame must be extremely precise. Throughout this section, we will assume that the inertial measurement unit (IMU) of our hypothetical system consists of three accelerometers, one mounted vertically, and two horizontally, with one perpendicular and one parallel to the trajectory plane. The platform is assumed to be stabilized by three single-degree-of-freedom gyroscopes, mounted so that each has its input axis parallel to one of the accelerometers (Gu9).

One possible error of this sort arises from the initial manufacturing of the guidance apparatus; if the rigid mounting of the accelerometers within the gimballed platform is not exactly orthogonal, some errors will be introduced. With state-of-the-art manufacturing techniques, this error should not be large. As an example, let us assume an error of 1 microradian in the orthogonality of each of the two in-plane accelerometers with respect to the out-of-plane accelerometer, and of the two in-plane accelerometers with respect to each other. We will call the vertical direction Y, the horizontal in-plane X, and the horizontal

Fig. 1.3.1



out-of-plane Z. (See Figure 1.3.1). The first figure represents the case of the non-orthogonality between the two accelerometers in the plane of the trajectory. We have chosen the vertical one as the one in error, because the initial vertical alignment we will describe in a moment involves sensing the horizontal, and assuming that the vertical is orthogonal to the two horizontal accelerometers.

From inspection of the figure, we see that:

(1.3.1) $a_y = |a|\cos\gamma$

(1.3.2) $a_x = |a|\sin\gamma$

(1.3.3) $a_{ye} = |a|\cos(\gamma+\theta)$

The error in the sensed acceleration as a result of the non-orthogonality will be:

$$(1.3.4) \quad a_y - a_{ye} = |a|(\cos\gamma - \cos\gamma\cos\theta + \sin\gamma\sin\theta)$$

Making the appropriate small-angle approximations, we find:

$$(1.3.5) \quad a_y - a_{ye} \simeq |a|(\cos\gamma\theta^2/2 + \sin\gamma\theta)$$

For small angles, the first term of the sum will be negligible compared to the second, and we notice that by geometric coincidence, the first two factors of the second term are equal to the other component of the sensed acceleration:

$$(1.3.6) \quad a_y - a_{ye} \simeq |a|\sin\gamma\theta = a_x\theta$$

The case of non-orthogonality of the in-plane accelerometers with respect to the out-of-plane accelerometer is somewhat simpler. From the figure, we see that:

$$(1.3.7) \quad a_{ye} = a_y\cos\theta$$

Making the small angle approximation:

$$(1.3.8) \quad a_{ye} \simeq a_y(1 - \frac{\theta^2}{2}) \simeq a_y$$

Again, the term proportional to the square of theta is negligible, for small theta. Thus, the only significant errors as a result of non-orthogonality arise from the non-orthogonality between the two accelerometers in the plane of the trajectory.

Since the error as a result of accelerometer non-orthogonality is constant throughout the flight, the errors in final position and velocity are simply:

$$(1.3.9) \quad V_y - V_{ye} = \int a_x\theta \, dt = V_x\theta$$

$$(1.3.10) \quad Y - Y_e = \int V_x\theta \, dt = X\theta$$

With our postulated boost phase trajectory as described in Appendix B, and our postulated non-orthogonality of 1 microradian, we find a vertical velocity error of .0067 m/sec, and a vertical position error of .44 meters. Using the error partials of Figure 1.1.6, we find resulting range errors of 15 meters and 3 meters respectively, for a total range error of 18 meters. A misalignment of more than one microradian will of course result in a proportionally larger range error. The error due to position error at thrust termination is much smaller than that due to velocity error; this is essentially always the case, and hence we will ignore thrust-termination position errors for the remainder of this section.

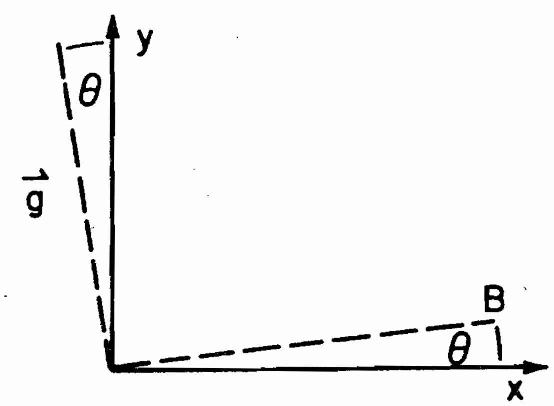
At the launch site, the guidance system must be aligned with respect to the reference coordinate system. Several methods are available; one common method is to use the properties of the guidance system itself to align the system with respect to the earth (Gu10).

To find the local vertical, the gimballed platform is rotated until two of the accelerometers read zero. Since the vertical accelerometer will always measure the force of the silo holding up the missile, the two accelerometers reading zero must be horizontal. There are two major sources of error in this method.

The first is what is known as "accelerometer bias." A given accelerometer usually has some constant bias in measurement, so that when it is experiencing no forces, it will register a force equal to its particular bias. (We will discuss this in more detail in the section on boost-phase errors). State-of-the-art electrostatic accelerometers for inertial navigation have biases on the order of 10^{-5} m/sec^2 (Gu11).

The error in alignment caused by a bias B is shown in Figure

Fig. 1.3.2



1.3.2.

$$(1.3.11) \quad \sin\theta = \frac{B}{|g|} \approx \theta$$

Thus, our postulated accelerometer biases lead to vertical alignment errors of 1 microradian about each axis.

Another source of error in this vertical alignment method arises from anomalies in the earth's gravitational field: the local vertical, defined by the direction of the gravity vector (which is what the accelerometers sense) varies about the true vertical, because of such factors as varying densities of the underlying materials. These variations are constant through time, and so can be mapped accurately; with careful mapping, it should be possible to limit the error from this source to an angle of the order of 1 microradian.

It should be noted that we have greatly over simplified the problem of initial vertical alignment, by assuming a steady-state case with a completely stable platform and time-constant accelerometer biases. In fact, the platform will be slowly shifting, due to fundamental instabilities of the environment, and the biases of the accelerometer will not be constant (indeed, much of the effect of time-constant accelerometer biases can be removed by careful calibration). Thus, the accuracy of the alignment will not be constant, but will decay slowly through time between calibrations.

We will assume an average total error in vertical alignment of the order of 1.5 microradians about each axis. The errors in sensed acceleration can be deduced from the last Figure, and the calculations of the errors due to accelerometer non-orthogonality. For the trajectory described in Appendix B, we find correlated errors in vertical velocity and horizontal in-plane velocity of .0097 m/sec and .0067 m/sec, respectively, resulting in a downrange error of 60 meters. The horizontal out-of-plane velocity error will be .0067 m/sec, resulting in a track error of 6 meters.

Alignment for azimuth can be accomplished by taking advantage of the rotation of the earth. Because of this rotation, precessional torques will have to be applied to the gyroscopes to keep them in a constant local orientation; if the system is rotated until one gyroscope no longer requires such torques to maintain its orientation, the spin axis of that gyroscope must be aligned north-south. Thus, the horizontal azimuth alignment is achieved. This method is known as "gyrocompassing" (Gu12).

Errors in this alignment come from a variety of sources; spurious precession of the gyroscope (referred to as "drift") will cause errors proportional to the drift, and inversely proportional to the horizontal component of the earth's rate at that latitude; the mathematics are identical to those of the vertical alignment errors just discussed, which were proportional to the accelerometer bias and inversely proportional to the magnitude of the gravity vector. Gyroscope drifts can be time-constant or random (gyroscopes, like accelerometers, will be discussed in more detail in section 1.3, dealing with boost phase errors). Constant drifts can be accounted for in the alignment process by careful calibration, but random drifts can still introduce error.

Another source of azimuth alignment error is tilt of the platform on which the gyrocompass is mounted. If the gyrocompass is tilted away from the horizontal, it will measure a fraction of the vertical component of the earth's rate of rotation. In addition, if the platform tilt is not constant, but has some noticeable "tilt rate," this rate will be inseparable from the earth's rotation. Because of the extreme accuracy in azimuth alignment now required for strategic weapon systems, these errors are now becoming significant. Significant tilts and tilt rates can be introduced from the fundamental instability of the environment: as an example, diurnal heating of the ground, with its attendant expansion, can introduce tilts. While the tilt and the tilt rate can be measured by tilt meters, the accuracy of the azimuth alignment cannot be significantly better than the accuracy of the tilt measurement (Gu13).

For our hypothetical system, we will assume an azimuth alignment error of 12 microradians. As with non-orthogonalities and vertical alignment errors, the rotation out of the plane of the horizontal in-plane accelerometer causes an error that is negligible in comparison to that caused by the rotation of the out-of-plane accelerometer toward the plane. Since this error is constant throughout the flight, we find an error in out-of-plane velocity of 0.080 m/sec, resulting in a cross-range miss of 77 meters (Gu14).

D. CALIBRATION

As with any high-precision technology, inertial instruments must be calibrated in order to perform accurately. Because many of the errors of gyroscopes and accelerometers change through time, this calibration cannot simply be done at the factory and then taken for granted from then on. It is necessary to remember, in this connection, that these instruments must be constantly ready for essentially instantaneous use over periods of months or years. This is a stupendous task; as an example, it is easy to imagine the difficulty in manufacturing bearings adequate to insure nearly error-free operation of high-speed gyroscopes for periods of thousands of hours.

Thus, it is necessary to monitor the changes in performance of the system through time, and to realign them periodically. Current Minuteman missiles are aligned and calibrated every 30 days, although Air Force sources indicate that the interval could be somewhat longer without significant degradation in accuracy (Gu15).

One method of calibrating the system is simply to rotate it to different positions, so that measurements by one of the three accelerometers or gyroscopes are compared with identical measurements made by the other two. Indeed, this method is taken to the logical extreme in the Advanced Inertial Reference Sphere (AIRS) being designed for the MX: the system can be tumbled continuously while in the silo, for a continuous self-calibration and alignment capability (Gu16).

1.4 BOOST PHASE ERRORS

Once powered flight begins, errors can arise from several sources. Both gyroscopes and accelerometers have a wide variety of error modes, some time-constant, some dependent on acceleration or rate of turn, some dependent on the square of acceleration, some essentially random. We will briefly discuss a few of these possible error sources here.

A. ACCELEROMETER BIAS

As has been described above (see section 1.1.A), an accelerometer acts by measuring the forces required to support a test mass within the instrument. An accelerometer will measure in error if forces other than those of the calibrated support structure are acting on the test mass, or if the calibration of the measurement of the support forces is incorrect. The first sort of problem will create accelerometer biases; their characteristics will depend on the behavior of the outside force involved.

A time-constant accelerometer bias might result from any constant extraneous force acting on the test mass; an example might be an electrostatic field arising from a charged object in the vicinity of the accelerometer. Many other types of biases arise from sources that behave in a way that is nearly random; as an example, the DC magnetic torquers on the gimbals of the platform inevitably create electromagnetic fields around the inertial instruments: since the current is typically changing through time, and the torquers are moving with respect to the inertial instruments, the extraneous forces on the accelerometers vary unpredictably with time, and can be an important source of error (Gu17).

State-of-the-art electrostatic accelerometers for earth-bound inertial navigation have biases of the order of 10^{-5} m/sec^2 (see above, section 1.3), but the boost phase environment is considerably less hospitable; for our hypothetical system, we will simplify the various accelerometer biases to a single time-constant bias of 4×10^{-5} m/sec^2, acting on each of the three accelerometers. With our postulated 180 second boost phase trajectory, this results in uncorrelated velocity errors of .0072 m/sec in each axis, resulting in a range miss of 43 meters, and a crossrange miss of 7 meters.

B. ACCELEROMETER SCALE FACTOR ERROR

If the measurement of the support force on the test mass (which is the output of the accelerometer) is improperly calibrated, it will result in an error in the sensed acceleration which is proportional to that acceleration, and will result in final velocity errors proportional to the sensed velocity. As noted above, the sensed velocity and the sensed acceleration will not be equal to the actual acceleration and velocity of the missile, because the accelerometers do not measure the force of gravity; thus, the sensed velocity at thrust termination will be roughly 8000 m/sec, although the actual velocity at thrust termination will be only 7200 m/sec. This sensed velocity is divided into a horizontal component of about 6600 m/sec, and a vertical component of about 4520 m/sec. Thus, if we postulate a scale factor error of one part per million about each axis, this would result in a range miss of 38 meters, and no crossrange miss.

C. GYROSCOPE BIAS DRIFT

Like accelerometer errors, spurious precessions, or "drifts" of gyroscopes can arise from a number of sources. Such drifts will cause the platform on which the accelerometers are mounted to rotate, degrading the alignment of the system, and hence introducing error in the accelerometers' measurements of the three components of the specific force. One type of gyroscope drift is constant with time, and is hence called "bias drift." It arises from a constant extraneous torque on the gyro support gimbals. In the inertial navigation system of a submarine or airplane, where the accelerometers must measure accurately over long periods of time, these sources of error are quite significant, and so enormous efforts have been put into reducing the drift of gyroscopes for these low-acceleration environments. Indeed, electrostatic gyroscopes for inertial navigation are reported to have fantastically low drift rates, on the order of 2×10^{-8} radians/hr. However, gyroscope performance in the much more demanding acceleration environment of a boosting ballistic missile is considerably worse. Indeed, given the magnitude of other errors in ballistic missiles, a bias drift rate of 5×10^{-5} radians/hr would be considered acceptable. The errors caused by gyroscope drift will depend on the specific boost phase trajectory; if we assume that each of our gyroscopes has an uncorrelated bias drift of 5×10^{-5} radians/hr, and integrate over the trajectory described in Appendix B, we find burnout velocity errors of .0062 m/sec horizontal, .011 m/sec vertical, and .013 m/sec horizontal out-of-plane, corresponding to a range miss of 43 meters, and a crossrange miss of 12 meters.

D. GYROSCOPE ACCELERATION-DEPENDENT DRIFT

There are many sources of torque in a typical gyroscope that depend on acceleration. As an example, if the center of mass is not exactly centered on the support, a torque will develop proportional to the sensed acceleration. In a typical gyroscope, a center of mass offset of no more than a few angstroms could cause substantial errors. Such offsets can be constant with time, as in the case of error in the fundamental manufacture of the gyro and its support gimbal, or they can change in complex ways, as in the case of unbalances caused by temperature gradients causing non-symmetric expansion or contraction of the instrument. The latter is a significant source of error in many systems of this type.

Another source of acceleration-dependent gyroscope error is the compliance of the instrument under acceleration. Under high accelerations, the structure will typically deflect somewhat, moving the center of mass. Theoretically this movement of the center of mass should be parallel to the acceleration, resulting in no torque, but asymmetries in the support structure or in the properties of the wheel bearings will often cause the motion of the center of mass not to be exactly along the acceleration axis, causing an extraneous torque to develop. Since both the motion of the center of mass and the torque caused by a given unbalance are proportional to the acceleration, the resulting precession will be proportional to the square of the acceleration. The gyroscopes can be arranged to minimize the effect of the actual thrust, but since the effect is proportional to the square of the acceleration, the effect of vibratory accelerations will not be nulled by their constant changes of direction, and this can cause significant errors. Errors of this sort are difficult to predict, since they depend not only on the properties of the gyroscope but on the types of vibrations caused by the rocket, which are more difficult to account for using most calibration techniques.

We will assume that acceleration-dependent drift errors result in a range of error of 75 meters and a track error of 25 meters.

E. GUIDANCE COMPUTATION ERRORS

The accuracy with which the guidance computer can decipher the outputs of the guidance instruments, calculate the necessary post-boost trajectory, and direct the thrust of the rocket accordingly is limited primarily by the speed and complexity of the computer.

Two main types of guidance programs are used in inertial guidance. The first is called implicit guidance: the appropriate trajectory is calculated on the ground beforehand, and the computer guides the rocket thrust to stay as close as possible to that reference trajectory. The advantage of this method is that the on-board guidance computer can be comparatively simple, since most of the calculations are done for it before launch.

The second type of guidance formulation is called explicit guidance: the computer is given only the coordinates of the target and a single parameter (such as the angle of travel at thrust termination) which specifies the trajectory to be flown. It then performs all the calculations necessary, and continuously recalculates the optimal way to reach the appropriate end conditions, given the trajectory flown up to that time. The advantages of this method are improved accuracy, in some cases, and improved retargeting capability.

Recently, the accuracy of the U.S. Minuteman III ballistic missiles was considerably improved by the NS-20 series of improvements in the guidance program. Most of the improvement arose from an improved computational model of the behaviour of the inertial instruments and of the forces the missile would experience after thrust termination.

There is no fundamental limit on the accuracy with which the program can execute the appropriate calculations; given the capabilities of current digital computers, this error source should by now be comparatively small. We will postulate errors of 15 meters in range and 5 meters in track.

F. THRUST TERMINATION ERRORS

As the missile approaches burnout, the rocket is providing thousands of pounds of thrust, which must then go to zero essentially instantaneously when the guidance computer determines that the missile has reached the velocity required to impact on the target. However, the thrust of any real rocket takes some noticeably non-zero amount of time to decay, and does so rather unpredictably. Given the errors caused by relatively small velocity errors at thrust termination, this would be a major error source if it were not given special attention.

Errors due to thrust termination are reduced to a minimum by the addition of a low-thrust "vernier-stage," often called the "post-boost vehicle." This stage will make final trajectory corrections using extremely low thrust, so that the unpredictable elements of thrust decay will be less of a problem. In MIRVed missiles, this stage is responsible for setting each warhead on its separate trajectory. The accuracy of the delivery of each warhead will be marginally worse than the delivery of the last, as the guidance errors will continue to build up through time. However, there is no reason to believe that MIRVed weapons will be fundamentally less accurate than single-warhead weapons, as similar guidance technologies are involved.

It should be noted that the choice of targets for the MIRVs on a given weapon is not completely open. The distance by which the targets may be separated is limited by the extra velocities the post-boost vehicle can impart to the warheads; typically, a post-boost vehicle might have a "footprint" of 500 km by 150 km.

We will assume that thrust termination errors in our hypothetical system cause a range miss of 40 meters, with no track miss.

The mere fact of thrust termination is quite significant. For the computer to send the signal to terminate thrust, all three components of the sensed velocity must have reached their correct values simultaneously; this usually means that the entire system has functioned without major failure up to that point. The only possible failures that can have occurred are a major failure in the computer, or an <u>undetected</u> failure in one or more of the guidance components. Thus, the thrust termination signal is often used for other purposes as well. It might be used to arm the warhead with reasonable assurance that the missile would not go significantly awry from the intended target. It could also cause a simple signal to be sent to command centers on the ground; they would then recognize those missiles that did not send such a signal as failures reasonably early in the flight, and could retarget other missiles for those targets. Since something on the order of 80% of failures will occur by the time of thrust termination, this ability to retarget for those missiles could be quite significant in some attack scenarios.

G. EXTREME COMPLEXITY OF THE SYSTEM

Once again, it should be noted that we have grossly over-simplified the guidance problem. In assuming much of our error to be time-constant or dependent on acceleration in a reasonably straightforward way, we have underestimated the difficulty of the problem, and exaggerated the ease of predicting the error resulting from given subsystem errors. In fact, much of the time-constant and linearly acceleration-dependent errors can be removed with careful pre-launch calibration; often the less predictable errors, arising from unexpected temperature changes, vibration effects, instabilities of the materials, anisoelastic properties of the gyro bearings, etc., will be even more significant in the final error budget of a weapon.

In the main, guidance errors will be random errors, of the sort measured by the CEP. If, when a new system begins flight tests, there are considerable biases attributable to the guidance system, that will be a clear signal that something is wrong, and should be changed. The confidence with which it can be assured that a series of adjustments that have the effect of eliminating the bias over one trajectory will eliminate the bias over other trajectories as well will depend on the degree of understanding of the guidance system and of the particular failure that caused the error; in general, it should be possible to eliminate most significant system-wide guidance errors, given careful testing and calibration.

The reader should note the truly phenomenal accuracy of the instruments we have postulated. The rotation of the azimuth we have assumed, for example, would amount to an error of only a centimeter over a distance of one kilometer. The development of such instruments has required whole new branches of knowledge, including the development of of new materials, detailed models of their stability and behavior, new types of bearings with essentially zero friction and incredibly long life, new advances in the stability of electronics, and highly specialized methods for production, assembly and calibration. One inertial guidance expert described current instruments as "almost unreal." (Gu18). Another, describing the process of designing inertial systems, referred to the "unforgiving art": "Every participant can tell stories of frustration when a technique or design which showed excellent results in test suddenly and uncontrollably goes bad with no apparent explanation...Miscellaneous spurious torques of miniscule size and near infinitesimal changes in structural geometry cause error." (Gu19). Indeed, that any system can navigate a distance of 10,000 kilometers with an error of less than a kilometer, using no outside references whatsoever, is an awesome technological achievement; in that it provides the theoretical possibility of destroying hardened missile silos, it is even more awesome in its implications.

1.5 THE EFFECT OF GRAVITATIONAL VARIATIONS

As was mentioned earlier, the accelerometers of the missile's inertial navigation system cannot measure the force of gravity. This necessitates providing the guidance computer with a model from which to calculate the gravity vector as a function of position, so that it can calculate the missile's real acceleration during the boost phase. In addition, the guidance system must be provided with accurate information about the gravity field the missile will encounter after rocket burnout, in order to calculate the appropriate burnout velocity to reach the target

If the earth were a perfect sphere of uniform density, this problem would be trivial; the magnitude of gravity at any point would be given by Newton's formula:

$$F = \frac{GMm}{r^2} \quad (1.5.1)$$

and it's direction would always be toward the center of the earth.

However, the earth is an irregularly-shaped ellipsoid with constantly varying density. This gives rise to a gravity vector that varies from place to place, in both magnitude and direction (G1). Thus, the gravity a missile experiences over one trajectory will be different from the gravity it experiences over another. If these variations are not predicted sufficiently accurately, they can cause significant impact errors at the target.

Variations of the magnitude of the gravity vector are referred to as "gravity anomalies;" variations in its direction are known as "deflections of the vertical." From these, it is possible to calculate the variations in potential. All these are measured as departures from the gravity that would hold for an earth that was a regular ellipsoid (ellipticity roughly 1/300) with uniform density, referred to as the "reference ellipsoid." To express variations in the potential, the height of the actual equipotential surface above or below that of the reference ellipsoid is calculated; this is referred to as the "geoid height."

In absolute terms, these variations are generally quite small. The root-mean-square value of the gravity anomaly in the continental United States is approximately 17 milligals (one milligal is roughly one millionth of the average acceleration of gravity). In mountainous regions, the anomalies can reach some hundreds of milligals (G2). Typical deflections of the vertical and geoid heights are equivalently small.

Gravity variations are often divided into two general categories: the short wavelength and long wavelength variations. In fact, the variations cover a spectrum with no rigid dividing line, so the division is somewhat arbitrary. The long wavelength variations can extend over many hundreds of miles. Substantial short wavelength variations can occur between measurements only a few miles apart.

As with most forces which are irregular close to their origin, the variations in gravity tend to smooth out with increasing distance from the earth. This is especially true of the short wavelength variations.

For this reason, gravity anomalies will have the largest effect on the missile's acceleration when it is closest to the earth, at the launch site and at the target. Variations in acceleration near the target will have very little time to propagate to significant position errors before the warhead detonates. Variations experienced near the launch region, on the other hand, will propagate over the entire trajectory, causing much larger final impact errors; thus, the need for accurate gravity modeling is most crucial in the neighborhood of the launch site.

A. GRAVITY MODELING

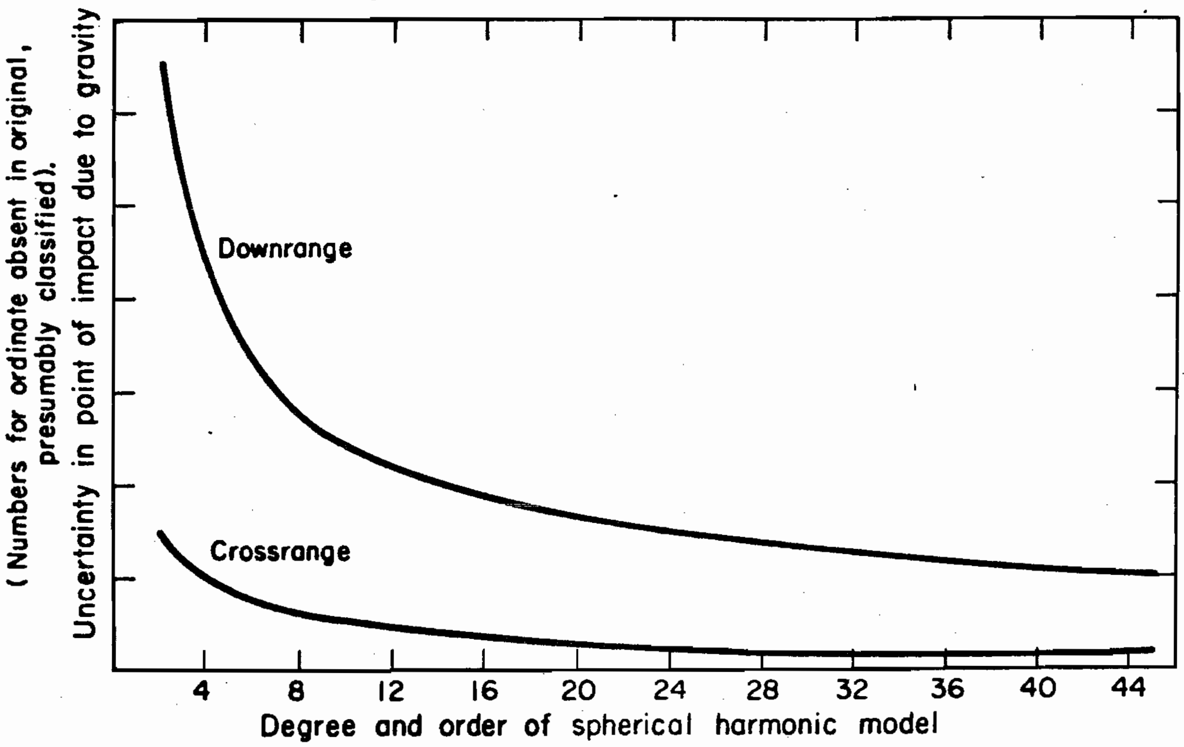
There are many methods currently in use for mathematical modeling of the earth's gravity field. Since the virtue of simplicity is usually in conflict with the virtue of accuracy, each modeling technique has both advantages and disadvantages; we will briefly discuss several of the more important techniques here (G3).

Obviously, the simplest such model would be the Newtonian one, taking the earth to have the gravity that a uniform sphere of the same mass would. This method is too inaccurate for most applications, and it is not used in inertial navigation systems.

Another method, still in wide use in commercially available inertial systems, is the use of the reference ellipsoid. This takes into account the ellipticity of the earth, but ignores the irregular variations of the field. Because of its simplicity, this method is quite useful for many purposes, but it is too inaccurate for many military missions, including the targeting of ICBMs.

The standard method for modeling the field with greater accuracy is to represent the field as the sum of a series of spherical harmonics, essentially a three-dimensional Fourier transform of the field. The accuracy of the representation depends on the number of harmonics included, as well as the accuracy of the coefficients for the included terms of the series. Such a representation is applicable over the entire globe. In theory, a spherical harmonic model can be made arbitrarily accurate by expanding the number of terms (reducing the errors of omission) and measuring the coefficients with high accuracy (reducing the errors of commission). However, to model the variation of the field down to a wavelength of roughly 20 kilometers, as is possible with some other representations, would require including all the terms up to degree and order 2000. This level of information is simply not yet available on a worldwide basis, and in any case, the computing time required would make its use impractical. Figure 1.5.1 shows the impact uncertainty that would be introduced in an ICBM system as a function of number of harmonics included. The uncertainty associated with a spherical harmonic model accurate to degree and order 44, already a model requiring enormous computer capabilities, was judged "excessive in terms of

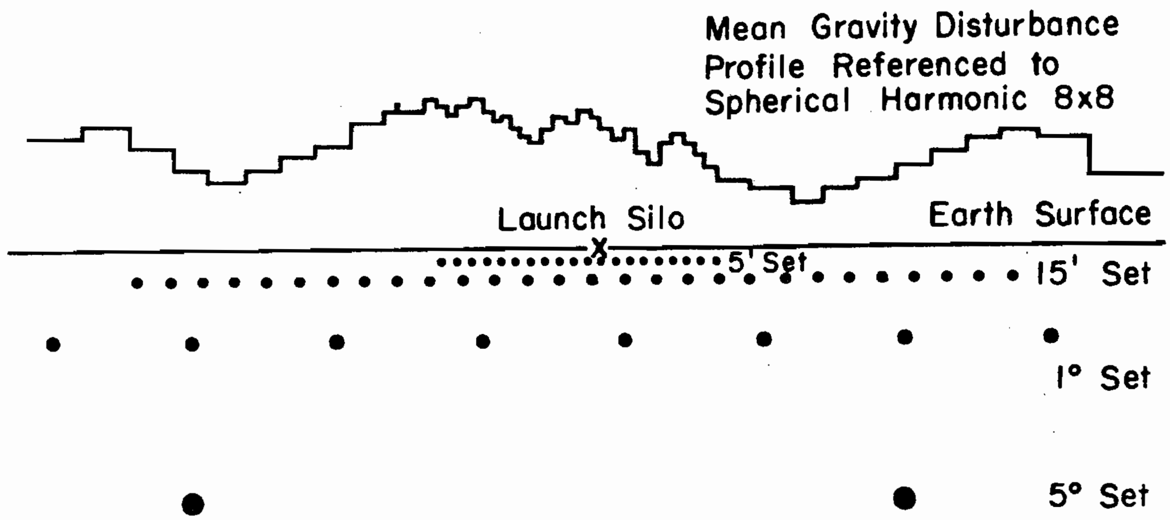
Fig. 1.5.1
Gravity Uncertainty vs. Number of Terms in SHM.



current [1976] weapon system requirements." (G4).

Two methods for modeling the fine detail of the earth's gravity field have been developed by the Defense Mapping Agency Aerospace Center (DMAAC). The first and most widely used, called Point Mass Modeling, represents the gravity field by the field that would be created by a series of point masses of varying magnitude, regularly spaced beneath the earth's surface. The second, called Finite Element Modeling, relies on polynomial representations of the gravity field in a small volume, the "finite element." With either of these methods, details of the gravity field can be modeled with reasonable accuracy (G5). However, adequate information for the development of these gravity models is not available over the entire globe, so accurate models can only be made for limited areas.

Fig. 1.5.2
Point Mass Representation Schematic



The current gravity model for the U.S. Minuteman missiles is a compromise between the global reach of spherical harmonics and the fine-detail accuracy of point mass modeling. A point mass model is used in the neighborhood of the launch region, supplementing a global spherical harmonic model including terms to degree and order 8. The point mass model consists of 4 sets of point masses, with each set extending over a wider area and positioned deeper beneath the ground, as shown in Figure 1.5.2. Figure 1.5.3 shows the geographic extent of the coverage (G6).

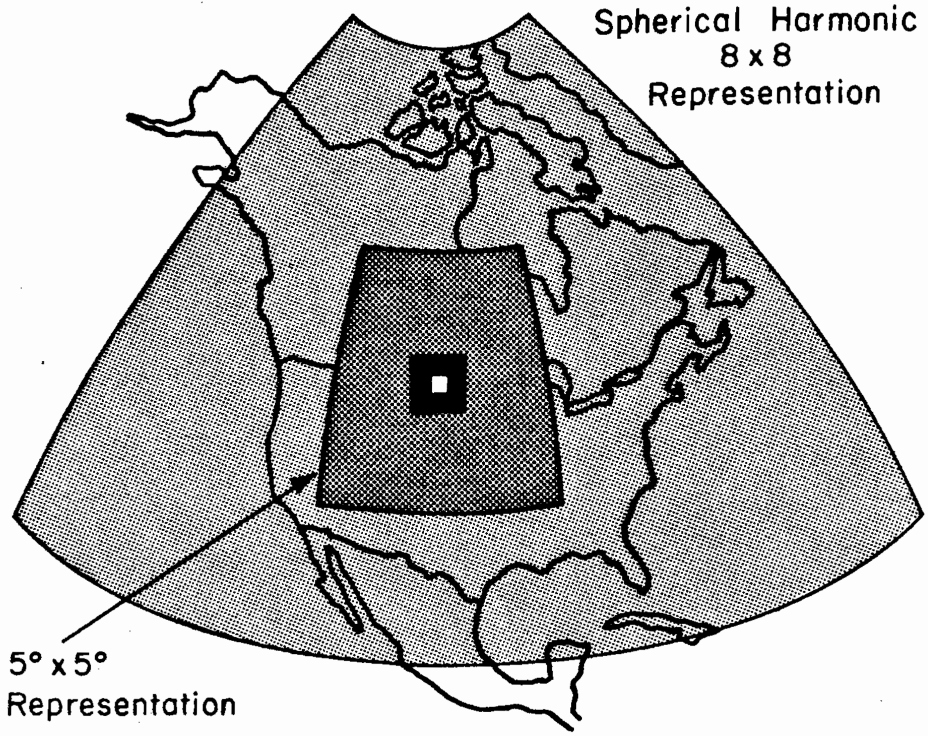
B. GRAVITY DATA

Gravity data for inclusion in this model included both satellite data and ground measurements of the gravity field, of which more than 5 million were on file at the DMAAC gravity library.

Satellite measurements, until very recently, have been incapable of providing fine-grain detail, because of the problem of gravity anomalies smoothing out at altitude, and were used primarily for deriving spherical harmonic coefficients. The method used was essentially to monitor the slow perturbations of the satellite's orbit, and from these to calculate the gravity forces causing the perturbations.

Two new methods are being used, which offer greater promise: the first is satellite-to-satellite tracking, using Doppler radars, which has been used to develop data for modeling with a resolu-

Fig. 1.5.3 LRGM Grid Areas



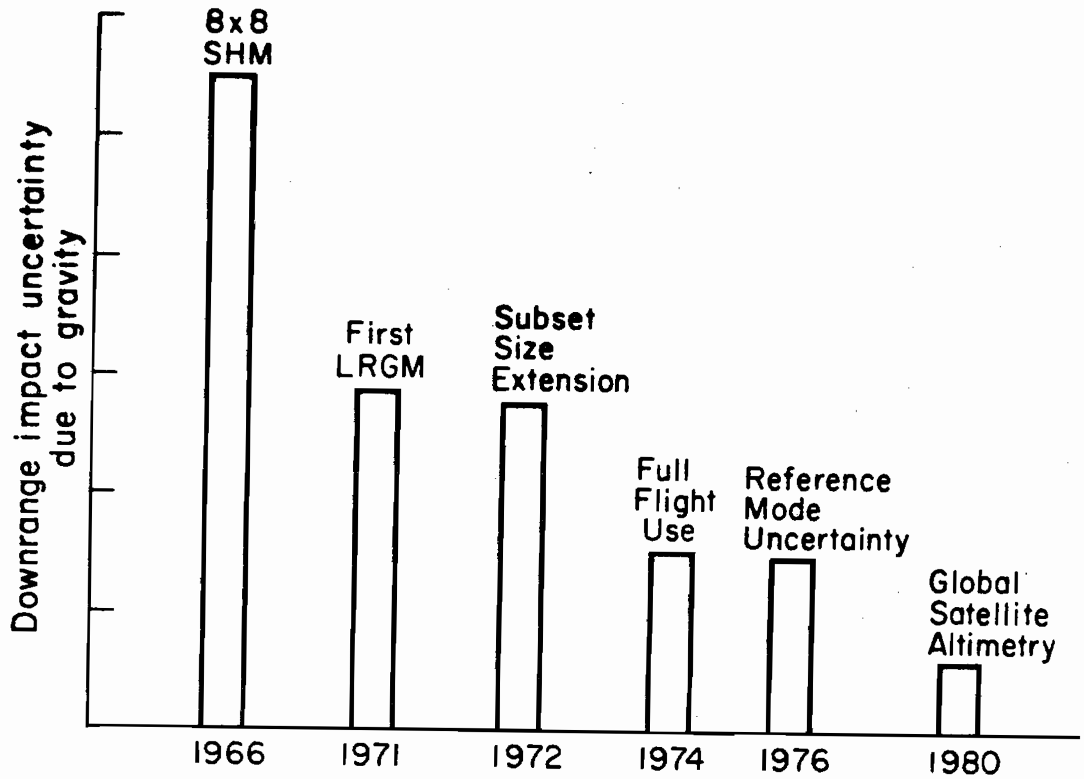
tion of 5 degrees by 5 degrees. The resolution is limited by the height at which the satellites must fly, which is determined by the altitude at which atmospheric drag becomes significant in determining their motion; this resolution probably represents the absolute limits of the method.

Another method is that of satellite radar altimetry. Since liquids will always flow in such a way as to minimize their potential energy, the ocean surface represents an equipotential surface of the earth's gravity field. This height of this potential surface (with respect to an equipotential of the reference ellipsoid) can then be measured with satellite-based radar altimeters, providing detailed information concerning the variations in the gravity field over ocean areas. However, this method cannot provide information on the gravity field over land.

C. THE ACCURACY OF CURRENT MODELS

Figure 1.5.4 shows a chronology of recent improvements in the accuracy of gravity modeling (G7). Of course, the vertical scale is classified, as is most information about the effect of gravity errors on military systems. This makes judgements as to the magnitude of these errors extremely difficult. J. Edward Anderson, a former inertial guidance specialist, has shown that an error in the average value of gravity over the whole flight of 4 parts per million would cause the missile to miss its target by 100 meters (G8). However, most errors will result from constantly changing

Fig. 1.3.4 Chronology of Improvements in Accuracy of Gravity Modeling



variations from the calculated value, not errors in the average value over the entire flight. Errors of the sort Anderson postulates would arise as a result of errors in the determination of the constant GM/a, but the uncertainties in this constant are comparatively small (G9).

Errors that could be introduced by irregular variations are more difficult to calculate, as they are dependent on the profile of the gravity disturbance along each individual flight path. We believe that errors due to inaccuracies in the gravity model are likely to be smaller than, but of the same order of magnitude as guidance error.

This conclusion is supported, among other things, by the combination of Figures 1.5.1 and 1.5.4; if one assumes that the uncertainty in the 1966 8x8 gravity model is equivalent to the theoretical uncertainty of an 8x8 model shown in figure 1.4.1, then it is clear that the uncertainty shown as the state of affairs in 1976 was still of the order of half that judged "excessive" for then-current weapon system requirements. Indeed, the authors state that the gravitational models have developed in parallel with improved guidance and control technology, which they describe as having been necessitated by both operational requirements and the requirement that gravitational uncertainties not completely obscure the results of flight tests of improved guidance and control components; such parallel improvement would not be necessary if gravitational errors were negligible in comparison to guidance errors.

For our hypothetical system, we will postulate gravity errors of 50 meters downrange, and 15 meters crossrange. Since much of the error will arise because of the gravitational effects near the launch site, and because many of the trajectories to be flown will be similar, most of the gravitational error will be in the form of bias, rather than random error.

In systems traveling closer to the earth, specifically submarines and cruise missiles, gravity is often a large source of error, sometimes the single dominant source; indeed, many of the current efforts in development of improved gravity models are motivated by the requirements of cruise missile and submarine systems.

1.6 BALLISTIC REENTRY ERRORS

The last stage of the flight of a ballistic missile is atmospheric reentry. Because the reentry vehicle (or RV) enters the atmosphere with a velocity of several kilometers per second, aerodynamic forces will create the most severe environment the warhead experiences during its flight, heating the RV to temperatures of thousands of degrees centigrade, and subjecting it to tens of gravities of deceleration. As a result, for most of its entry, the RV will be surrounded by a flow-field of ionized plasma, and will appear very like a burning meteor as it streaks across the sky.

The design of vehicles that could survive such environments was one of the foremost challenges in the early days of ballistic missile development. To protect the warhead from the extreme heat of reentry, blunt high-drag RVs were designed, which would slow down quite rapidly as soon as they encountered the upper atmosphere, reducing the thermal load experienced later; large and heavy heat shields abosrbed what heat did build up, protecting the warhead inside the RV.

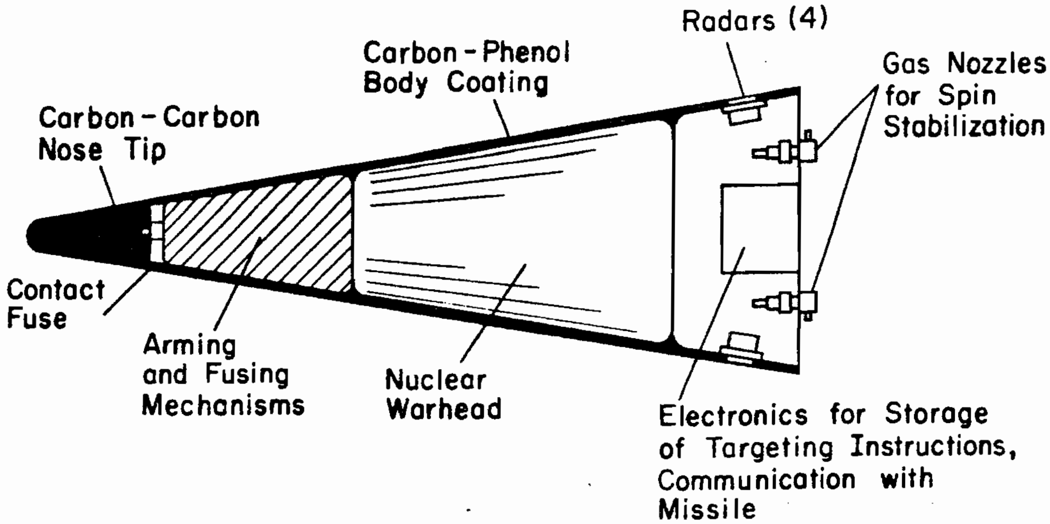
There were two major disadvantages in this approach. First, the heat shields were often quite heavy, reducing the yield of the warhead an RV of given weight could carry; second, the high-drag shapes and comparatively slow travel through the atmosphere meant that the RV was strongly affected by winds and density variations in the atmosphere, greatly reducing its accuracy.

Subsequently, a fundamentally different method was developed, which is used on all modern RVs. Rather than absorbing the heat in a heat shield, these RVs are coated with material that burns away, or ablates, during the course of reentry, carrying the accumulated heat with it as it goes. With this method, much lighter RVs with enormously greater accuracy can be produced. Currently, the thrust of reentry technology is not so much on mere survival through the reentry envoirnment as on the design of ablative materials, especially for the nosetip of the vehicle, which will ablate symmetrically and predictably at extremely high reentry speeds, and under a variety of reentry conditions. A diagram of a typical modern reentry vehicle is shown in Figure 1.6.1.

A. ATMOSPHERIC EFFECTS

Three main forces will operate on the RV during reentry. By far the largest of these will be the aerodynamic drag; second is the force of the earth's gravity. If the RV is not absolutely symmetric with respect to its line of flight, it will also experience some lift; but the lift vector is largely averaged out by spinning the RV, much as a football is stabilized by spin when it is thrown.

Fig. 1.6.1 Typical Modern RV



The deceleration caused by the aerodynamic drag on a reentry vehicle is described by the equation:

(1.6.1) $$A_D = \frac{\rho V^2}{2\beta}$$

Where rho is the density of the atmosphere, a function of height and of atmospheric conditions; beta is the weight-to-drag ratio of the reentry vehicle, which is a design parameter of the RV, but is dependent on the mach number at which the RV is traveling, and which will change slightly as the RV ablates (R1); and V is the vehicle's velocity with respect to the air. The beta is also sometimes referred to as the ballistic coefficient of the vehicle, and is usually measured in pounds/sq. ft.

Peak aerodynamic accelerations will generally be of the order of 50 gravities. The point at which the RV experiences its peak deceleration depends on the beta; RVs with higher betas will experience their peak deceleration later in flight, meaning that they travel through the atmosphere at extremely high speed for longer periods of time. See Figure 1.6.2 (R2).

The force of drag will always act directly opposite to the RV's current velocity; thus, it will not significantly change the direction of the RV's travel. The force of gravity, on the other hand, will bend the RV's path toward the vertical. Systems with low drag shapes (that is, with high betas) will pass through the atmosphere so quickly that this bending is hardly noticeable, and their path is essentially a straight line. See Figure 1.6.3 (R3).

Since the aerodynamic force is related both to the density of the

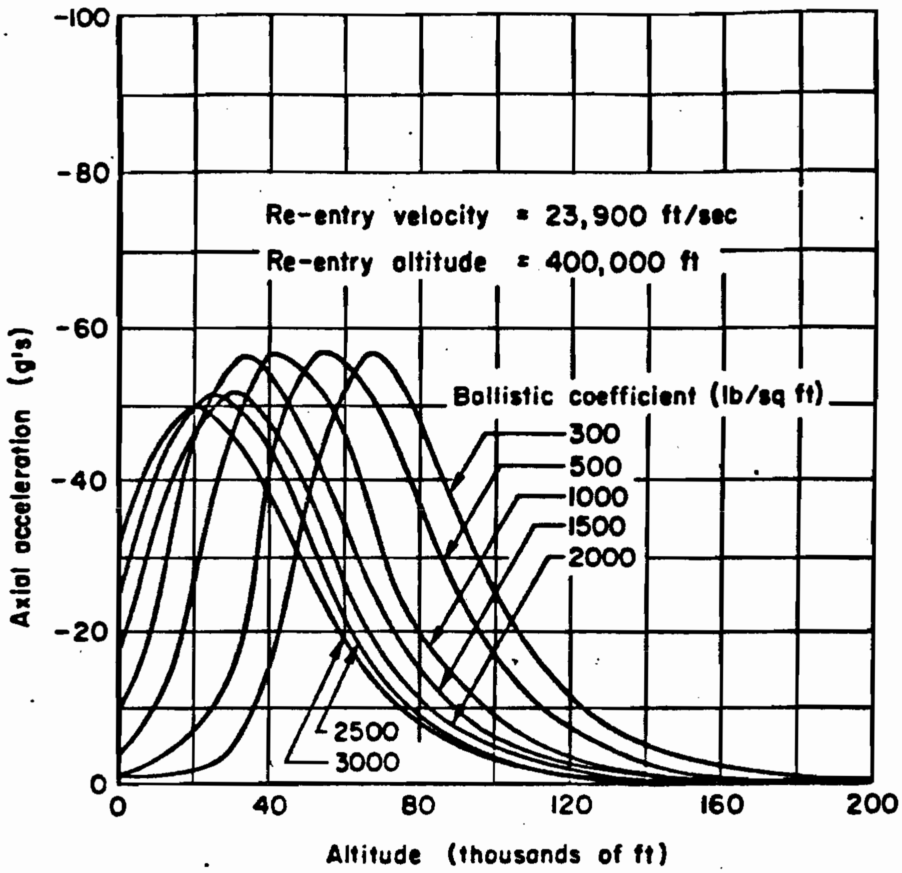


Figure 1.6.2 - Axial Acceleration for Reentry 20° From the Horizontal

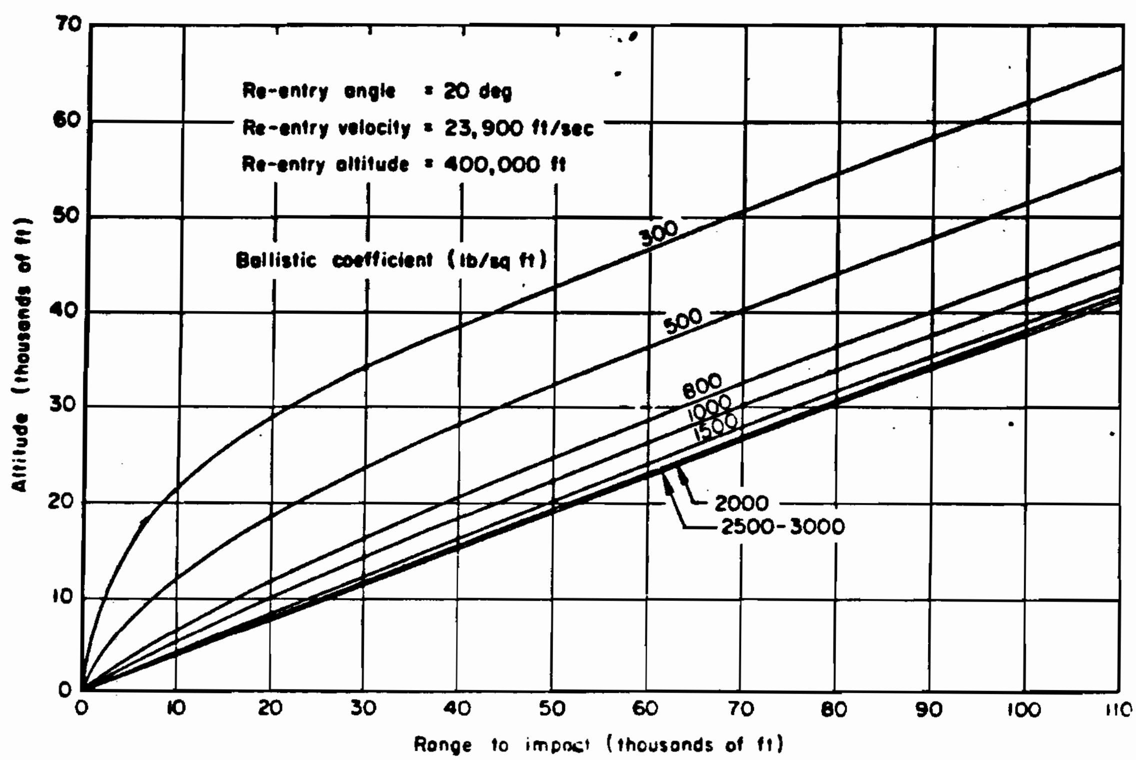


Figure 1.6.3 - Trajectory Contours for Reentry 20° From the Horizontal

atmosphere and to the RV's velocity with respect to the atmosphere, the RV's path will be affected by both atmospheric density variations and winds, both of which change rather unpredictably with the weather. These variations will cause significant impact errors at the target, amounting to some tens or hundreds of meters, depending on the type of RV and the degree of the variation.

Gross atmospheric disturbances, such as rain, snow, hail, etc., will have even more drastic effects; not only do such disturbances substantially change the average density of the atmosphere in the area in which they are taking place, but more importantly, such particles of ice or water vapor will cause the nosetip of the RV to ablate much more quickly and more unpredictably than under normal conditions. This effect can be quite significant; it has been estimated that with current RVs, severe weather conditions can decrease the accuracy of an ICBM by 25% or more, and can even destroy the RV outright in extreme cases (R4). Indeed, one of the main thrusts of reentry vehicle development in the United States is the development of nosetip materials capable of performing adequately in particulate environments. We discuss the effect of variations in ablation of the nosetip later in this section.

In general, reentry vehicles with higher betas will be less affected by winds and density variations, since they pass through the atmosphere more rapidly; they will therefore be more accurate than RVs with lower betas. Figure 1.6.4 represents a very rough estimate of the impact uncertainty attributable to atmospheric variations, for different values of beta. The reader is cautioned that Figure 1.6.4 provides only a very rough order-of-magnitude estimate, and includes only those errors attributable to the weather, not those attributable to variations in the RV itself (R5).

Like guidance errors, errors due to atmospheric variations can be reduced significantly by lofting the reentry vehicle. Figure 1.6.5 shows the atmospheric error versus the reentry angle, measured from the vertical, for an RV with a beta of 1000 lbs/sq.ft. (R6). Figure 1.6.5 is drawn with a constant reentry speed, but in reality, the beneficial effects of lofting the trajectory would be even greater, since RVs on lofted trajectories would also be traveling at greater speeds.

As examples, the betas of reentry vehicles of the early 1970s were of the order of 1000 lbs/sq.ft; Soviet RVs were considerably behind their American counterparts. Currently, the situation is much different: it appears that American RVs now have betas in the realm of 1800-2000 lbs/sq.ft., while the beta of Soviet vehicles is of the order of 1500-1800 (R7).

B. REENTRY VEHICLE VARIATIONS

Fig. 1.6.4 Atmospheric CEP vs. β

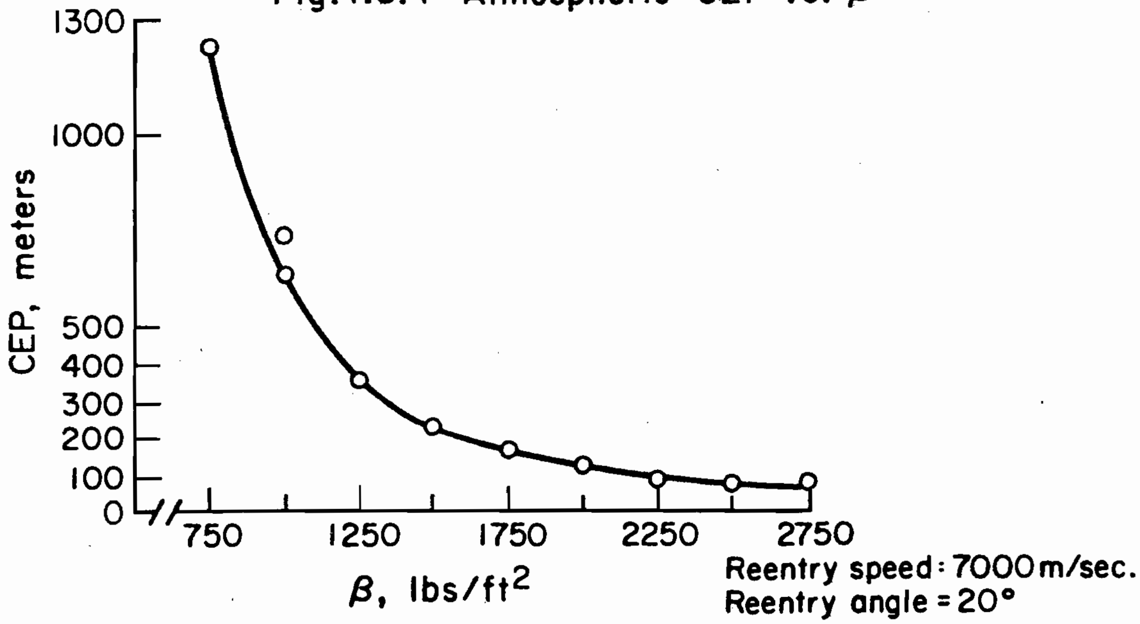
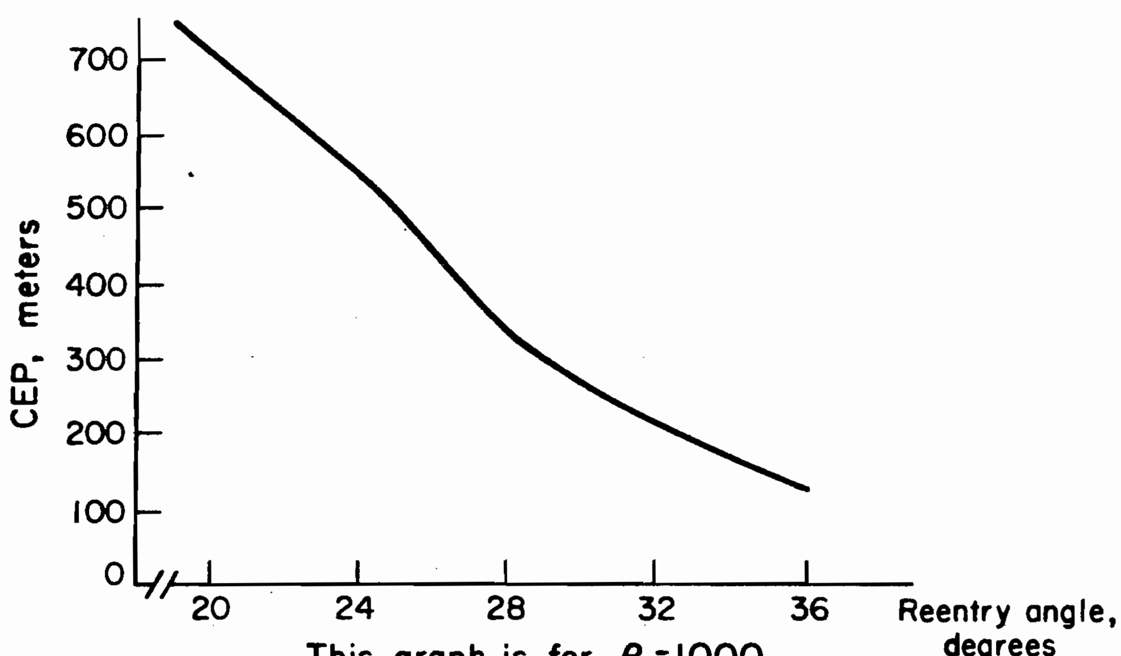


Fig. 1.6.5 Atmospheric CEP vs. Reentry Angle



This graph is for β = 1000, and a reentry speed of 6500 m/sec.

In addition to atmospheric variations, uncertainties in the RV itself can also cause significant errors. Probably the largest of these errors are caused by asymmetries of the RV with respect to the axis of motion. Such asymmetries cause lift, and cause the RV to fly with its tip slightly misaligned from the axis of motion; the angle between these two is the angle of attack.

If the lift vector and the spin vector were both constant, the lift vector would be averaged to exactly zero over the course of the flight. However, the lift vector will often be changing, and there can be torques about the spin axis, causing the spin rate to vary. Either of these effects will result in the lift vector not averaging to zero, which can cause significant errors (R8). For some vehicles, it is even possible for the roll rate to reverse directions, passing through zero; this would obviously cause large errors, as for the instant that the roll rate was zero, the lift vector would not be averaged at all (R9). In addition, since the warhead will be spiraling, in response to the rotating lift vector, the effective area will increase, decreasing the beta; however, this effect should be small, as long as the angle of attack is within reasonable limits (R10).

Asymmetries can arise from several sources. If the manufacturing of the RV is adequate, the effect of such things as mass unbalances or shape asymmetries from the machining of the RV should be very small. Often, RVs will reenter the atmosphere with some non-zero angle of attack, but because of the aerodynamic properties of the RV, this converges to zero (R11).

The most significant asymmetries, then, are those that arise from asymmetrical ablation of the RV nose-tip. While the nose-tip of a typical RV starts out as a hemisphere, by the end of its passage through the atmosphere, the nose-tip will have several deep gouges running outward from a relatively sharp central point, which is often offset from the actual center by as much as 10 or 20% of the original radius of the nose-tip (R12). Such asymmetries can cause the direction the RV is pointed to move off slightly from its direction of motion; this is referred to as an "angle of attack." Nosetip asymmetries of this magnitude can cause angles of attack of .1 to .6 degrees to develop (R13). Other analyses indicate that if an angle of attack were combined with a variation in the spin rate, or worse yet, a momentary stoppage of spin, errors of the order of several hundreds of feet per degree of angle-of-attack might result (R14). Indeed, according to Air Force officials, "asymmetic nosetip ablation is the largest potential dispersion contributor" in current reentry vehicles (R15).

Another important contributor to RV dispersion is the flow transition, which occurs at high altitude. When the RV first enters the atmosphere, the flow of air over the RV is relatively smooth, referred to as a "laminar flow." At a certain point, the flow will become quite turbulent, and will remain so for the rest of

RVs entry. The transition from laminar to turbulent flow tends to occur quite asymmetrically, meaning that the forces on the RV will also be asymmetric until transition is complete: this is also a significant source of dispersion.

From this discussion of reentry, it is clear that several factors determine the accuracy of a reentry vehicle; principal among these are the beta, or weight-to-drag ratio, and the degree to which the ablation of the vehicle is symmetric and predictable under the necessary range of trajectories and weather conditions. Although ingenious methods have been developed for testing RVs in wind tunnels, one such facility utilizing a 50 MW arcjet to simulate the temperature conditions of reentry (R16), in the end, there will be no substitute for extensive flight testing of these vehicles under a wide range of weather conditions. With the limited flight testing now carried out, there will continue to be uncertainty in predicting the performance of RVs, especially under adverse weather conditions (R17).

In tests, only a very small number of warheads is tested at any one time, so that the effect of atmospheric variations will appear as random error in a typical series of tests conducted over a long time period. However, in a large-scale counterforce attack, all the RVs in the first attack wave against a given missile field will be reentering the same area of the atmosphere at the same time, and so their errors due to atmospheric variations will be strongly correlated, appearing as a systematic bias; if one RV is blown off target, it is quite likely that other RVs targeted on the same area will experience similar effects.

For our hypothetical missile system, we postulate reentry errors of 90 meters in range, and 60 meters in track.

C. FUSING OF NUCLEAR WARHEADS

There are several options available for fusing of a nuclear warhead; the preferable option depends on the particular mission. For groundburst weapons, fusing can be accomplished with great simplicity and reliability with either a contact fuse in the nose, or, if there is some probability that the warhead will hit some object (such as a low wall or stake) without touching it with the nose, shock fuses can be designed that will perform quite well.

A more difficult problem arises in the case of airbursts. Here, the fusing requirements for different missions are quite different. The radius at which relatively soft targets will be destroyed is very closely dependent on the height of burst; accuracy in the determination of the RV's distance from the ground is thus very important in countercity attacks, although, as we explained earlier, the accuracy of its horizontal position over the ground is usually not crucial. In the case of hardened missile silos, however, the situation is just the opposite; the dependence of destruct radius on height of burst is extremely weak (R18), while the requirement for horizontal accuracy is tight.

The two preferred methods are path-length fusing, which relies on an accelerometer in the RV integrating over the entire path, and setting off the fuse when the appropriate path length has been traversed, and radar altimetry, which relies on radars mounted within the RV sensing the distance between the RV and the ground. In this particular application, this is more difficult than it might seem, both because of the environments the radars must withstand, and because the RV is spinning, so that any single radar will only be looking directly down a small proportion of the time.

The accuracy of these fusing methods depends, of course, on the quality of the design of the fuse. One of the significant advantages of the Advanced Ballistic Reentry Vehicle was said to be its improved fuse, which integrates both a path-length fuse and a radar altimeter; the radar altimeter fuse of the current Mk. 12A warhead was said to be inaccurate enough to noticeably reduce its kill probability against hardened targets, implying an inaccuracy of several tens of meters (R19). The ABRV fuse was also said to have improved resistance to jamming of the radar.

For our hypothetical system, we will postulate a path-length fuse with an error of 45 meters, resulting in a range error over the target of the order of 40 meters; the error in height of burst will have a negligible effect on the destruct radius.

1.7 OTHER ERRORS

In some articles on missile accuracy that have appeared in the popular press, a wide range of other possible error sources, arising from a variety of geophysical forces, have been postulated. Closer examination leads us to believe that all of these error sources are likely to be of small importance.

An unexpected acceleration of 6.0×10^{-6} m/sec^2 (or about .6 milligals, in the notation used in the discussion of gravity), acting throughout the flight, will cause 10 meters of error at the target. Thus, to be of much significance, an error source must involve a force of about 60 dynes acting on the roughly 100 kilogram warhead. With this lower limit on the size of significant forces in mind, we can proceed to examine some of the sources of error that have been postulated.

Much has been made of the possible errors caused by the RV's travel through the magnetic field near the pole. The most common idea is that the RVs would become charged as a result of charge separation during rocket firing, and that since the charged RVs would be travelling through a field of roughly .5 gauss at several thousand meters per second, they would experience significant magnetic forces. In fact, in order for such forces to be of much consequence, the charge on each warhead would have to be truly enormous, of the order of 10^{13} electrons; indeed, the repulsive forces between individual similarly-charged RVs would be enormously greater than the forces exerted by the earth's magnetic field. We find it very improbable that charges of this sort would build up unintentionally, especially on reentry vehicles, the exteriors of which are composed of graphite-epoxy composites. If such charges did build up, the effect would certainly be noticed in test, and corrected for. AVCO Systems Division, the designers of many U.S. RVs, have studied the effects of the magnetic field in more detail, and come to similar conclusions (O1).

Some calculations indicate that the gravity of the moon and the sun could have a significant effect on the trajectory of the RVs, introducing an error of some tens or hundreds of meters. However, these calculations ignore the fact that such gravitational forces will be largely balanced by the centrifugal force of the missile's motion around the earth-moon or earth-sun center of mass. As a result, the largest tidal variations in gravity caused by the moon are less than .12 milligal; those caused by the sun are approximately half as great (O2). Such variations would not cause significant errors. Even if lunar and solar gravity were significant, they could easily be accounted for, as the motion of the sun and the moon with respect to the earth is very well known.

Similarly, errors such as the motion of the poles, forces caused by solar winds, and high-altitude atmospheric drag in the free-flight phase, should not introduce errors that are significant in terms of the targeting of ballistic missiles.

1.8 OVERALL SYSTEM PERFORMANCE

Figure 1.8.1 is a compilation of the errors we have assumed for our hypothetical missile system:

Fig. 1.8.1

Error Source	Miss Effect Range	Miss Effect Track
Initial Position and Targeting	20	20
Accelerometer Non-orthogonality	15	0
Initial Alignment - Vertical	60	6
Initial Alignment - Azimuth	0	77
Accelerometer Bias	43	7
Accelerometer Scale Factor	38	0
Gyroscope Bias Drift	43	12
Gyroscope Acceleration - Sensitive Drift	75	25
Guidance Computation	15	5
Thrust Termination	40	0
Gravity	50	15
Reentry	90	60
Fusing	40	0
Root-sum-square:	170	105

It should be noted here that the total uncertainty in the downrange direction is considerably larger than that in the crossrange direction; indeed, in systems where the azimuth alignment error was a less dominant factor, the discrepancy would be even greater. As can be seen from the table, azimuth alignment and reentry errors are among the most significant individual errors of this system. We reiterate here that the figures that were chosen for this table were to some extent arbitrary; they are intended to be illustrative, not definitive. In no sense do they represent specific data for any current weapon system.

If we treat the root-sum-square of the errors in the crossrange and downrange directions as being the standard deviations of the system in those directions, it is possible to roughly calculate the CEP. For a normal distribution, the CEP and circular standard deviation are directly proportional (for derivation, see section 2.2):

1.8.1 $CEP = 1.1774\,\sigma$

If the ratio of the standard deviations in the x and y directions is reasonably close to unity, then the following approximation is valid:

1.8.2 $CEP = 1.774\,\frac{(\sigma_x + \sigma_y)}{2} = .5887\,(\sigma_x + \sigma_y)$

The CEP of our hypothetical system is then:

1.8.3 $CEP = .5887\,(170 + 105) = 162\text{ m} \quad .08\text{ n.mi.}$

Thus, the system we have described is an extremely capable one; its CEP of .08 nautical miles is midway between the .1 n. mi. CEP attributed to the Minuteman III with its recent guidance improvements, and the .05 n. mi. CEP predicted for the MX; it is slightly more than half the .13-.15 n. mi. CEP usually attributed to current Soviet missiles. It should be noted that for the sake of simplicity, we have counted all the error sources as random errors, to be included in this estimate of the CEP, rather than as systematic errors. In fact, as we have suggested in earlier sections, errors resulting from gravitational uncertainties, reentry, and targeting will often be systematic, rather than random.

This completes our discussion of the guidance of ICBMs. In the second half of this paper, we provide a rough description of some of the uncertainties that would be encountered in planning a large scale countersilo attack, utilizing some of the information we have developed thus far.

PART TWO: UNCERTAINTIES IN COUNTERSILO ATTACKS

2.1 THE IMPORTANCE OF UNCERTAINTY

Modern nuclear arsenals have the capability to completely devastate any target nation, destroying both its population and its industrial base, and removing completely its capacity to function as a modern nation-state. For this reason, any use of nuclear weapons would represent a gamble on a scale completely unprecedented in human history; the survival of whole civilizations would hang in the the balance. Thus the importance of uncertainty: such gambles are not made without extremely high confidence in the outcome. Any uncertainty will be a powerful deterrent to a nuclear strike.

In this regard, one might say that there are two types of uncertainty. First, there is the political uncertainty in the mind of the leaders contemplating an attack: even if their expert advisers tell them that the attack is technically possible, they may question the experts themselves; they cannot have complete certainty that all of the human elements that must necessarily be involved in such a strike will perform as expected; and most important of all, the political calculations of the gains to be had from a strike are crucially dependent on the response of the defender when thousands of megaton-range nuclear weapons begin to detonate on his soil; this last is something that simply cannot be guessed ahead of time. Regardless of the technical performance of the systems involved in the strike, such uncertainties can never be completely resolved.

The second type of uncertainty, the technical uncertainty, is of a much more limited kind; it is merely the uncertainty in the technical outcome of the attack, largely a result of the limits inherent in the process of peacetime testing of weapon systems.

The first type of uncertainty is an imponderable, in our view, having more to do with psychology than with the technical characteristics of the weapons involved; for this reason, we will concentrate on the second, purely technical sort of uncertainty. While more limited than the political uncertainty, the technical uncertainties in any strike would be far greater than is commonly perceived in the United States.

Former Secretary of Defense James Schlesinger stressed this point in recent Senate testimony: "perhaps the dominant element in measuring nuclear forces against each other is the unknown and immeasurable element of the possibility of major technical failure. It would tend to dominate any outcome." (K1). Thus, the question for the planner of even the most limited strategic strike must always be not only "What is the expected outcome?" but also "What is the worst plausible outcome?" Since the latter question must be a fundamental issue in considering a strike, it should also be considered in assessing the probability of a strike by the other side; it is crucially important to assess the possibilities of failure.

Unfortunately, this is not done in most public assessments of the vulnerability of U.S. ICBM silos; in general, the results of an idealized attack are considered, while the uncertainties are ignored (K2). In this portion of the paper, we attempt to rectify this situation by presenting a very rough quantification of some of the technical uncertainties involved, and the effect they might have on the outcome of an attack.

We begin by describing the methods used in most calculations of ICBM vulnerability, in order to clarify how given uncertainties enter the calculations. We then briefly discuss the effects of bias, fratricide, uncertainties in the performance of the weapons, and uncertainties in the hardness of the silos.

After assessing the effect of these uncertainties on the current situation, we devote a section to an examination of future trends in weapons technology, and assess the effect of the same uncertainties on an attack involving a possible future generation of Soviet weapons.

2.2 SILO RESPONSE TO NUCLEAR EFFECTS: THE PROBABILITY OF KILL

Nuclear weapons have a wide range of destructive effects (K3), any of which may damage or destroy an ICBM silo in the vicinity of a nuclear explosion (K4). At the instant of the detonation, the weapon gives off an enormous burst of radiation, mostly extremely high-energy electromagnetic waves such as gamma rays and X-rays, accompanied by some neutrons. Most of this initial pulse of radiation is absorbed by the surrounding air, heating it to millions of degrees, hotter than the surface of the sun.

Since most of the energy of the nuclear reaction is released in the first few nanoseconds (billionths of a second), the heated air does not have time to expand, and initial pressures reach millions of pounds per square inch (psi). This extremely hot, pressurized air then expands rapidly in a blast wave, radiating energy and cooling as it does so. This shock wave will cause extreme air turbulence and winds of hundreds or thousands of miles per hour. The expanding sphere of radiating gas is called the "fireball"; it will begin to rise, since it is hotter than the surrounding air, creating the characteristic "mushroom cloud".

The frequency of the electromagnetic radiation emitted by the air decreases as the air cools; following the initial pulse of X-rays and gamma rays, there will be ultraviolet, and then as the fireball expands outwards, the radiation will fall into the visible range, and finally into the infrared and below.

If the explosion occurs on or near the ground, it will dig a substantial crater, sucking dust and debris into the rising cloud. If this occurs, much of the vaporized nuclear material from the weapon will coalesce onto these particles as it cools; the particles will then fall back to the earth, creating lethal local "fallout." If the explosion is too high to suck up material from the earth, this radioactive nuclear debris will be lifted into the upper atmosphere and distributed over much of the world, thus minimizing its local effect. In addition, if the blast occurs near the ground, the blast wave will propagate into the earth, creating "groundshock."

The initial burst of X-rays will create a large body of ionized gas; if the symmetry of this ionization is disturbed (as, for instance, if the explosion takes place on the ground, making the ionization distribution hemispherical rather than spherical), it will constitute an effective current flow that creates strong electric and magnetic fields, in a phenomenon known as the electromagnetic pulse (EMP). Since the X-rays are mainly given off in the first few nanoseconds, the rise time of this pulse is extremely short, making it difficult to protect electronic circuits from its effects.

Current ICBMs are stored in underground concrete structures known as "silos," which are "hardened" against these effects, so that an ICBM can survive nuclear detonations at much closer range than can the structures of a city. However, if the detonation occurs close enough to the silo, any of these effects might damage or destroy the missile in its silo. Usually, the most important "kill mechanism" is considered to be the rupturing of the silo cover by the high overpressures in the shock wave. Second on the list, perhaps, is cratering: for nearly all conceivable silo designs, if the silo is within the radius of the crater dug by the explosion, the missile will be destroyed. In addition, burial by the ejecta of the crater may prevent the missile from launching; strong groundshock may damage or destroy sensitive equipment within the silo or the missile; and lastly, radiation and EMP could affect sensitive electronics.

Silo response to these effects is highly classified; however, Air Force officials have stated that an effort is made to design the silos such that their vulnerability to these effects is not greater than their vulnerability to the overpressure of the shock wave. Thus, most unclassified calculations of the vulnerability of ICBM silos are based on the silos' response to a shock wave. We will also follow this convention; given the understandable classification of data concerning the design of silos, there is no other way to make detailed calculations of vulnerability.

However, it should be noted that even if this design effort has been reasonably successful, some of these effects will vary greatly depending on unpredictable factors. As an example, the propagation of the groundshock depends very strongly on the level of the water table in the vicinity of the silo, which is impossible to predict prior to the attack.

While exact figures are classified, it is usually reported that current U.S. silos are capable of withstanding shockwaves of up to 2000 psi of overpressure (K5). In fact, the situation is infinitely more complex than this simple figure would seem to indicate; the hardness of silos actually covers a broad range, from around 1500 psi to about 2500 psi. In addition, a silo's response to a shock wave is determined not only by the shock wave's strength, but also by its duration, which varies for warheads of different yields. A method of calculating target vulnerability has been developed by the Defense Intelligence Agency (DIA), which attempts to take this effect into account; the DIA method also uses a lognormal model of the probability that a silo will be destroyed at a given radius from the explosion (K6).

In this paper, we use a conceptually clearer but less realistic model, which models the vulnerability of the silo using simply the maximum overpressure it can withstand, neglecting the effect of pulse duration, and assuming a "cookie cutter" damage function, meaning that within a given radius of the explosion, a silo would certainly be destroyed, while outside that radius it would certainly not be destroyed. For the cases of interest, the results of the two methods differ by only a few percent, with our method slightly overestimating the probability that a silo will be destroyed (K7).

In examining the following derivation of the standard equations for calculating the kill probability of a warhead against a silo, the reader should recall our previous statements concerning the uncertainties of these calculations. In developing the standard formulas, we will follow the standard convention of quoting their results to two significant figures, but as is argued in subsequent sections, this grossly and misleadingly overstates the precision with which the outcome of an attack can be predicted.

In order to calculate the probability that a warhead of given yield, accuracy, and reliability will destroy a silo of given hardness, it is usually assumed that the warheads will tend to fall in a circular Gaussian (or normal) distribution (K8). In fact, as we saw in the first half of this paper, the distribution will be elliptical, with the downrange errors often twice to three times as large as the crossrange errors; however, this changes the calculated probability that a given warhead will destroy a given silo by only a few per cent (K9). Given this assumption, the probability of a warhead falling within an infinitesimal area is given by:

$$(2.2.1) \quad \frac{1}{2\pi\sigma^2} e^{-(\frac{r^2}{2\sigma^2})} r \, dr \, d\theta$$

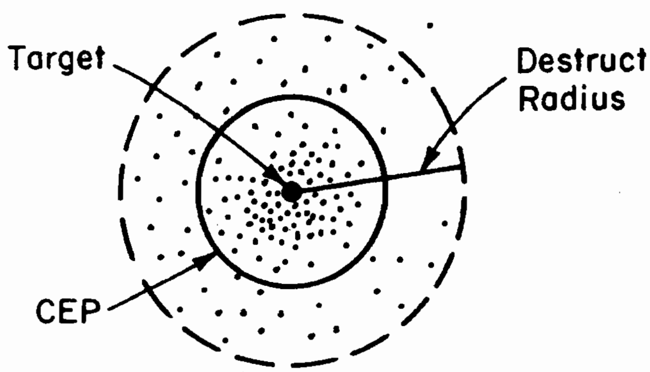
Where sigma is the standard deviation of the distribution, a function of the precision of the weapon system, and r is the radius from the center of the impact distribution, i.e., the average point of impact. To calculate the kill probability, it is necessary to integrate this equation over the area within which a detonation would destroy the silo, consisting of a circle of radius R, centered at the silo, where R is the destruct radius. See Figure 2.2.1.

Assuming, for the moment, that the center of the impact distribution coincides with the target, the appropriate limits of integration are as follows:

$$(2.2.2) \quad \frac{1}{2\pi\sigma^2} \int_0^{2\pi} \int_0^{R} e^{-(\frac{r^2}{2\sigma^2})} r \, dr \, d\theta$$

Since the distribution is symmetric, the integration with respect to theta is trivial, yielding:

Fig. 2.2.1



(2.2.3) $$\frac{1}{\sigma^2}\int_0^R e^{-\left(\frac{r^2}{2\sigma^2}\right)} r\,dr$$

The next integration is simplified by setting:

(2.2.4) $$Q = \frac{r^2}{2\sigma^2}, \qquad dQ = \frac{rdr}{\sigma^2}$$

which gives:

(2.2.5) $$\int_0^{R^2/2\sigma^2} e^{-Q}\,dQ = 1 - e^{-(R^2/2\sigma^2)}$$

This relates the kill probability to the standard deviation of the impact distribution, and to the destruct radius. It would be more useful to relate it to actual weapon system parameters, such as the warhead yield, the hardness of the target, and the CEP of the weapon. The first two of these will determine the destruct radius; the last is proportional to the standard deviation.

Formulas relating the maximum shockwave overpressure to the yield of the weapon and the distance from the detonation are given in reference K3; a simplified formula for the effect of a groundburst, applicable for high overpressures, is:

(2.2.6) $$H = \frac{16.4Y}{R^3}$$

Where H is the maximum overpressure, in psi, R is the distance from the detonation, in nautical miles, and Y is the yield of the weapon, in megatons (K10). Solving for R gives:

$$(2.2.7) \quad R = \frac{2.54Y^{1/3}}{H^{1/3}}$$

This is the destruct radius for a warhead of given yield and a silo of given hardness.

The relationship between the CEP and sigma, the standard deviation of the impact distribution, can be derived from the definition of the CEP. Since the CEP is the radius of a circle within which 50% of the RVs will fall, integrating the probability of a warhead falling in any given infinitesimal area (equation 2.2.1) over the circle defined by the CEP should yield 50%:

$$(2.2.8) \quad .5 = \frac{1}{2\pi\sigma^2}\int_0^{2\pi}\int_0^{CEP} re^{-r^2/2\sigma^2}\,drd\theta$$

$$(2.2.9) \quad .5 = 1 - e^{-(CEP)^2/2\sigma^2}$$

Simplifying and solving for the CEP yields the relationship between CEP and the standard deviation of the distribution:

$$(2.2.10) \quad CEP = 1.1774\sigma$$

If we now plug equations (2.2.7) and (2.2.10) into equation (2.2.5), we find:

$$(2.2.11) \quad P_K = 1 - e^{-\left[\left(\frac{2.54Y^{1/3}}{H^{1/3}}\right)^2/2(.8493\ CEP)^2\right]}$$

Simplifying gives the "probability of kill" for a given warhead against a given silo:

$$(2.2.12) \quad P_K = 1 - e^{-\left(\frac{Y^{2/3}}{.22H^{2/3}CEP^2}\right)}$$

In this equation, the CEP is also in nautical miles, to cancel the units of the destruct radius.

Note that the kill probability is related to the 2/3 power of the yield of the weapon and the hardness of the silo, but to the square of the CEP. Thus, an attack on hardened silos is much more sensitive to the accuracy of the weapon than to its yield or the hardness of the silo; a factor of two increase in the accuracy would have the same effect as increasing the yield of the weapon by a factor of eight, and would completely counterbalance the effect of increasing the silo hardness by a factor of eight.

While a silo can withstand shock waves of up to 2000 psi, most buildings will be severely damaged by shock waves in the neighborhood of 5 psi; this is why cities are often referred to as "soft" targets. A one megaton weapon, similar to many in the Soviet arsenal, would create overpressures of 5 psi at ranges of 4 km. Thus, while an accurate weapon is critical for attacking missile silos, it is not really necessary for attacking soft targets such as cities, or most military and industrial targets.

The kill probability given above assumes that the warhead will arrive at the target and function properly; in reality, it is necessary to factor in the reliability of the weapon system, a unitless constant usually between 50 and 90%.

$$\text{(2.2.13)} \quad OPK = \rho(P_k)$$

This gives the "overall probability of kill," the probability that a single warhead of given reliability, accuracy, and yield will destroy a silo of given hardness, assuming that both the weapon and the silo behave as expected, and that the impact probability distribution is centered at the target.

However, many attacks will involve more than one warhead attacking a single target. What is the probability that n warheads will destroy a given silo? If all n warheads come from a single missile, the probability is:

$$\text{(2.2.14)} \quad OPK(n) = \rho(1-(1-P_k)^n)$$

In this case, the probability of destroying the target could never be higher than the reliabiliity of the missile. A superior tactic for the attacker would be to target several warheads from different missiles on the target. In this case, the probability of destroying the target would be:

$$\text{(2.2.15)} \quad OPK(n) = 1-(1-\rho P_k)^n$$

This gives a result that approaches arbitrarily close to 100% as more and more warheads are fired at the target.

Both of these equations assume that the detonation of a warhead does not affect subsequent RVs; this is not true, as nuclear effects can seriously damage or deflect other RVs entering the atmosphere in the neighborhood of the explosion. This phenomenon, known as "fratricide," is discussed in section 2.4.

For example, this formula gives a probability of 60% that a single warhead from a Soviet SS-18 Mod 4, having a yield of .5 megatons, an accuracy of .14 nautical miles, and a perfect reliability would destroy a Minuteman silo hardened to 2000 psi. For a warhead from the SS-19 Mod 3, with a yield of .55 megatons, and the same accuracy and reliability, the figure is 63% (K11). For the remainder of this paper, we will refer only to the slightly higher-yield SS-19, to simplify the calculations. The reader should keep in mind that this formula overestimates the probability of damage, both by assuming a circular impact distribution rather than an elliptical one, and by assuming a "cookie cutter" damage function with a lethal radius that neglects the effect of pulse duration; thus, the kill probabilities for given parameters that would result from using a slightly more realistic model of the situation would be several percent lower than those we cite.

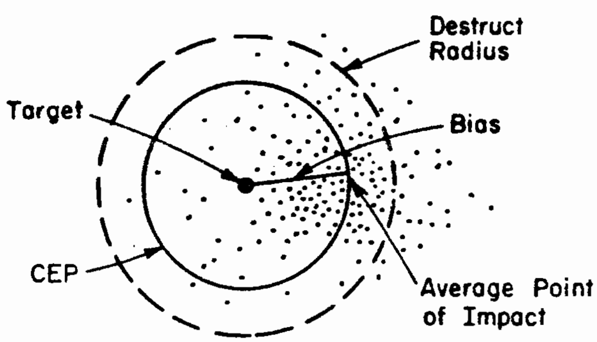
These equations give a probability of 86% that two statistically independent SS-19 warheads would destroy a Minuteman silo, assuming that both warheads are 100% reliable. This is the sort of alarming figure that has been given wide circulation. However, assuming a more realistic reliability of 75% (K12) drops this figure to 72%, which agrees well with the 70-75% estimate currently being cited by the U.S. Joint Chiefs of Staff (K13). This, then, is the result of the "standard" calculations, as applied to the current situation; in the next several sections, we examine some of the uncertainties that are ignored by these calculations.

2.3 SYSTEMATIC BIAS

In the discussion so far, we have assumed that the center of the impact distribution is coincident with the target, that is, that all of the errors of the system will be random errors, so that the average impact point is precisely on target. In fact, as with most technical systems, the possible error sources of an ICBM are a complex combination of random errors and systematic errors, so that the center of the impact distribution is generally offset from the target by some distance, known as the bias. The significance of bias has been the subject of considerable debate in the popular literature in the last few years (B1).

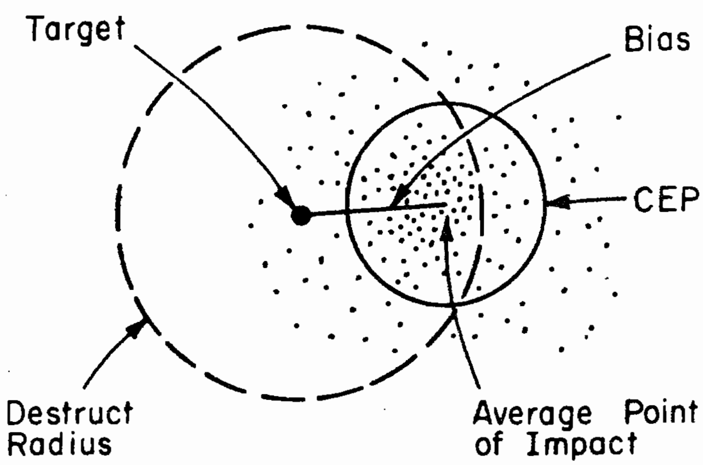
Much of this popular debate has been somewhat confused; part of the problem is that much of the relevant information is classified. In addition, there are two competing definitions of CEP and bias. The first is the definition generally used by the Air Force: this defines the CEP as the radius of the circle, centered on the target, which contains half of the impact points, and the bias as the distance from the target to the average point

Fig. 2.3.1



of impact. See Figure 2.3.1. The second definition also defines the bias as the distance between the average point of impact and the target, but uses the average impact point, rather than the target, as the center of the CEP circle. See Figure 2.3.2. As can be seen from the figures, the first definition of the CEP includes the bias, in some sense, providing a real measure of the accuracy of the system, that is to say, how far from the target the warheads will land. The second definition of the CEP, on the other hand, measures only the precision of the weapon system, or how far the warheads are scattered from the average point of impact; with this definition, both the bias and the CEP are required to determine how close to the target the warheads would land. At first glance, it would seem that the first definition would be more useful; however, in the first definition, the CEP no longer uniquely describes a normal circular distribution, so the relationship between CEP and the standard deviation of the distribution no longer holds; without knowing the bias, it is

Fig. 2.3.2

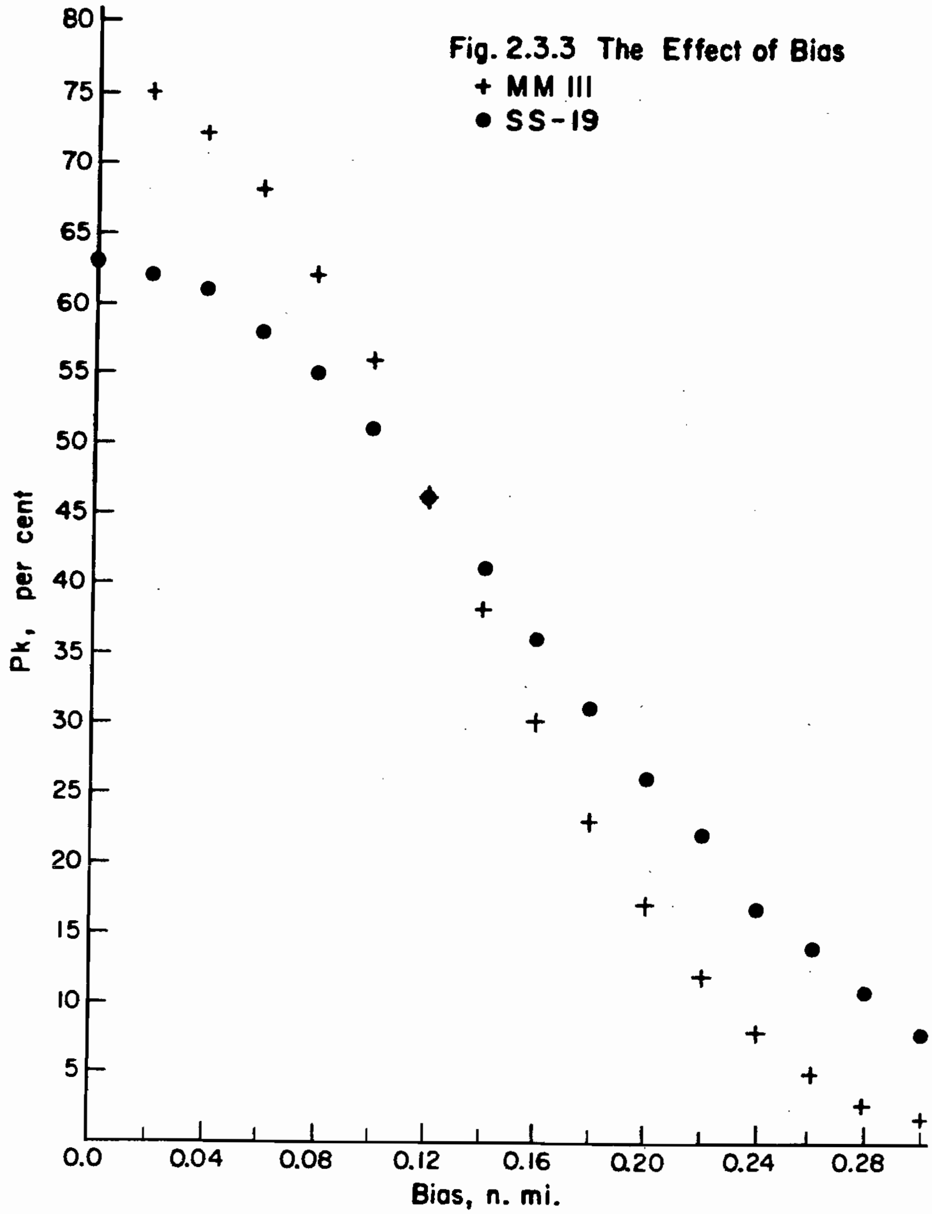


impossible to calculate the standard deviation from this definition of the CEP, so it is impossible to perform the necessary integrations to calculate the probability of kill.

The second definition of the CEP retains the same relationship between the CEP and the impact distribution described in the last section, and so can be used more easily to calculate the kill probability for a given value of the bias. One possible reason for the continued appearance of the first definition is simply that given an impact distribution containing only twenty or thirty impact points, and biases that are not large enough to dominate over the CEP, it is difficult to statistically separate the two types of error (B2).

Although both these definitions refer to a single target with a very large number of warheads landing around it, this will not be the case in a real attack; instead, there will be a large number of similar targets, with perhaps two warheads falling near each one. If the targets are assumed to be essentially the same, then the situation is statistically identical: the CEP and the bias are then defined by taking a large number of targets together. For example, if, in an attack on 1000 targets, the warheads, on the average, fall 50 meters short of their target, then the weapons are said to have a bias of 50 meters, just as would be the case with an attack on one target.

To calculate the effect of a bias of given magnitude, it is necessary to integrate the distribution over the circle that is defined by the destruct radius of the weapon, as we did in section 2.2. However, as can be seen from Figure 2.3.2, if the impact distribution is offset from the target, the area over which it is necessary to integrate is no longer symmetric with respect to the center of the impact distribution; in this case, no single analytical expression for the probability of kill is possible, as the equations are not generally integrable. We have solved the problem numerically with the aid of a computer. Figure 2.3.3 shows the effect of various biases on two modern weapon systems, the Soviet SS-19, and the American Minuteman III



(B3).

From Figure 2.3.3, it is clear that if it can be determined with high confidence that the systematic bias will be less than .05 nautical miles, then the effect of bias on the kill probability of the weapons of interest will be insignificant. Otherwise, bias could cause significant degradations in the kill probability of the weapon. Thus, the question becomes one of whether the magnitude of systematic errors that would appear in wartime can be bounded within this limit.

Most of the error sources of modern ballistic missiles can have both systematic and random components. For example, a given accelerometer error might vary randomly from one missile to another, or all of the accelerometers of that type might have similar errors. This type of systematic error, arising from such sources within the missile itself (such as the guidance components and program) should be possible to eliminate, or at least reduce to tolerable levels, given rigorous calibration and testing.

Systematic errors that arise outside the missile present a greater problem. As we discussed in the first half of this paper, gravity anomaly errors, errors due to atmospheric variations, and targeting errors will all act largely as systematic errors in a countersilo strike, and their effect will change from one trajectory to another, making them more difficult to eliminate by testing over a small number of trajectories.

These problems have been described by Dr. Richard Garwin, a physicist with some experience with the U.S. ICBM testing program (B4).

"In every ICBM you have an inertial package. Accelerometers and gyros and things like that are mounted in your missile. You've got to fire your missiles from operational silos to points in your enemy's country. Now, obviously you've never done this before and so you have to base your calculations on test shots---in our case from Vandenberg to Kwajalein lagoon, that is, east to west; and in the Russian's case from northern European Russia to Kamchatka in the northern Pacific, west to east. Judging from how far each test shot falls from the target, you adjust your accelerometer or your gyro model for the inaccuracy, until in the end your test shots are landing in the prescribed area. But every time you fire a new-model missile over the same range, or the same missile over a slightly different range, the bias changes. Sometimes it is greater, sometimes it is smaller, but it never has been calculated beforehand.

"So you go back to readjusting the gyros and so on, to try and eliminate the novel bias. But if we were firing operationally, both we and the Russians would be firing over a new range in an untried direction---north. And a whole new set of random factors would come into play---anomalies in the earth's gravitational field, varying densities of the upper atmosphere or unknown wind velocities. They may adjust and readjust in testing and eventually they might feel sure that they have eliminated the bias. But they can never be absolutely certain. We certainly cannot be, and although we are less informed about the Russian ICBM test program than our own, there is no reason to suspect that they are any more successful than we are at dealing with the problem. If you cannot be sure that you would hit the enemy silos, there is no point in trying---because the idea is that one side could wipe out the other's missiles before they are launched in a first strike."

Garwin was even more emphatic in another discussion (B5):

"When you try a new guidance system on your old missiles over the same range, and the missile lands two thousand feet from where it should have landed, and that is far beyond the sum of the inaccuracies of the guidance...You correct for that error, and if you are naive, you say there is no more bias. The fact is that generation after generation of innovations have turned up biases of this sort. Sometimes it gets even worse after adjustment. You may look at a problem and change something you think is causing it, and then get worse answers than before, so that you have to go back and undo the correction that you've made..."

Specific data on bias and CEP in U.S. test experience are classified, so Garwin did not give an estimate of the size of biases in current U.S. testing. However, he has said that biases are large enough to have a "significant" effect on the outcome of an attack. As we said previously, in order to have a substantial effect on current weapon systems, the bias would have to be of the order of .05 nautical miles or larger.

Former Secretary of Defense James Schlesinger has made similar comments on several occasions; one of the most widely quoted comes from Congressional testimony on strategic policy in 1974 (B6):

"I believe there is some misunderstanding about the degree of reliability and accuracy of missiles. As this chart explains, it is impossible for either side to acquire the degree of accuracy that would give them a high confidence first strike because we will not know what the actual accuracy will be like in a real-world context.

"As you know, we have acquired from the western test range a fairly precise accuracy, but in the real world we would have to fly from operational bases to targets in the Soviet Union. The parameters of the flight from the western test range are not really very helpful in determining those accuracies to the Soviet Union. We can never know what degrees of accuracy would be achieved in the real world. I think that that is probably advantageous...

"The effect of this is that there will always be degradation in accuracy as one shifts from R&D testing, which is essentially what we have at the western test range, to operational silos...

"We know that and the Soviets know it, and that is one of the reasons that I can publicly state that neither side can acquire a high-confidence first-strike capability. I want the President of the United States to know that for all the future years, and I want the Soviet leadership to know that for all the future years."

In that testimony, Schlesinger cited .1 and .2 nautical miles as possible "operational degradations" of accuracy. He has repeated his comments quite recently, again in Congressional testimony (B7):

"Happily, no one has ever fought a nuclear war. Not only have ICBMs never been tested in flying operational trajectories, they have not been tested flying north, and this may or may not introduce certain areas of bias in the estimates of accuracy.... Consequently, neither the Soviet Union nor ourselves has appropriate test data to buttress the estimates regularly made about either nation's strategic forces... For these reasons, perhaps the dominant element in measuring nuclear forces against each other is the unknown and immeasurable element of the possibility of major technical failure. It would tend to dominate any outcome. Given the spotty Soviet history in dealing with modern technologies, one would hypothesize that this must be a constant worry of the Soviet leaders..."

J. B. Walsh, who had a more direct role in the development and testing of ballistic missiles than Secretary Schlesinger (he was then Deputy Director for Strategic and Space Systems, Defense Research and Engineering) made some similar observations in 1976 testimony (B8):

"The problem with increased accuracy is your confidence in that accuracy...I have concern about uncertainties and factors that might have been left out, biases in the system for example, I might be able to fire 10 RVs from 10 separate missiles and land in exactly the same spot, except that the spot is removed by a fraction of a mile from the target. And it is very difficult to find that kind of error or to know it exists. And that, of course, is the purpose of many of our flight test programs, to be sure such errors do not exist. So there is a problem...of acquiring confidence that you really have achieved the accuracy."

Another analyst, who declined to be named, was even more emphatic. For the Defense Department, he had performed statistical analyses of the Titan, Minuteman I, Minuteman II, Minuteman III, and Poseidon testing programs. Each weapon system, he said, had extremely large biases, large enough to very substantially degrade their kill capabilities. While the CEPs of the systems had become substantially smaller over the years, the bias had not gone down proportionally; the bias of the Minuteman III system was still large enough, in his opinion, to make it ineffective as a counterforce weapon. Other defense analysts have made statements to the same effect (B9).

However, an equally large body of opinion exists that systematic errors will be small enough to have a negligible effect on the outcome of an attack. The active Air Force personnel with whom we spoke were unanimously of this opinion. In a recent issue of Strategic Review, Gen. Robert Marsh argues that bias is much less of a problem than it has been made to seem, and states unequivocally that no current U.S. weapon system has a bias larger than its CEP (B10).

In Congressional testimony in 1979, Dr. Seymour Zeiberg, then Deputy Undersecretary of Defense for Strategic and Space Systems, was asked about uncertainty introduced by shifting from the test ranges to attacks on the Soviet Union, and replied (B11).

"We were never able to find any factual evidence of that kind of concern. We had the Defense Science Board look at that a few years ago. Nobody could put their fingers on a real problem. It was a concern, but as long as we have the model of the earth improving as it does with our satellite data, the confidence builds up that there is no hidden phenomena that we are not modeling. As of their report, which was about the beginning of 1975, they felt there was no known problem then and matters would get better as time went on."

He went on to say, in reference to Minuteman tests, "there is no bias in there that we know about. Every now and then, because of some trouble with one flight, you find something but it gets unraveled in the post-flight analysis. We don't have a bias in Minuteman that is concerning us."

Readers should note that much of this controversy centers around the accuracy with which peacetime testing of ICBMs models their performance over different trajectories in wartime; this issue is also of importance in determining the degree of confidence that can be placed in estimates of the CEP. The testing of ICBMs is therefore discussed in some detail in Appendix C, which we urge readers not to overlook.

We take an intermediate view, between those who argue that the possibility of systematic bias introduces enough uncertainty to prevent any conceivable attack, and those who argue that it is a completely insignificant factor. It seems clear that given the limited nature of the testing process, and the fact that no weapons have ever been tested over the trajectory between the United States and the Soviet Union, some systematic errors would be inevitable in any countersilo attack. Given that errors resulting from targeting, gravity anomalies, and atmospheric variations will all act largely as systematic errors in the context of a large countersilo strike, systematic biases are unlikely to be negligible. However, given that guidance errors, thrust termination errors, initial alignment errors, reentry ablation errors and others will act largely randomly, it would be surprising if, on the average, the bias were not considerably smaller than the CEP.

However, the task of predicting upper bounds for such errors is complicated by the fact that, unlike random errors of the sort described by the CEP, the "law of large numbers" would not apply to systematic errors in a countersilo attack. In a major countersilo attack, involving some 2000 warheads, the probability of a significant random variation from the mean CEP is very small, as the number of trials is very large; the only significant uncertainty would be in extrapolating the mean CEP itself from a limited number of tests (the latter uncertainty is discussed in section 2.5). In the case of systematic errors, however, the number of trials will be quite small; for example, if there are 6 ICBM fields being targeted, there will be essentially only 6 trials for atmospheric errors, and the possibility of significant random variation from the "expected" outcome is quite large. Indeed, a much larger than expected bias at even one field could cause a significant percentage of the silos in that field to survive. Even if the "expected" bias could be determined, it would be essentially impossible to eliminate the possibility of a large random variation from this value over one field.

In summary, it is our view that in most cases, the bias in a counterforce attack would be substantially smaller than the CEP, but of roughly the same order of magnitude. However, for the reasons stated in the previous paragraph, it will be difficult for the planner to insure that this will be the case in a specific strike. Figure 2.3.4 shows the double-shot kill probability for an SS-19 warhead against a Minuteman silo, for 4 possible values of the bias. While we believe that a bias of the order of .05 nautical miles or less will be much more likely than one of .1 or .15 nautical miles, we have included the latter two cases because of the difficulties we have discussed in placing upper bounds on systematic error. We have not included values of bias between 0 and .05 nautical miles, for the simple reason that biases smaller than .05 nautical miles have an extremely small

Figure 2.3.4 Bias, n. mi.

	0.0	0.05	0.10	0.15
OPK(2)	.72	.70	.62	.50

effect on the outcome of an attack with these weapons.

2.4 FRATRICIDE

Many of the effects of nuclear weapons have the potential to damage, destroy, or degrade the accuracy of an RV reentering in the area of the detonation. This phenomenon is known as "fratricide."

A. FRATRICIDAL NUCLEAR EFFECTS

Fratricidal effects can usefully be separated according to the period of time during which they occur (F1). In the first millisecond after the detonation, an enormous initial burst of radiation is given off, consisting mostly of X-rays and neutrons. The X-rays are largely absorbed by the air (helping to create the superhot fireball), but the neutrons travel long distances through the air with little attenuation, at significant fractions of the speed of light. The resulting neutron flux is great enough to be lethal to an incoming warhead at ranges of the order of 500-800 meters (F2); it is therefore essentially impossible to detonate two warheads over the same silo simultaneously without one destroying the other.

The flux of neutrons dies off after a few milliseconds, however. There is also a considerable flux of gamma rays during this period, extending for a considerably longer time than the neutron flux. Unlike X-rays, gamma rays travel long distances through the air, and can damage sensitive electronics in an incoming RV. However, the blast wave and fireball extend over much greater ranges and times; in most cases, they are therefore a more important source of fratricide.

The fireball from a half-megaton weapon (such as those on the recent modifications of the SS-19 and SS-18), would expand to a radius of more than 400 meters in roughly 50 milliseconds; it would then nearly double in size within the first second, and reach a maximum radius of roughly 1000 meters in less than 10 seconds (F3). Within this fireball, temperatures range from several thousand to several tens of thousands of degrees centrigrade, accompanied by extremely turbulent winds with velocities exceeding 900 km/hr; these conditions last for several seconds after the blast (F4). Accompanying the expansion of the fireball is the shockwave, which quickly outruns the fireball (referred to as "breakaway"), extending over much greater ranges. At a distance of 300 meters, the overpressure of the shockwave reaches a peak of more than 2000 psi, probably enough to crush the RV. Shockwave overpressures of 20 psi, accompanied by winds of 800 km/hr, reach out to ranges of the order of 2000 meters (F5). It is extremely unlikely that an RV that passed through the fireball during the first several seconds after a detonation would survive: the combination of extreme heat, extraordinarily powerful winds, and strong shockwaves would probably destroy the RV outright, and would certainly degrade its accuracy.

As soon as it forms, the fireball begins to rise quite rapidly, carried upward like a hot air balloon. Within 5-10 seconds, the fireball will no longer be touching the ground, and another RV could attack the same target without passing through it (F6). In addition, within 10 seconds, the shockwave overpressure has decayed to of the order of 5 psi, accompanied by winds of roughly 250 km/hr. While such a shockwave might still affect the accuracy of an incoming RV, it is almost certain that it would not destroy it; at this point, the primary source of fratricide is likely to be the dust and debris lifted from the ground by the rising fireball.

The quantity of debris lifted into the air by the detonation will depend on the height of burst. A weapon burst at or below ground level will dig an enormous crater, lifting thousands of cubic meters of dirt into the air. However, if the weapon is burst above the ground, a smaller crater will form, meaning that less dirt is injected into the cloud; at heights of burst higher than 100-150 meters, no appreciable crater will form (F7). However, while the avoidance of a crater will greatly reduce the quantity of dust and debris lifted into the air, substantial volumes of dirt are still lifted into the cloud in any detonation in which the fireball touches the ground; indeed, the vertical winds from the rising fireball are sufficient to hold aloft a 2-ton boulder (F8).

In the particular case under discussion, the height of burst will be constrained by the need to maintain high overpressures on the ground over the maximum possible range. For a silo hardness of 2000 psi, the burst must be below roughly 250 meters to maintain an acceptable kill radius (F9); indeed, it is likely that an attacker utilizing weapons with imperfect fuses would choose to burst below this altitude to avoid the degradation of the kill proability caused by bursts above the optimum height.

As the radius of the fireball from a half-megaton blast reaches 400 meters within 50 milliseconds, and nearly 800 meters in less than a second, it is clear that if such a weapon is detonated at an altitude of 250 meters or below, the fireball will be in contact with the ground over a wide area. The fireball rises at approximately 100-200 m/sec during this time period, so the outer surface of the fireball will not leave the ground for several seconds (F10). As a result, several thousand tons of dust and debris will be sucked into the rising cloud.

This cloud of dust continues to rise rapidly, leaving behind it the characteristic "cloud stem" of the mushroom cloud. Within one minute, the cloud has risen to an altitude of 8 kilometers, and has expanded to between two and three kilometers in radius. The altitude of the cloud stabilizes after approximately 10 minutes, at which time the cloud's bottom is roughly 10,000 meters high, and its top some 18,000 meters. The cloud radius at ten minutes is roughly 6500 meters, and the radius of the cloud stem is of the order of 1000 meters (F11). Although the height of the clouds stabilizes at this time, the clouds continue to expand horizontally, largely as a result of spreading by atmospheric winds. The large size of these clouds means that in an attack on the American Minuteman missile fields, the clouds would merge into one enormous dust cloud covering essentially the entire field. This is shown in Figure 2.4.1, which shows the dust clouds over a portion of Malmstrom Air Force Base 10 minutes after the detonations of the first wave (F12). The black spots which represent the silos are also roughly the size of the cloud stems extending below the dust blanket toward the ground.

Particles and dust have an extremely destructive effect on incoming RVs, because of the extremely high speed at which the RVs are reentering the atmosphere; any collision will take place at speeds of several kilometers per second. Interaction with a heavy particle would destroy the RV outright, much like shooting it with a bullet. Smaller particles will erode the nosetip of the RV quite rapidly and unpredictably; such unpredictable erosion will greatly reduce the accuracy of the RV, and in some cases can cause the RV to fail outright.

These clouds of dust persist for significant periods of time. The heavy particles fall back to the ground first; particles of seven grams or more will have fallen out of the cloud completely within the first 20-25 minutes (F13). It has been estimated that passage through the nuclear dust cloud could have severe effects on the an RV for 1-2 hours after the detonation (F14).

Figure 2.4.2 provides an overview of the sequence of fratricidal effects (F15).

It is useful to make a distinction between "point" fratricide and "area" fratricide. Point fratricide refers to those effects that will only damage RVs targeted on the same silo as was the warhead causing the effect. Thus, point fratricide will have no effect on RVs targeted on silos at which previous warheads have failed to detonate. Area fratricide refers to those effects which affect RVs targeted on other silos as well, primarily silos downrange (south) of the detonation. From an examination of Figure 2.4.2, it is clear that for the first several seconds, point fratricide dominates; there is essentially no area fratricide until the shockwave and fireball reach as high as the paths of RVs targeted on downrange silos. However, after a minute or so, the cloud has risen to such an extent that point fratricide effects are dominated by area fratricide effects.

B. TACTICS TO MINIMIZE FRATRICIDE

From this physical description of fratricidal nuclear effects, it is possible to make some judgements as to the types of tactics the attacker could use to minimize fratricide.

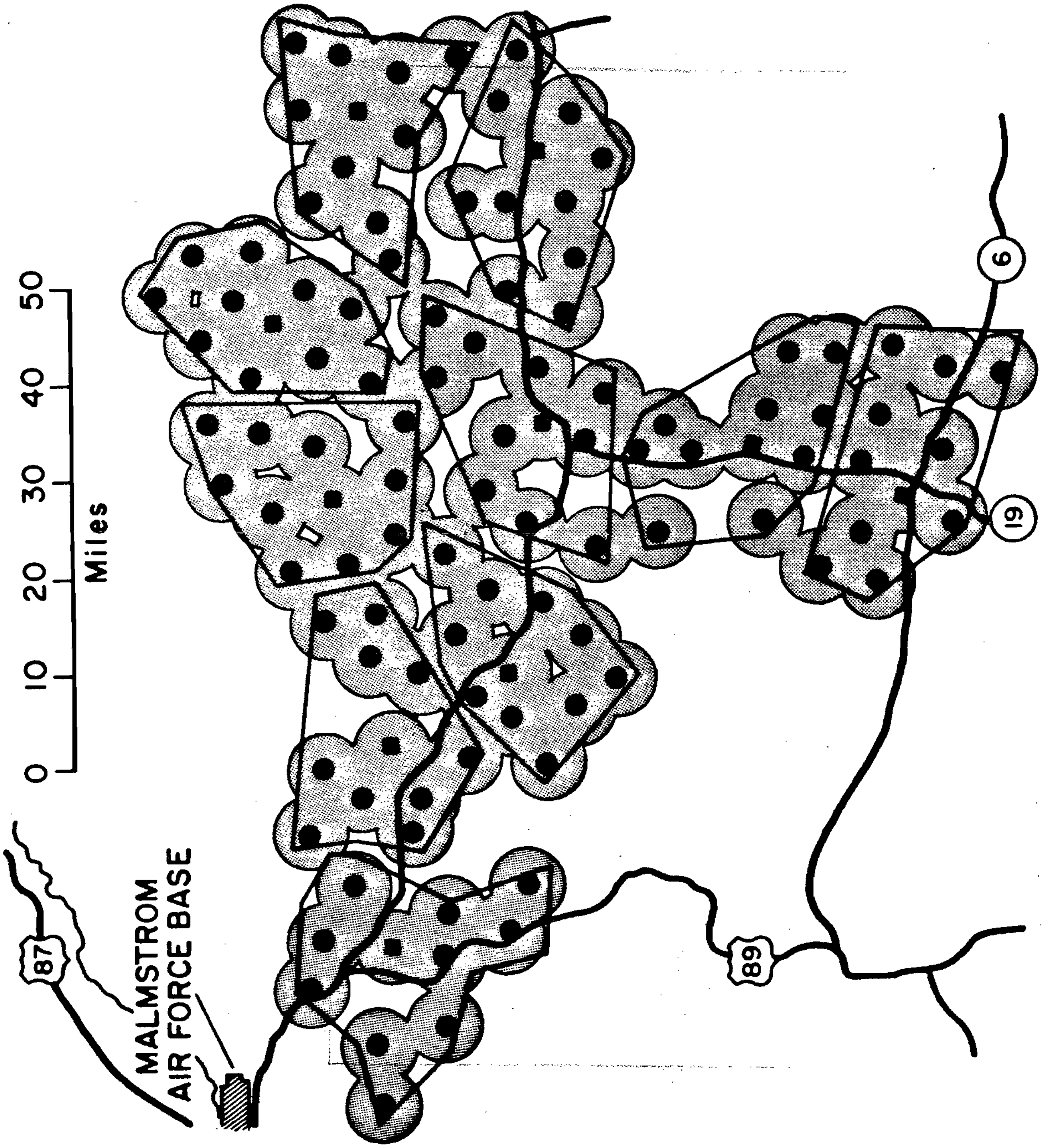
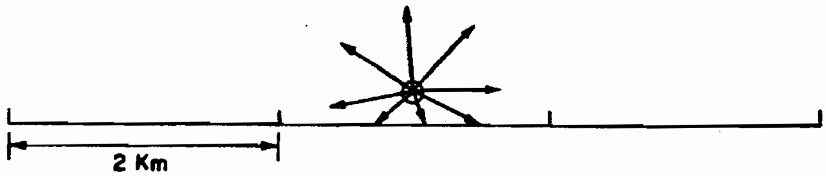


Fig. 2.4.1

Fig. 2.4.2

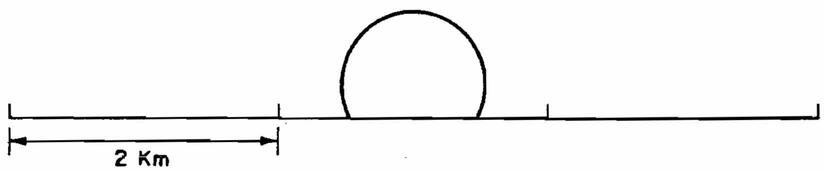
First Millisecond

Small fireball, temperature ~ 400,000 °C
Shock front overpressure ~ 100,000 psi
Neutron flux lethal to RV at 500–800 m



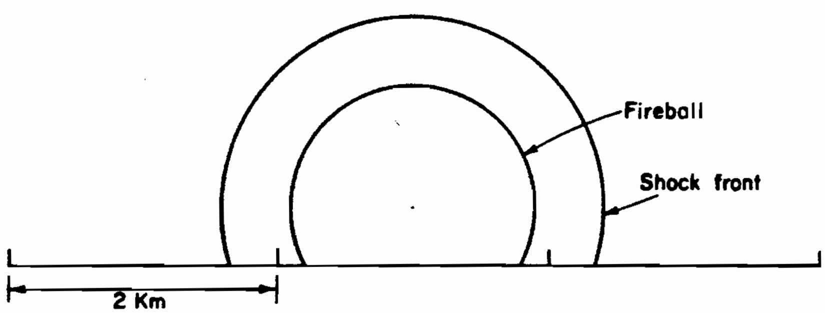
50 Milliseconds — Breakaway

Fireball radius ~ 500 m
Internal temperature ~ 75,000°C
Surface temperature ~ 3,000°C
Shock front radius ~ 500 m
Shock front overpressure ~ 600 psi
Winds several thousand Km/hr



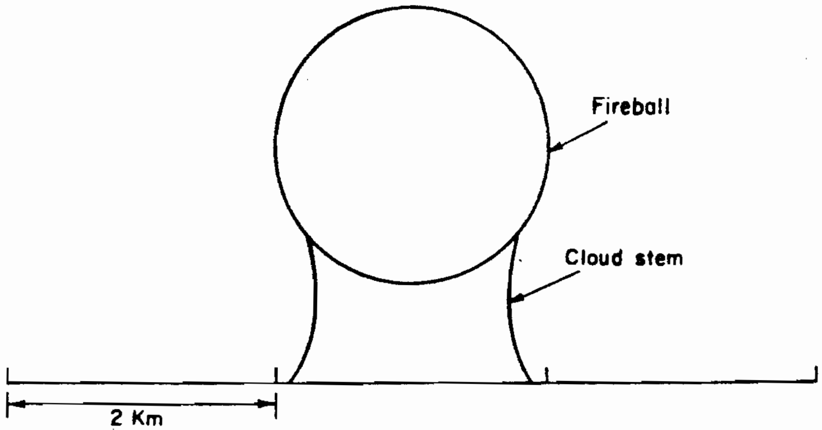
1 Second

Fireball radius ~ 900 meters
Interior temperature ~ 10,000°C
Surface temperature ~ 6,000°C
Shock front radius ~ 1,400 meters
Shock front overpressure ~ 40 psi
Shock front winds ~ 1,200 Km/hr



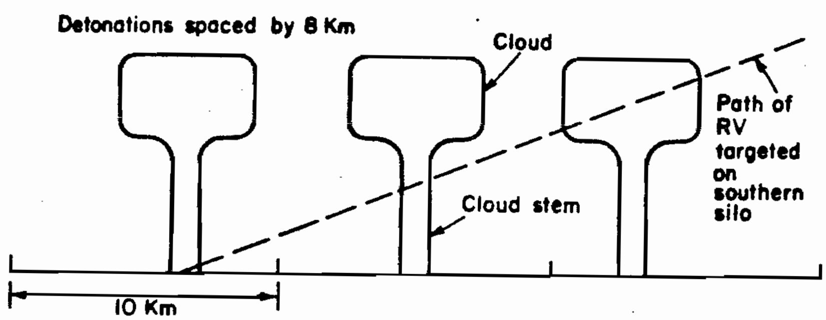
10 Seconds–Fireball Maximum Size

Fireball radius ~ 1,000 meters; height ~ 1,700 m
Fireball surface temperature ~ 2,000°C
Shock front radius ~ 5,000 meters (no longer visible in figure)
Shock front overpressure ~ 5 psi, wind ~ 250 Km/hr
Vertical winds ~ 600 Km/hr
Particles and debris sucked into cloud



1 Minute.

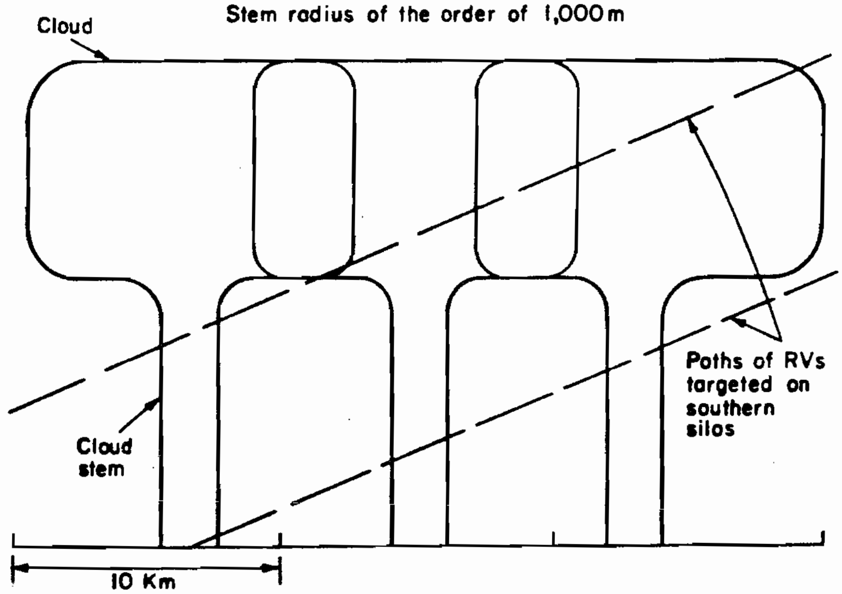
Cloud radius – 2,500 m
Cloud height (center) – 6,500 m
Vertical winds several hundred Km/hr
Fireball ceases to radiate in visual range
Large particles remain in cloud and cloud stem



10 Minutes–Cloud Height Stabilizes

Detonations spaced by 8 Km

Clouds have largely merged into one huge cloud
Cloud top height – 18,000 m. Thickness: 8,000 m
Stem radius of the order of 1,000 m



Let us begin by considering an attack which involves only one warhead on each silo. The distances between individual Minuteman missile silos are between 3 and 10 kilometers (see Figure 2.4.1). An RV would therefore pass near the silo just north of that on which it is targeted at an altitude between 1 and 4 kilometers. If this RV arrives more than a few seconds after the detonation of a weapon over this next silo north, it will be struck by the shock wave from that blast, and may pass through the rising cloud (see Figure 2.4.2).

Thus, in order to avoid significant fratricide, the attacker must strike the southern silos first, moving north, in what is referred to as a "rollback" attack. This imposes strict requirements on the timing of the attack; it is necessary to leave enough time between attacks on adjacent silos to be certain that possible timing errors will not cause warheads to arrive late enough to be affected by neighboring detonations, but it is also necessary to proceed with the attack as rapidly as possible in order to prevent the missiles under attack from being launched before the attack is completed. If timing uncertainties can be reduced to a very few seconds, this tactic should enable an attacker to detonate one weapon over each silo without noticeable fratricide.

The arrival of more than one weapon at a silo presents a more serious problem. Several possible tactics are available to the attacker in this case. If the attacker believes that the reliability of the weapons is the most significant limiting factor on the success of the attack, one possible tactic would be to target two weapons simultaneously on each silo; if both weapons detonated, one would destroy the other, but the extra weapon would provide a hedge against those weapons that fail to arrive and detonate. In the case of an attack by SS-19s on Minuteman silos, such as that described in section 2.2, an attack involving one warhead on each silo would destroy only 47% of the Minuteman silos, while an attack in which two warheads were targeted to arrive simultaneously at each silo would destroy roughly 59% of the silos (F16). It should be noted that such a tactic would roughly double the timing problems involved in a rollback attack, since twice as many warheads would have to arrive within a time window of the same size.

Another possible approach is to schedule the attack in two waves, each of which would be a rollback attack like that described above. From an examination of the time-series of fratricidal effects summarized in Figure 2.4.2, it would appear that a second wave of RVs would have little chance of surviving to its targets at least until the largest airborne particles, that is, those large enough to destroy the RV outright, have fallen back to the ground. Depending on the ability of the RV to withstand collisions, this might take anywhere from 10 minutes to half an hour (F17).

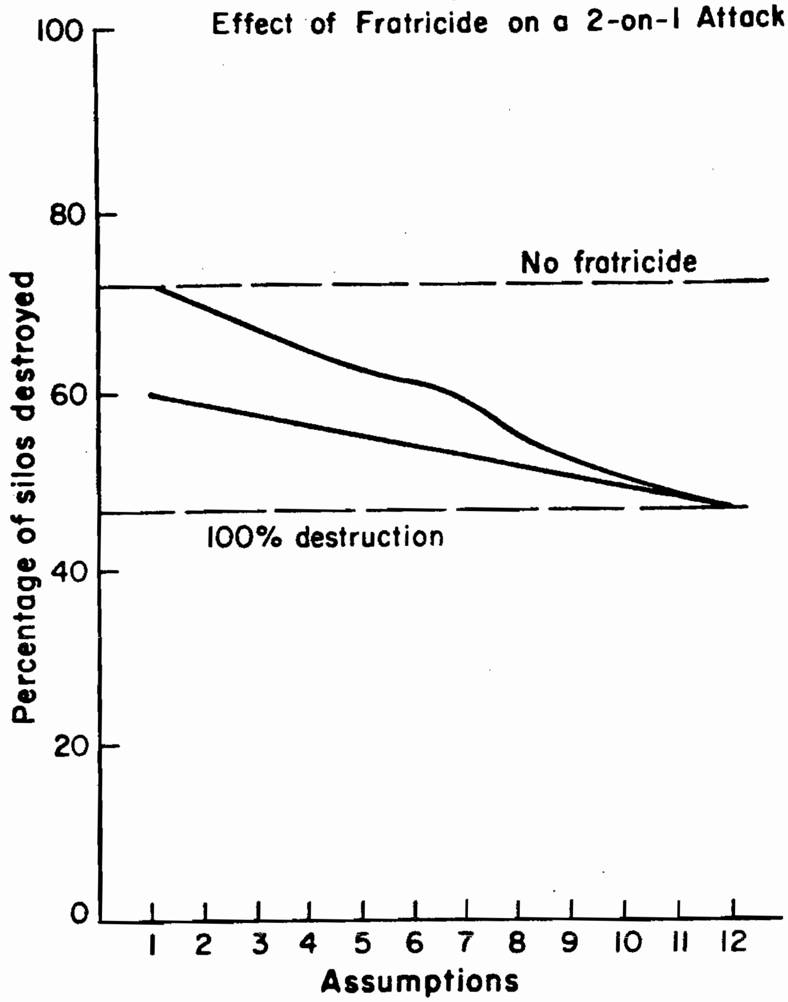
An RV reentering the atmosphere 10 minutes or more after the first wave of the attack would face a completely different reentry environment than did the RVs of the first wave. The 1000 near-ground detonations of the first wave will have completely altered the atmospheric density and wind profiles up to alititudes of tens of thousands of meters; these profiles will now be completely unpredictable, and indeed, unlike any that have ever been experienced or tested. In addition, at an altitude of some 18,000 meters, the RV would enter the dust blanket, which by 10 minutes after the first wave would cover the entire silo field, and would contain some hundreds of thousands of tons of dust. When it entered the cloud, the RV would be traveling some 6000 m/sec. The RV would then travel a slant distance of roughly 20 km through the cloud; at such speeds, the effect would be similar to being exposed to an extraordinarily powerful sandblaster for several seconds. Even once the RV has left the cloud, it would have a good chance of passing through one or more cloud stems, also laden with dust and particles (See Figure 2.4.1).

Thus, it is clear that considerable fratricidal effects would be unavoidable. Indeed, as pointed out above, it has been estimated that passage through the dust cloud would have severe fratricidal effects as long as 1-2 hours after the detonations of the first wave. The accuracy of the incoming RVs will be greatly reduced, both by the atmospheric disturbances and by the severe ablation uncertainties imposed by the dust; some warheads may be destroyed, either by a collision with a large particle that has not yet fallen, or as a result of a failure of their heat shielding resulting from the greater rate of ablation and higher thermal loads caused by the 20 km trip through the erosive environment of the dust cloud.

Figure 2.4.3 shows the percentage of the U.S. Minuteman silos that would be destroyed in a two-wave attack by Soviet SS-19 Mod 3 warheads, given varying assumptions about the severity of fratricide. The extreme left point shows the result if no fratricide is encountered at all, while the extreme right point is the result if the entire second wave is destroyed. It is assumed that the first wave encounters no fratricide, and the fratricide assumptions for the second wave are given in (F18).

Since this graph shows essentially the entire possible range of fratricide, it is necessary to estimate which portions of the chart are more plausible than others. In our view, the most extreme right point would be quite plausible in the event of the second wave arriving a very few minutes after a groundburst first wave; however, for the "optimum" attack we have described, values several points to the left of this are considerably more likely. Given the atmospheric disturbances and dust that the RV would have to face, it is our view that the best case for the attacker that is reasonably plausible is number four, in which 5% of the

Fig. 2.4.3
Effect of Fratricide on a 2-on-1 Attack



RVs are destroyed, and the reentry errors are multiplied by a factor of two (F19). An attack suffering this level of fratricide would destroy roughly 65% of the Minuteman silos, a reduction of some 7% over an attack which suffered no fratricide.

The reader should note that this represents only the very roughest estimate of the effects of fratricide. For example, we have assumed that all warheads in the second wave experience the same effects; this is clearly an extreme simplification. A more adequate analysis would require a detailed model of the effects of the earlier detonations on atmospheric wind and density distributions, the detailed characteristics of the cloud and the debris within it, and the parameters of the RV, all combined into an extensive Monte Carlo simulation. Even if such an analysis were done, it should be remembered that many of the most important parameters have simply never been tested. No one knows how such a large number of detonations would interact, or what the precise effects of dust and particles on the RV would be. As a result, any attack involving more than one attack wave will be tinged with considerable uncertainty as to its probable result; an attacker certainly could not have high confidence in achieving the result represented by our "best plausible" estimate.

C. LAUNCH UNDER ATTACK, PINDOWN, MULTIPLE ATTACK WAVES, AND REPROGRAMMING

In an attack in which the two waves are separated by several minutes, such as the one we have described, there would be a significant possibility that the surviving ICBMs would be launched between the two waves of the attack. The flight time of ballistic missiles on intercontinental trajectories is of the order of 30 minutes; thus, warning of the attack would become available at least 20-25 minutes before the first detonations. U.S. policy has been to avoid a policy of "launch on warning," because of the possibility that a mistaken warning would escalate into a nuclear war; however, the actual detonation of the nuclear weapons of the first wave would be incontrovertible proof that an attack was under way. Since ICBMs immediately after launch are traveling quite slowly, by comparison with incoming RVs, they are much better able to withstand passage through clouds of debris; the severity of a collision is proportional to the square of the velocity at which it takes place. As a result, it is quite possible that if an attack involved two waves separated by several minutes, the ICBMs that survived the first wave would have launched before the second wave arrived. This is referred to as "launch after impact," (the possibility of launching the ICBMs before the arrival of the first wave, but after the first nuclear detonation on U.S. soil, is known as "launch under attack", and is discussed briefly in Appendix A.)

If <u>all</u> of the ICBMs that survived the first wave were able to launch immediately, the attack we have been considering would destroy only 47% of the U.S. ICBMs, i.e., no more than a single-wave attack. However, we regard it as unlikely that an ICBM that had sustained a near miss from a powerful nuclear detonation would be able to launch in the next few minutes. A potential attacker, however, would have no way of confidently estimating what percentage of the ICBMs which survived the first wave of the attack would remain capable of launching immediately. A lower limit on the number which could escape is provided by the fact that in those cases where the first-wave warhead failed, the ICBM at which that warhead was targeted would remain essentially undamaged, and could be launched immediately (providing, of course, that the command and control system had also survived). The attack we have been considering involves RVs with an overall reliability of 75%; the lower line in Figure 2.4.3 shows the percentage of U.S. ICBMs that would be destroyed if 25% of the force escaped between the two waves of the attack (F20).

One tactic to prevent the launch of the undamaged ICBMs would be to attempt what is known as a "pindown" attack. Since ICBMs are much more delicate once out of their silos than they are within them, weapons burst at regular intervals over the silo field would make it impossible to safely launch the ICBMs. There are two possible methods that could be used to pin down a group of

ICBMs. Weapons burst within the atmosphere (endoatmosperic pindown) could destroy rising ICBMs by blast and wind. However, for silo fields as large as those containing the U.S. Minuteman ICBMs, this tactic would require an enormous allocation of warheads to keep the missiles pinned in their silos. A more sensible tactic for the attacker would be rely on exoatmospheric pindown. If a nuclear weapon is burst above the atmosphere, the X-rays it releases will not be absorbed immediately, and will travel enormous distances. A sufficiently high flux of X-rays would destroy or confuse the sensitive guidance electronics of the rising ICBM. Using this method, an attacker might be able to pin down an entire Minuteman field with as little as 1-2 weapons per minute (F21). The six U.S. ICBM fields could then be pinned down for 20 minutes (long enough for large particles to fall out of the cloud) with an allocation of 120-240 warheads. However, it should be noted that such a tactic involves considerable uncertainties. It will be extremely difficult for the attacker to be certain of the precise hardness to X-rays of U.S. ICBMs, and a factor of two increase in the X-ray hardness of the ICBMs would increase the number of warheads required for a high-confidence pindown by a factor of roughly 16. Indeed, if the MX missile, which has more X-ray hardening than does the MX, were placed in Minuteman silos, it would require "hundreds of megatons per minute in the flyout corridors to guarantee pindown." (F22). Since, in addition, pindown strategies cannot be tested, due to the Atmospheric Test Ban Treaty, an attack which relied on pindown would face additional uncertainty.

An attack designed for exoatmosperic pindown is essentially identical to one designed to maximize the electromagnetic pulse (EMP) effects. An attack involving several megaton-range weapons bursting above the atmosphere every minute for tens of minutes, over areas in the central United States, would destroy most of the U.S. electrical and telephone systems. This may, however, be a minor problem when compared to the millions of casualties that would be caused by the fallout from an attack of U.S. ICBMs.

So far, we have been discussing the effectiveness of attacks involving two weapons targeted on each silo; it is, of course, possible for the attacker to target more than two weapons on each silo. For example, with 3000 warheads, an attacker could combine a second attack wave with the tactic of targeting two warheads simultaneously on each silo in the first wave. With 4000 warheads, two warheads could be used in each wave. The former attack would raise the percentage of silos destroyed in the "best plausible" fratricide case from 65% to 72%, while the latter would destroy roughly 76% of the silos under attack. Alternatively, the attacker could choose to target warheads in more than two separate waves; if the fratricide experienced by the third wave could be limited to the same level as that we have assumed for the second, a three-wave attack could destroy 76% of the defending silos, with an allocation of 3000 warheads.

However, several factors argue against this course of action. First, it is clear that the utility of the third wave is much less than that of the first two; the first wave will destroy roughly 470 silos, the second roughly 170, while the third will destroy of the order of 100. At this rate, the "exchange ratio" is extremely unfavorable to the attacker; the attacker is disarming himself more rapidly than the defender (F23). In addition, the time period required to complete the attack would double, for a three-wave attack, vastly increasing either the probability of launch under attack or the requirements for pindown; even so, the third wave would encounter significant fratricidal effects from both the first and the second wave, reducing its effectiveness still further. Last but not least, it is estimated that the Soviet Union simply does not currently have enough accurate warheads to execute an attack involving more than two waves (F24).

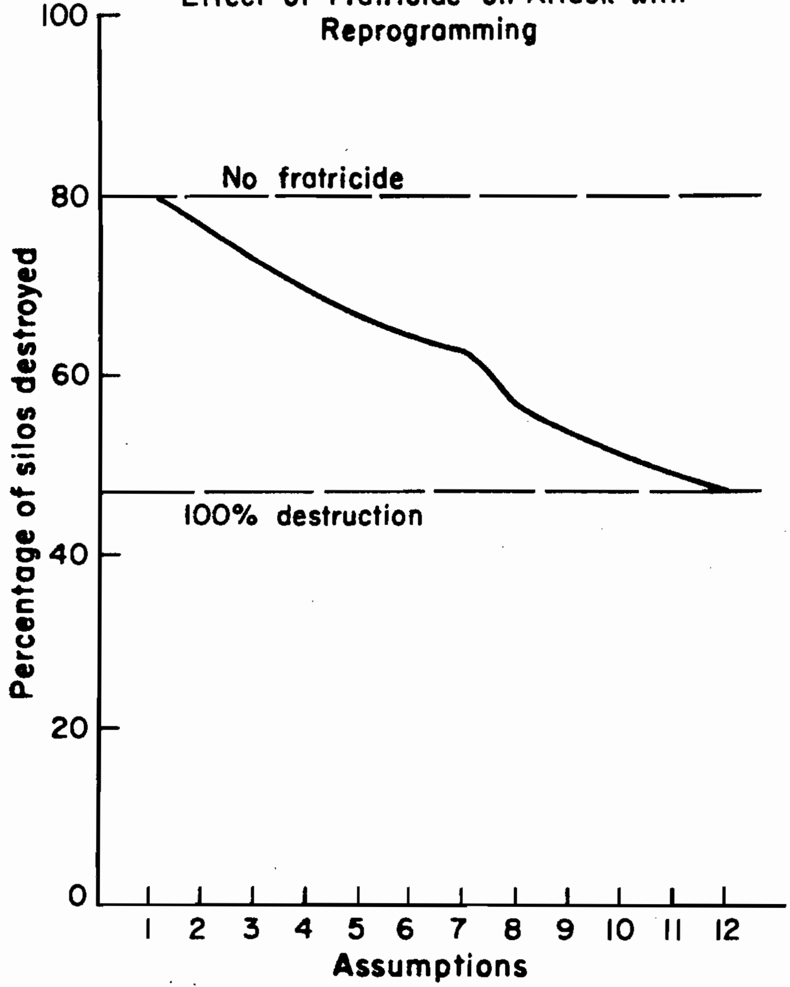
Another possible tactic which is frequently discussed is the possibility of "reprogramming" additional warheads to replace those that failed in the first attack. As we mentioned in the section on boost phase errors, most reliability problems will occur either during launch or in the boost phase; five or ten minutes into the flight, command centers on the ground might well be aware of 80% of the failures that will occur. If the missiles being used in the attack could be retargeted extremely quickly, it would then be possible to fire additional missiles to compensate for the known failures. These reprogrammed warheads would then arrive in a third attack wave some minutes after the second. This tactic has some of the disadvantages of other multiple-wave attacks described above, in that it requires more time to execute, increasing either the possibility that the surviving ICBMs will launch under attack, or the requirements for pindown. In addition, the technical requirements for such an attack are quite stringent: it would require a failure assessment system, combined with command and control and retargeting of hundreds of ICBMs within a very few minutes. In our view, the Soviet Union could probably not execute such an attack today; however, it is not inconceivable that such a capability could be developed within the next few years.

Figure 2.4.4 shows the effect of fratricide on a reprogrammed attack (F25).

As can be seen, this tactic raises the percentage of silos destroyed to roughly 70%, given our "best plausible" fratricide assumptions, with an additional allocation of some 400 warheads.

It should be noted that, as Dr. Richard Garwin has pointed out (F26), it would be quite possible for the defender to create "artificial fratricide" as a defense against attacks on hardened silos. For example, small nuclear weapons could be buried north of each silo, and detonated on warning from a series of

Fig. 2.4.4
Effect of Fratricide on Attack with Reprogramming



relatively inexpensive, redundant radars. Such weapons could be designed to both minimize the quantity of fallout that would result from their use, and maximize the quantitiy of debris they lifted into the air. Since such clouds would affect both waves of the attack, and would contain much larger quantities of debris than those we have been discussing, they would have a much larger effect on the outcome of an attack, providing what has been called a "dust defense." (F27). However, it is often argued that the placement of nuclear weapons designed to detonate on U.S. soil would be politically unpalatable, even if intended only to deter a nuclear attack, and never to actually be used.

2.5 UNCERTAINTY IN ATTACK PARAMETERS: ACCURACY, YIELD, RELIABILITY, AND HARDNESS

So far, we have examined uncertainties caused by fratricide and bias, two parameters that are not included in the standard calculations described in section 2.2, whose results are usually cited as indicating the vulnerability of ICBMs. In addition to these uncertainties arising from factors outside the traditional models, there is considerable uncertainty in the parameters that are considered: the precision, yield, and reliability of the warheads and the hardness of the silos.

In this section, we present a rough description and quantification of some of these uncertainties. It is impossible to assign precise levels of confidence or probability distributions to any of these parameters: there are simply too many different technologies and different quantities and qualities of testing involved. In addition, the amount of information concerning these uncertainties that is available in the unclassified literature is extremely small. For these reasons, we have not attempted any precise or rigorous analysis of these uncertainties, but have limited ourselves to qualitative descriptions of the sources of uncertainty and order-of-magnitude estimates of its effects (U1).

A. UNCERTAINTY IN CEP

Information concerning the precision of a given weapon system comes from a variety of sources. While the weapon is still in development, some predictions can be made, based on the performance of the guidance and reentry components in comparison to those of previous systems. Indeed, current weapons are engineered to meet specific accuracy requirements. In the last stages of development of a new system, flight tests are conducted, from which the CEP can be directly estimated from the impact points, and from extensive engineering analysis of each test, which helps to confirm or modify predictions concerning the performance of the various parts in the demanding flight environment.

Before deployment of a new weapon system, both the United States and the Soviet Union typically perform 20-25 full flight tests; more flight tests would give higher confidence in system performance, but the cost of an ICBM ranges from several million to several tens of millions of dollars, which places a severe constraint on the number of complete flight tests. After deployment, both countries typically conduct something of the order of 5-10 tests of operational missiles of the given type each year, as well as several additional research and development tests; the former monitor changes in the performance of the system components through time, while the latter help to assess the effect of periodic changes in system hardware and software.

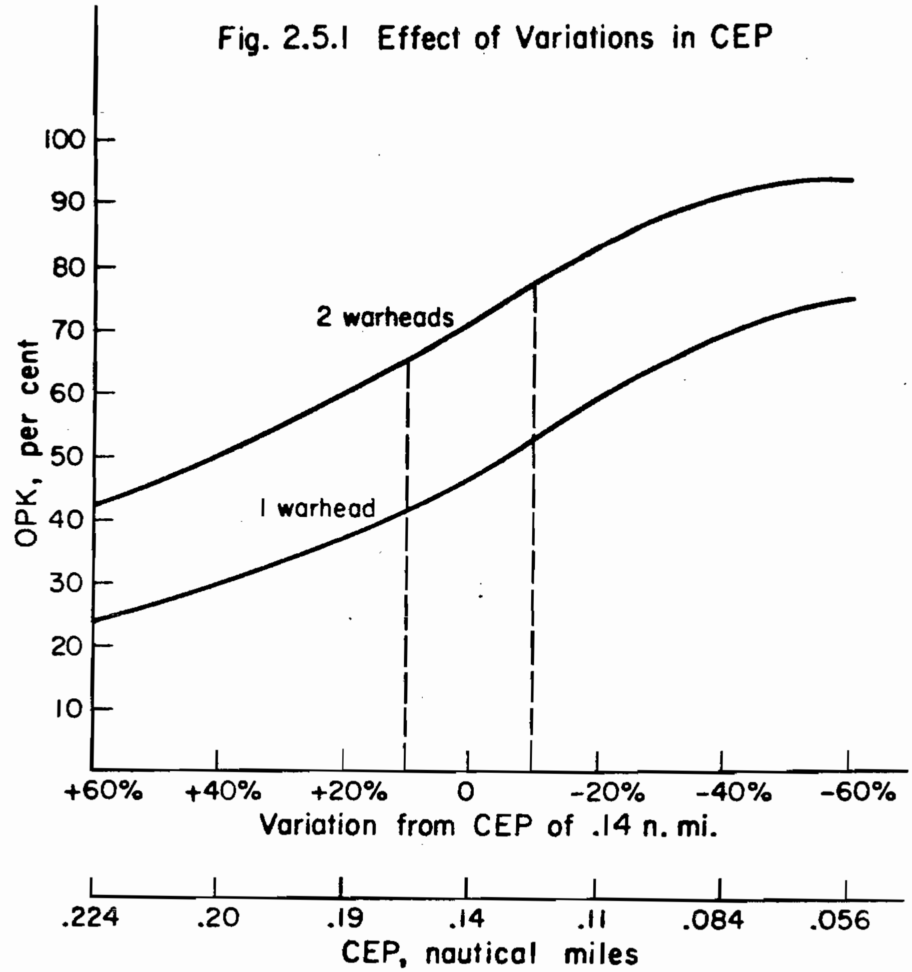
In general, these test shots are fired over special test ranges; the United States fires most of its test shosts from a special silo at Vandenberg Air Force Base in California to a target range at Kwajalein Atoll in the Pacific; the Soviet Union fires most of its test shots from a missile and space base near Tyuratam to the Kamchatka peninsula. Each country has fired missiles over other trajectories as well, but no weapon has ever been fired over the Arctic trajectory that would be flown in an actual attack, for obvious reasons. In addition, while the Soviet Union sometimes conducts flight tests from operational silos, the United States has never conducted a realistic test from such a silo.

Uncertainty in CEP arises primarily from two limits on the testing of ICBMs. First, the small number of full flight tests would leave some uncertainty even under ideal conditions. Second, the main test ranges of each country are significantly different than the ICBM flight paths between the United States and the Soviet Union. In addition to differences in the gravitational fields and atmospheric conditions the missile will experience (which contribute largely to uncertainty in the systematic bias), the main test ranges of both countries (and especially that of the Soviet Union) are noticeably shorter than many operational trajectories. This difference has a significant effect on almost every error source in the system, and in some cases, this effect is difficult to predict (U2).

Because of this, a variation of 10% between the CEP estimated from shots over test ranges and the actual CEP in a large-scale counter-silo strike could not by any means be ruled out; indeed, we believe this to be a very conservative estimate. A more detailed discussion of CEP uncertainties requires a detailed discussion of ballistic missile flight testing: both are provided in Appendix C, which we urge readers not to overlook. Figure 2.5.1 shows how the kill probability of an SS-19 against a Minuteman silo changes with variations in CEP (U3). As can be seen from the figure, even small variations in CEP can have quite substantial effects on the outcome of an attack. An unfavorable variation of 10% in this factor alone would reduce the percentage of silos destroyed in a two-on-one attack from 72% to 66%.

B. RELIABILITY

Until fairly recently, most estimates of the reliability of ICBMs were based largely on simple calculations of the number of successes out of a given number of full-system flight tests; if the system had been tested 50 times and had suffered 10 failures, then its reliability was taken to be 80%. The uncertainty in such calculations was easily computed using straightforward statistical methods, and for the small number of flight tests usually conducted, was in fact quite high. As an example, of the first 29 research and development tests of the SS-18, 7 were failures, indicating a reliability of around 75%; but the SS-19, a weapon utilizing a similar level of technology, suffered only



two failures in its first 27 tests, indicating a reliability of 92% (U4). (It should be noted, however, that these were engineering tests of prototypes: it is unlikely that operational ICBMs which had recieved no special maintenance before test would achieve reliabilities as high as 92%).

However, as in the case of the CEP, a great deal more information conerning the reliability is available from each flight test than a simple "yes" or "no." Extensive engineering analysis of the performance of each subsystem is carried out after each flight test; in addition, subsystems are constantly undergoing test on the ground, and overall reliability estimates can be made from combining these sources of information. As an example, the sensitive guidance system must be "powered up" while the missile is in its silo, so that it can maintain constant readiness; the mean time between failure of these systems can then be measured: for the NS-20 guidance system of the Minuteman III, the mean time between failure was of the order of 40,000 hours, more than three times the stated requirement (U5). Increased sophistication in the use of such information has reduced the need for extensive full-system flight testing; unfortunately for our purposes, it has also made it impossible to use unclassified information to accurately calculate the uncertainty in reliability estimates (U6). However, extrapolation of full system performance in the demanding flight environment, from subsystem testing on the ground, is itself an extremely uncertain process.

Indeed, in a counterforce first-strike, there would be an additional complicating factor: launching such a strike, involving some 2000 warheads, would require the timely cooperation of several tens, more probably hundreds of people. Their behavior under such circumstances is fundamentally unpredictable. In many cases, provisions to prevent unauthorized launch require the simultaneous agreement of several individuals to launch any given weapon. Given the obvious consequences of a nuclear first-strike, the possibility that significant numbers of the critical personnel will refuse to perform their assigned roles, or even attempt to sabotage the effort, will never be completely insignificant.

In assessing the confidence level of reliability estimates for U.S. ICBMs, there is yet another problem; the U.S. has never conducted a realistic test from an operational silo. At least one source has argued that current procedures do not adequately test the launch control electronics in operational silos, and that this subsystem contributes significantly to overall reliability problems (U7). This is discussed in more detail in Appendix C.

Given the limited number of full flight tests of a given system, the uncertainties in extrapolating full system performance from subsystems, and the human factors necessarily involved in a first strike, it would be very difficult to rule out the possibility of an unfavorable variation of at least 10% in the mean reliability of the weapons used in an attack. Figure 2.5.4 shows the effect of variations in reliability on the kill probability of an SS-19 against a Minuteman silo. As can be seen, for the weapons under discussion, the outcome of an attack is approximately as sensitive to changes in this parameter as it is to changes in the CEP; an unfavorable variation of 10% in the reliability of the weapons would reduce the number of silos destroyed in a two-on-one attack from 72% to 67%. The curve is truncated because the maximum value of the reliability, 100%, is only one-third larger than the base value we have been using.

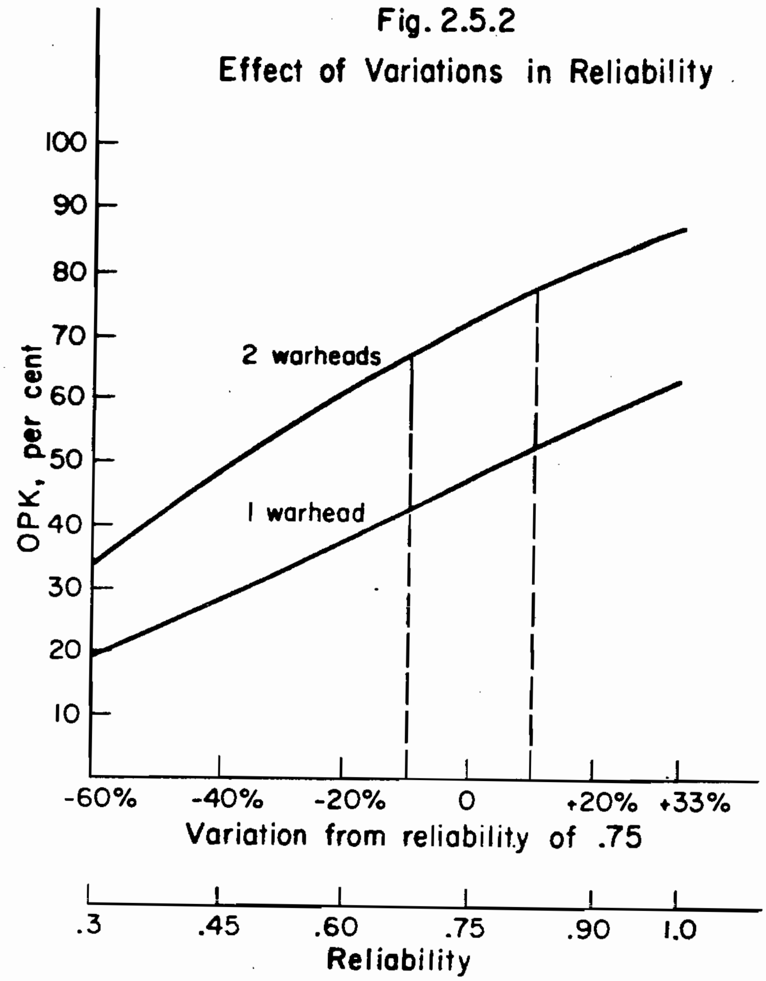
C. UNCERTAINTY IN WARHEAD DESTRUCTIVENESS

There are two interrelated sources of uncertainty in determining the effects of a given warhead: first, the effects of warheads of given yields are known only within fairly wide confidence intervals; second, there is some uncertainty in calculating the mean yield of a given type of warhead.

These problems have familiar sources: they are essentially

Fig. 2.5.2

Effect of Variations in Reliability

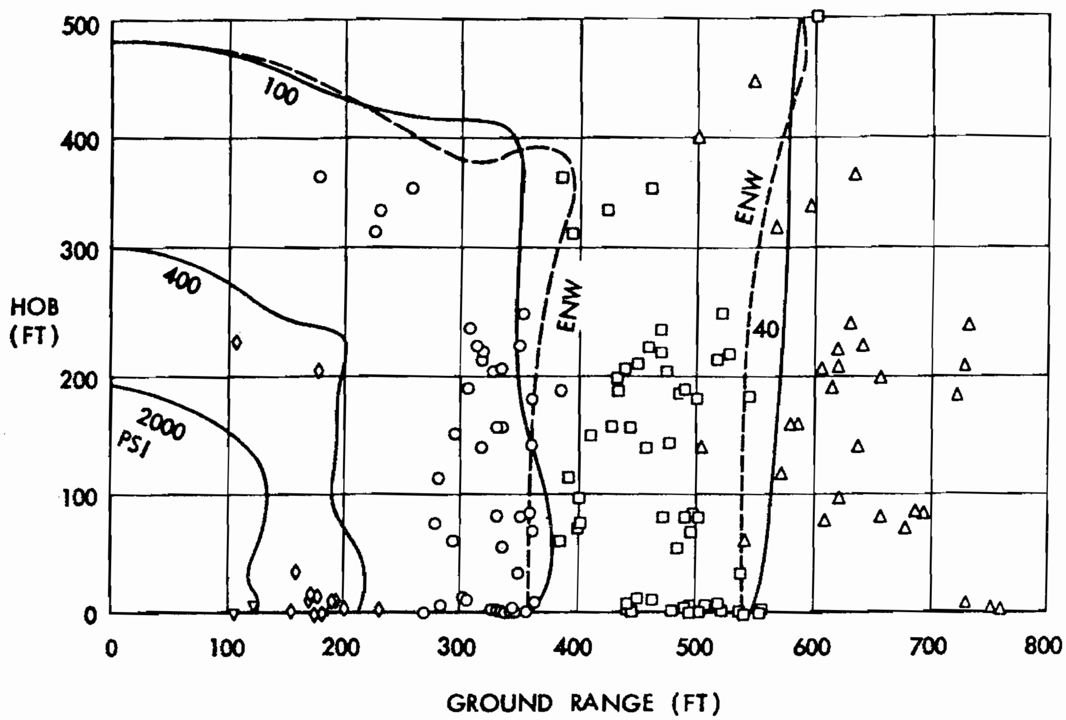


results of the limited nature of the testing these weapons have undergone. Testing of nuclear weapons has been severely limited, not only by cost considerations, but by other factors as well, including treaty limitations, safety considerations, political impact, and the extreme difficulty of instrumentation. Measurement of weapons effects in the range necessary to destroy a modern hardened silo has been especially limited, both because of the instrumentation difficulties associated with attempting to accurately measure transient overpressures of more than 100 atmospheres, and by lack of pressing interest: at the time when atmospheric nuclear tests were being conducted, the hardest targets of interest were roughly an order of magnitude "softer" than current missile silos. As a result, estimates of overpressure effects greater than 100 psi are based on extremely limited data, usually scaled from blasts of completely different sizes; often, much of the available data is simply scaled from tests of conventional weapons.

Indeed, weapons effects are one of the few parameters concerning which statements of uncertainty are widely available in the unclassified literature. In <u>The Effects of Nuclear Weapons</u>, the standard text on the subject, one finds the following: "numerical values given in this book are not---and cannot be---exact. They must inevitably include a substantial margin of error. Apart from the difficulties in making measurements of weapons effects, the results are often dependent upon circumstances which could not be predicted in the event of a nuclear attack." (U8). Defense Intelligence Agency reports estimate the uncertainty in overpressure at a given range as plus or minus 20% (U9), and the uncertainty in yield of given warheads as plus or minus 10% (U10).

However, a review of the available data leads one to the conclusion that the uncertainty in weapons effects may well be considerably greater. H. L. Brode, a leading nuclear effects specialist, pointed out in a 1970 RAND report (U11) that "little attention has in the past been given to the effect [of height of burst] at high overpressures...A review of air blast data showed them to be inadequate or nonexistent in the high pressure region (above 200 psi). The two-dimensional calculations proved unreliable... Unfortunately, the air blast data from nuclear tests is sparse in the higher overpressure region, and the Mach reflection is not well described theoretically." Figure 2.5.2 shows a plot of all of the peak overpressure data in the high-pressure region available to Brode at the time (one point is taken from each test where that overpressure was measured, without regard for variations in surface conditions or quality of measurement, so points do not have equal weights) compared to the overpressure ranges predicted in The Effects of Nuclear Weapons (solid lines), and an analytic approximation of Brode's (dashed lines) (U12). Several points can be made from this graph: first, the data shows a very wide spread, especially for bursts above 100 scaled feet (a "scaled foot" is the number of feet that would be applicable to a one-kiloton blast, times the one-third power of the yield of the blast in question; thus, for the .55 MT blasts we have been considering, this distance would be of the order of 275 meters); second, as Brode puts it, the data points are "inadequate to nonexistent above 200 psi;" third, the data points show the relevant overpressures at ground ranges almost uniformly lower than the ranges predicted by the curves; and lastly, almost all of the small amount of data available for high overpressures is for surface bursts, not the low air bursts we have postulated would be used to minimize fratricide. While it is clear from the chart that the data for surface bursts are better than those for low air bursts, Brode goes on to say that some of the surface burst data shows a spread of plus or minus 25% below 40 psi, increasing to plus or minus 50% above that overpressure. (U13). It is difficult to have much statistical confidence in mean values calculated from such sparse data with such a wide spread, especially when the instrumentation difficulties that obtained at the time are considered; it is even more difficult to have confidence in the result when such mean results are extrapolated to apply to bursts of the order of 100 times as large as the bursts from which the data were collected.

Figure 2.5.3 --- Overpressure Data From Nuclear Tests



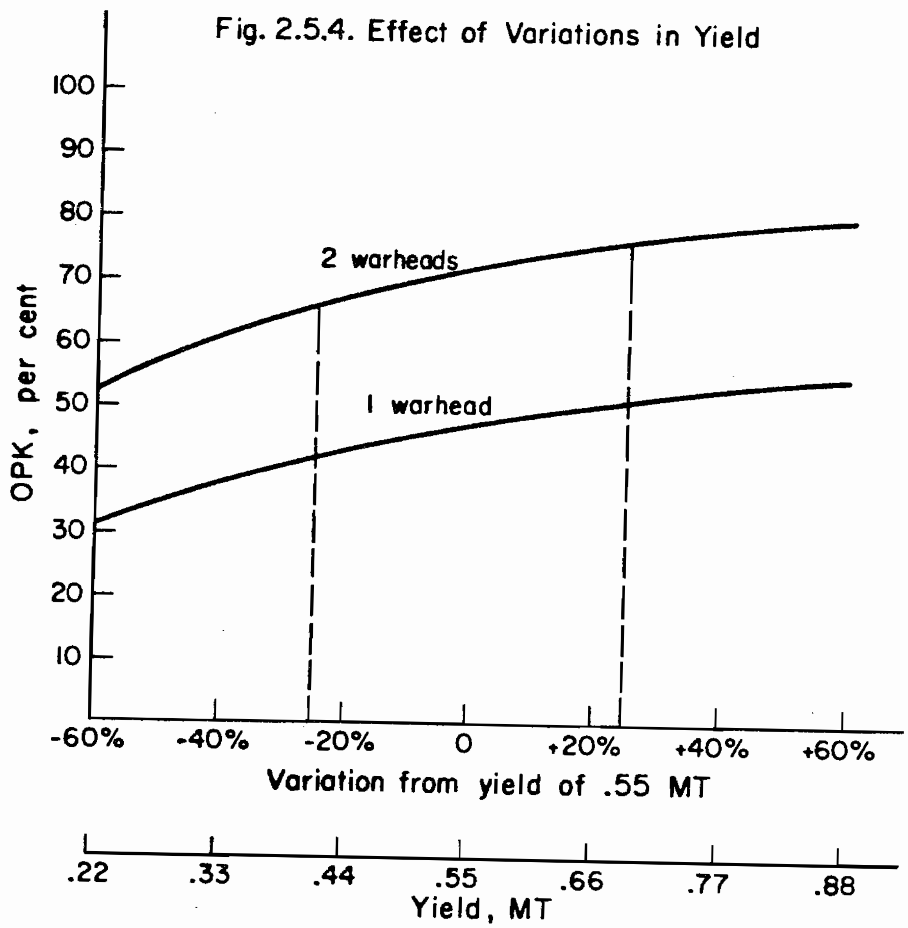
Overpressure Data vs HOB and Range (scaled to 1 KT) --Triangles = 15 psi, Squares = 40 psi, Circles = 100 psi, Diamonds = 400 psi, Inverted Triangles = 2000 psi.

Indeed, the situation contains greater uncertainty than even these data would indicate; the probabality that a missile silo will fail is in fact more closely related to the <u>impulse</u> (overpressure integrated over time) than to the peak overpressure, and the impulse data are even more fragmentary. According to Brode: "there are fewer data for impulse than for overpressure [and] there is more scatter in the data. Impulse measurements are more demanding of the intrumentation...Impulse data are inadequate at 4 psi-sec (about 500 psi) and completely lacking at higher levels" (U14). It should be pointed out in this connection that the Soviet Union has conducted far fewer atmospheric nuclear tests than has the United States.

Thus, the relevant data for high overpressures is limited in number of points, and shows a wide spread among those points, especially if the attacker chooses to burst above 100 scaled feet to avoid fratricide, as described in section 2.4. It is clear that any estimates of warhead destructiveness based on these data contain very large uncertainties. Indeed, even the official U.S. estimates in <u>The Effects of Nuclear Weapons</u> and Defense Intelligence Agency reports differ from each other by as much as 18% (U15). However, to be conservative, we will use the DIA estimate of an uncertainty of plus or minus 20% in the overpressure at a given range. To simplify our modeling of the effect, we will translate this overpressure uncertainty into an uncertainty in the yield, using equation 2.2.6: a 20% variation in overpressure at a given range would be caused by a yield variation of about 20%.

In addition to these effects uncertainties, there are some uncertainties in estimating the mean yield of a given weapons design. These uncertainties may be marginally larger for extremely recent designs, since neither side has conducted full-scale tests of large warheads for several years, as a result of the as-yet unratified Threshhold Test Ban Treaty. As mentioned above, uncertainties in warhead yield are commonly given as plus or minus 10%, although given the uncertainties with regard to measurement described above, it is possible that the uncertainty may be higher. Again, we will be conservative, and assume that the combination of these two types of uncertainty result in an overall uncertainty in the mean destructiveness of

Fig. 2.5.4. Effect of Variations in Yield



the warheads of roughly 25%. Figure 2.5.3 shows the effect of variations in the effective warhead yield on the kill probability of an SS-19 against a Minuteman silo. Again, the kill probability is reasonably sensitive to small variations of the parameter, although less so than is the case with the CEP; an unfavorable variation of 25% in the average yield of the warheads would reduce the number of silos destroyed in a two-on-one attack from 72% to 66%.

D. HARDNESS

The hardness of the missile silos to be attacked is perhaps the most difficult parameter for a potential attacker to assess with confidence, for the simple reason that the silos were designed and constructed by the opponent, and are not available for examination and testing.

While intelligence regarding ballistic missiles and nuclear warheads can be gathered by monitoring tests of the opponent's weapons, this is not possible with hardened missile silos; they are essentially inanimate objects with comparatively few easily observable features. The overpressure at which a silo will fail is related in a complex way to the mass, the thickness, the strength, and the ductility of the silo cover, and it would be extremely difficult for an attacker to have precise, high-confidence estimates of these parameters prior to an attack.

Indeed, it is difficult to precisely assess the hardness of one's own silos. Although assessments such as this one commonly concentrate on the blast wave overpressure as the primary kill mechanism, a wide range of nuclear effects can inflict damage on a hardened missile silo, and the magnitude of many of these effects is impossible to predict beforehand; as an example, the propagation of the groundshock, one of the more important damage mechanisms, is crucially dependent on the state of the local water table. In a nuclear detonation, these effects would act synergistically; it is thus quite possible that the vulnerability of silo-based missiles is greater than calculations based on the overpressure alone would indicate. However, it would be completely impossible for an attacker to have reasonable confidence that this would be the case.

The fact is that <u>no silo has ever been exposed to a nuclear detonation in any test</u>. Some tests have been done involving shaped-charge conventional explosives, but the uncertainties in such a procedure are very great; the available data for assessing the capabilities of hardened structures is extremely limited, and the uncertainties in such assessments remain high. Given the difficulties of assessing the hardness of one's own silos, it is nearly impossible to accurately estimate the hardness of the opponent's silos, as pointed out by by Gen. Alton Slay in 1979 testimony: "The only reason for goin through this rain dance is to say that we are expecting intelligence people to do an awful lot with an analysis when we had to spend $300 million to find out how hard our own silos were." (U16).

Thus, an uncertainty of at least 20% in estimates of the hardness of silos to be attacked would be very difficult to eliminate.

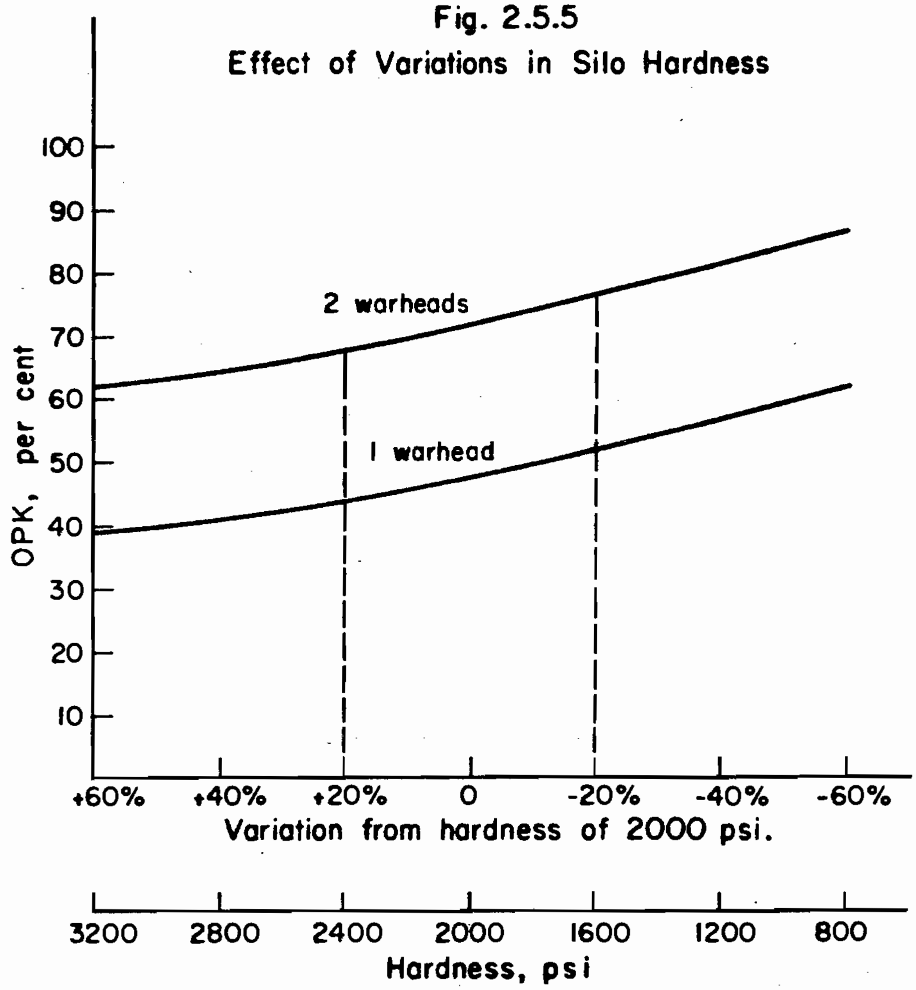


Figure 2.5.5 shows the effect that variations in the hardness of the Minuteman silos would have on the probability that attacking SS-19 warheads would destroy them. As can be seen, the sensitivity of the outcome to this parameter is similar to that for the yield, as would be expected from their similar positions in the kill probability equations developed in section 2.2; an unfavorable variation of 20% in this parameter would reduce the number of silos destroyed in a two-on-one attack from 72% to 68%.

2.6 OVERVIEW: THE EFFECT OF COMBINED UNCERTAINTIES

In the last several sections of this report, we have discussed a variety of uncertainties that would be involved in any large-scale countersilo attack, and have made very rough quantitative estimates of the effect each uncertainty, acting individually, could have on the outcome of an attack by current Soviet weapons on current U.S. Minuteman silos. However, in a real strike, these uncertainties would all be present, making the final outcome of the attack even more difficult to predict. In this section we will provide a rough description of the combined effect of these uncertainties (U17).

Figure 2.6.1 shows the effect that simultaneous variations in all of the parameters discussed in the last section would have on the outcome of an attack on the Minuteman silos by SS-19s (The format on this graph is the same as that of the previous ones, except that the negative and postitive signs refer only to the effect of the given variation on the kill probability, not to the actual direction in which a parameter has varied; on the negative side of the chart, the yields are smaller than the base value of .55 MT, while the CEPs are larger). As can be seen, if all of the attack parameters are varied simultaneously, even small variations can have a very noticeable effect on the outcome of an attack.

However, while incorporating the uncertainties in the basic parameters of the attack that we discussed in the last section, Figure 2.6.1 ignores the effect of bias and fratricide, and the fact that the uncertainties we assumed in some parameters were larger than the uncertainties in others. For these reasons, Figure 2.6.2, which includes the effect of bias and fratricide, is perhaps more useful. Each row of the figure represents a different basic set of assumptions concerning the performance of the weapons involved in the attack, while each column represents a different value of the bias; combined, they show the effect that biases of the given magnitudes would have on the given assumed attacks.

Row I shows the result of an idealized attack with perfectly reliable weapons, such as is often assumed in the popular literature. In the absence of bias, such an idealized attack owuld destroy nearly 90% of the U.S. ICBM force. Row II shows the result of an attack with 75% reliable weapons; as can be seen, the result is considerably less favorable to the attacker. Row III shows the result of an attack with imperfectly reliable weapons that also encounters light fratricide (U19); as can be seen, this also substantially degrades the probability that a given silo will be destroyed. Row IV is perhaps the most important: it shows the effect of combining light fratricide with unfavorable variations in all of the basic parameters of the attack (U20), representing one possible "bad case" which the attacker must consider. The result in this case is drastically

Fig. 2.6.1

Effect of Combined Parameter Variations

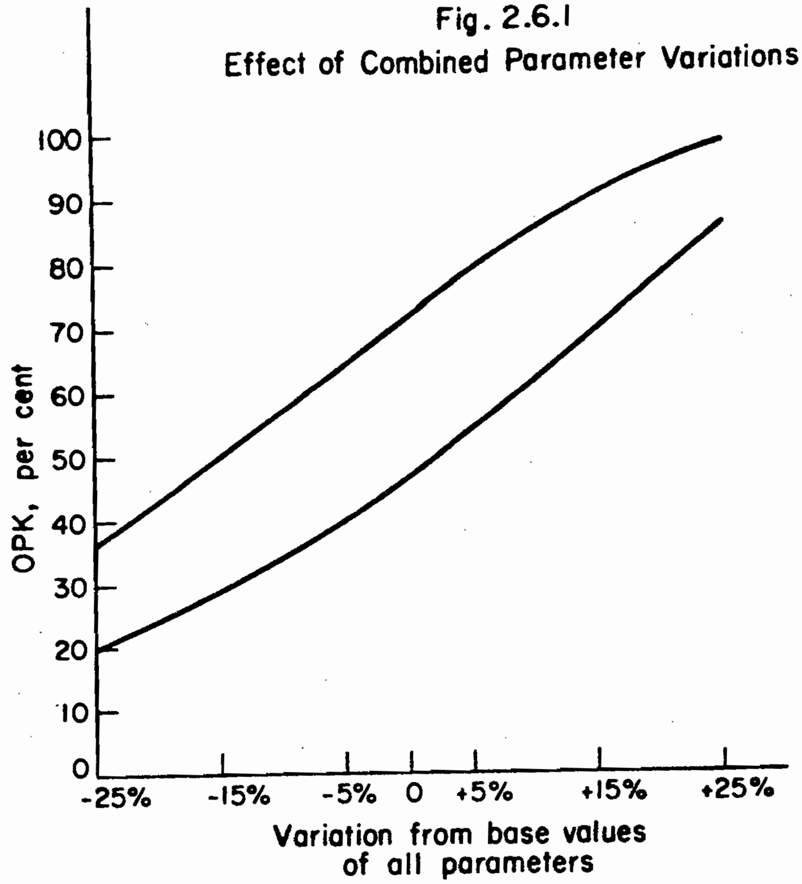


Fig. 2.6.2

Effect of Combined Uncertainties

Assumptions	Bias, in n. mi.			
	0.0	0.05	0.10	0.15
100% reliability	.86	.84	.76	.63
75% reliability	.72	.70	.62	.50
light fratricide	.65	.62	.56	.45
unfavorable variations	.45	.43	•.38	.31

less favorable to the attacker than those of the idealized attack in Row I; the number of surviving silos in the first column has nearly quadrupled between the two, and the percentage destroyed has dropped below 50% in the latter case. While it could be argued that a case involving large unfavorable variations in <u>all</u> of the attack parameters simultaneously is unlikely to occur, it should be noted that an unfavorable variation of any two of the four basic attack parameters, when combined with light fatricide, would lower the percentage of silos destroyed to 55% or below, even in the absence of bias.

Thus, if the descriptions of the technical capabilities of Soviet weapons available in the unclassified realm are approximately correct (and we believe that they are, if anything, conservative), it would be essentially impossible for a Soviet planner to have reasonable confidence of being able to destroy significantly more than half the U.S. land-based missile force. However, this comparatively comforting conclusion will not remain valid indefinitely: weapons technology is never in stasis, and this situation is likely to change drastically in the coming years. It is to the future that we turn in the next section.

2.7 LOOKING TOWARD THE FUTURE

In the last several sections, we have argued that technical uncertainties would make it impossible for a Soviet planner to have reasonable confidence in destroying significantly more than 50-60% of the current U.S. ICBM silos in a first strike, given the capabilities of current Soviet weapons. However, in the absence of any significant limitations, the technology of strategic weapons is almost certain to improve; while technological improvements cannot eliminate many of the uncertainties we have discussed, they could significantly reduce their impact on the outcome of an attack. In this section, we will discuss some likely developments in weapons technology, and the effect they would have on the outcome of an attack on the Minuteman silos.

Both the USSR and the US have had the capability to produce nuclear warheads with a very broad range of explosive power for many years now; technological advances will not increase the possible yield of nuclear weapons. However, noticeable improvements continue to be made in the weight of nuclear weapons of given yield; in the future, missiles similar to current missiles in the weight of the payload they are capable of carrying to the target ("throw-weight") will be able to carry either warheads of larger yield, or larger numbers of warheads. Since the Soviet Union is, at the moment, considerably behind the United States in this respect, they have more room for improvement in the coming years. While the total destructive capacity of a given missile force may thus increase, the yield of individual warheads will be a function of policy decisions, rather than directly of technological improvements. Improvements in various aspects of missile technology and modeling methods will tend to improve the reliability of ICBMs, but these improvements are likely to be fairly small; an ICBM is an extremely complex technical device, and it is probably unrealistic to expect operational total-system reliabilities of greater than 90% (Fu1). In contrast to weapon yield and reliability, the field is wide open for drastic improvements in missile accuracy, which could have an enormous impact on the outcome of countersilo attacks, and the confidence with which such outcomes can be predicted. It is these developments, therefore, that we will discuss in this section.

A. THE NEAR TERM: INCREMENTAL IMPROVEMENTS IN TECHNOLOGY

Both the United States and the Soviet Union are currently engaged in active ballistic missile development programs, intended to significantly enhance the technical capabilities of their weapon systems. In the United States, these efforts are centered around the MX ICBM, the D5 Trident II SLBM, and the Pershing II intermediate-range ballistic missile (IRBM). All of these systems are predicted to have accuracies considerably greater than those of their predecessors. For its part, the Soviet Union has been testing a fifth, more accurate modification of the SS-18, initial deployments of which may begin as early as 1985 (Fu2), as well as a new generation of ICBMs; two apparently distinct systems have been tested so far,although one may be classed as a modification of the old SS-13 (Fu3). Most of these systems will be significantly more accurate than their predecessors, as has been the rule with strategic nuclear weapons since the earliest stages of their development: the MX, for example, is predicted to be roughly twice as accurate as the latest modification of the Minuteman III, with a CEP of .05 nautical miles.

For the most part, systems such as the MX rely on improvements in the same basic technologies we discussed in the first half of this paper, rather than revolutionary new technologies. Most of the improvement in the MX will result from the Advanced Inertial Reference Sphere (AIRS) guidance components, which will offer radically increased azimuth alignment and inertial sensing capabilities (Fu4). In addition, the MX is currently scheduled to be armed with the Advanced Ballistic Reentry Vehicle, which will be somewhat more accurate than the Mk. 12A, primarily because of improved fusing capabilities, and will have a larger yield and a better ability to survive reentry under adverse weather conditions (Fu5). Other incremental improvements are under development which are not directly associated with specific missile programs. One such program is the efforts to develop RV nosetip materials better able to survive passage through clouds of water vapor, ice particles, or dust, to provide all-weather capability and to minimize the impact of fratricide. Another is the continuing effort to develop more accurate gravity information and models. One of the most significant recent developments in this field has been the beginning of global satellite altimetry: since fluids always flow in such a way as to minimize their potential energy, the ocean's surface represents an equipotential surface of the gravity field; detailed data concerning the gravity field over ocean areas can therefore be obtained by measuring the height of this surface using satellite-mounted radar altimeters (Fu6). In addition, efforts are always under way to develop more capable gyroscopes and accelerometers for a variety of missions.

The Soviet Union is pursuing similar incremental improvements of basic inertial technologies, and it can be expected that the new Soviet ICBMs currently being tested will be considerably more capable than their predecessors. Unfortunately, the Soviet Union never publishes estimates or predictions of the accuracy of its weapon systems, and with only a tiny number of tests of each of the new ICBMs having been conducted so far, it is far too early for U.S. intelligence to make estimates of their accuracy; however, for the sort of order-of-magnitude estimates that we are interested in here, a useful rule of thumb is that the accuracy of each nation's ICBMs increases by a factor of two roughly every seven years, with the Soviet Union several years behind the

United States in the progression (Fu7). Given that current Soviet ICBMs are reported to have a CEP in the range .13-.15 n. mi., it is not unlikely that by the late 1980s, the USSR will be beginning to deploy systems with a CEP comparable to that of the hypothetical system discussed in the first half of this paper, i.e., of the order of .08 n. mi. Indeed, since the most accurate current Soviet guidance systems first began to be tested as early as 1977-78, it is by no means out of the question that by the beginning of the 1990s, the Soviet Union will be deploying ICBMs of considerably greater accuracy.

It is possible to estimate roughly what effect changes in accuracy would have on the technical uncertainties we have been discussing. Figure 2.7.1 shows the effect the same combined uncertainties we discussed in the last section would have on a possible (but completely hypothetical) Soviet system that might be deployed in the late 1980s or early 1990s: the system has a CEP of .08 nautical miles, carries several warheads with yields of .6 MT, and has a reliability of 80%. The calculations assume that the hardness of the U.S. ICBM silos does not increase in the interim (Fu8).

Fig. 2.7.1

Effect of Uncertainty on Hypothetical Future System

Assumptions	Bias, n. mi.			
	0.0	0.05	0.10	0.15
100% reliability	.99	.99	.96	.79
80% reliability	.95	.93	.86	.68
+ light fratricide	.92	.90	.82	.64
+ unfavorable variations	.80	.77	.64	.45
+ 80% reprogramming	.87	.84	.72	.52

As can be seen, the increase in accuracy and the slight increases in yield and reliability have created a much more serious situation. Even though we have not reduced the <u>magnitude</u> of the various technical uncertainties we have assumed, the <u>effect</u> of these uncertainties has been greatly reduced. Even with all of the postulated unfavorable variations, light fratricide, and a bias of .05 nautical miles, such a system could still destroy something like 80% of the U.S. Minuteman ICBM silos; if the Soviets develop the capability to launch a quick reprogrammed attack wave to replace 80% of the failures of the first two waves, they could cut the number of surviving silos in half again, destroying of the order of 90% of the U.S. silos. If the unfavorable variations did not occur, an even larger percentage of the U.S. silos would be destroyed. It should be noted, however, that this does not necessarily <u>prove</u> that an attacker could have high confidence in the success of a countersilo attack, if only such accuracies could be achieved: our estimates of the uncertainties involved are very rough, and in any case, consider only the technical, and not the broader political uncertainties.

It should also be noted that our estimate of the CEP is completely hypothetical, and does not represent any intelligence data whatsoever; the facts may prove it to be either an underestimate or an overestimate. Of course, a lower CEP would mean even higher kill probabilities than those shown here. However, this provides a rough estimate of the effect of foreseeable changes in technology; the increasing accuracy of ICBMs will considerably reduce the effect of the technical uncertainties we have been discussing, with the result that in the 1990s, the real countersilo capability of the ICBMs of both nations will be very significantly greater than it is today.

B. THE LONGER TERM: REVOLUTIONARY NEW GUIDANCE TECHNOLOGIES

The improvements in accuracy we have just discussed will begin to strain the limits of conventional all-inertial, all-ballistic guidance technology. As the reader will remember from the discussion of reentry technology in the first half of this paper, efforts to reduce the atmospheric contribution to CEP by increasing the beta of the reentry vehicle will soon encounter diminishing returns; it is unlikely that atmospheric contributions to CEP can be reduced to less than several tens of meters (Fu9). To this relatively fundamental barrier must be added a myriad other error sources, all of which are possible, but are now becoming difficult and costly, to reduce: unpredictable ablation phenomena, inertial sensing and alignment errors, gravity errors, and so on. As a result, it is not possible to achieve arbitrarily low CEPs with all-inertial, all-ballistic technology; we very much doubt that a system could be designed using this technology that could achieve a CEP lower than .03 nautical miles, over the 10,000 km range. Indeed, it is quite possible that it will be found uneconomical to attempt to achieve accuracies greater than the .05 n. mi. CEP forecast for the MX without incorporating more revolutionary guidance concepts.

Accuracies in this range would greatly reduce the technical uncertainties involved in an attack utilizing weapons with yields similar to those of current weapons; indeed, with current yields and foreseeable developments in silo hardness, such accuracies could be described as overkill. However, the detonation of 2000 or more half-megaton weapons at or near the ground would cause tens of millions of civilian casualties; this is hardly the sort of "precision" strike described in many popular scenarios. In order to reduce the number of civilian casualties, warheads with much smaller yields must be used; to achieve high confidence of destroying a hardened target would then require greater accuracies. If one stretches the theory to its extreme, a weapon with a CEP and bias of essentially zero might conceivably be able to destroy a hardened silo with conventional explosives.

As a result of such considerations, a variety of new technologies are being developed which represent fundamental modifications of the all-inertial, all-ballistic guidance concept; that is to say, either the weapon receives additional information concerning its trajectory beyond that available from its inertial sensors, or guidance continues after thrust termination, making the path no longer entirely ballistic, or both. The classification of these technologies as falling into the "long term" future is in some sense arbitrary, as several weapons already under development in the United States incorporate some of these guidance concepts, including the cruise and Pershing II missiles.

The NAVSTAR Global Positioning System (GPS) satellite now being deployed by the U.S. has a wide variety of possible uses, including applications to ballistic missile guidance. GPS will eventually consist of 18 satellites (scaled down from an original plan for 24) in 6 orbital planes, with orbital periods of roughly 12 hours. The satellites will continuously broadcast their position: with 18 satellites, at least three will be within line-of-sight on any point of the earth at any time, and users with appropriate receivers will be able to triangulate from the three signals to find their current position and velocity. Military users should be able to determine their position to within 10 meters in three dimensions, three-dimensional velocity to within .03 m/sec, and time to within a millionth of a second; civilians will also be able to utilize the system, but will receive much less accurate information (Fu10).

This type of continuous position and velocity information has an enormous range of possible military applications, including the possibility of improving the accuracy of certain types of ballistic missiles. The most immediate application is to submarine-launched ballistic missiles: since the bulk of the error budget of current SLBMs results from uncertainties in the initial position and velocity of the submarine at launch and the launch region gravity, an update from GPS satellites before the end of the boost phase would make the accuracy of SLBMs competitive with that of land-based missiles. Indeed, this concept was considered for the Trident II D5 missile now under development, which is intended to be accurate enough to enable it to attack hardened targets.

Even greater accuracy could be achieved if additional corrections were made at the end of the flight; if each warhead received position information from the GPS satellites immediately before reentry, and corrected its trajectory accordingly, all errors except those associated with the reentry process itself could be eliminated. If the warheads were designed to fall through the atmosphere slowly, so that an ionized plasma would not form around them and prevent radio communication, each warhead could theoretically continue to correct its trajectory all the way to the target, eliminating even reentry errors. However, any guidance concept that involves corrections _after_ warhead release requires that each warhead have its own receiver, guidance, and propulsion system, greatly increasing the complexity of the warhead, and the weight required for a given yield.

GPS satellites have one very significant weakness as aids to ballistic missile guidance: given the continuing development of anti-satellite weaponry by both superpowers, and given the importance either superpower would attach to preventing the successful guidance of the opponent's missiles, it is impossible to guarantee that the satellites will survive long enough to be used in an actual exchange, or that communications between the satellites and ballistic missiles would not be interrupted. In the absence of arms-control limitations on antisatellite capabilities, this will substantially limit the usefulness of GPS satellites for ballistic missile guidance purposes.

For this reason, another, similar concept has been more actively pursued: tracking on invulnerable stations, the stars. This method is commonly known as stellar-inertial guidance (SIG), and has been in common use for some years; the U.S. Poseidon SLBMs utilize the concept, and the Soviet Union has demonstrated SIG capabilities as well (Fu11). In the past, it has been impossible to achieve accuracies comparable to GPS with this method, but the Trident II missile is now expected to achieve accuracies better than the current Minuteman III ICBM, using improvements of this method (Fu12), as well as high-frequency sonar for determining the submarine's intial velocity.

Another new technology, called gravity gradiometry, offers the theoretical possibility of real-time measurement of the gravity field, as an alternative to reliance on gravity models developed from prior measurements. In principle, a gravity gradiometer is somewhat like an accelerometer: although Galileo pointed out that it is impossible to measure one's own velocity without reference to the outside world, an acelerometer-based inertial system gets around that difficulty by measuring not the velocity but the _rate of change_ of the velocity. Similarly, although Einstein showed that it was impossible to distinguish the presence of a gravitational field from an acceleration, gravity gradiometers get around this difficulty by measuring not the gravitational field, but its rate of change, or the gravity gradient. Gravity gradients were first measured by the Baron Roland von Eotvos, in the 19th century; however, instruments sensitive enough to be useful in inertial guidance applications have been under active development only in the last several years (Fu13).

Since the gravity field is extremely erratic, it has proven impossible to model it in a simple analytical way: to provide gravity models over flight paths that are not predetermined has proved to be an extremely difficult process, and for systems that travel close to the ground for long distances (such as airplanes, submarines, and cruise missiles), the inadequacy of these gravity models has sharply limited the accuracy of inertial navigation. Development of accurate, mobile gravity gradiometers (still some years away) would greatly increase the accuracy of inertial navigation for these systems. In addition, gravity gradiometers allow very rapid area gravity surveys: this would have a wide range of civilian applications, as well as assisting in the development of launch-region gravity models for fixed-based and especially for mobile ballistic missiles. Such techniques could drastically improve the accuracy of SLBMs, in reducing both the uncertainties in the submarine's inertial navigation, and the uncertainties in the launch-region gravity, which is much more difficult to model for missiles launched from moving submarines than it is for fixed-base ICBMs (Fu14). The usefulness of gravity gradiometry to fixed-base ICBMs is less clear, because gravity errors cause a much smaller proportion of the total error budget.

Since the inherent uncertainties of ballistic reentry represent the largest fundamental barrier to the accuracy of all-ballistic systems, perhaps the most important long-term development in ballistic missile guidance technology is the development of maneuvering, guided reentry vehicles. Preliminary tests of such vehicles were undertaken in the United States in the 1960's, but it was not until the mid-seventies that the United States began a serious exploration of this technology; the Soviet Union is considerably behind the United States in this respect.

In concept, a maneuvering reentry vehicle requires two things: a method of changing the vehicle's course, and a guidance system to direct those changes. A number of methods for maneuvering the vehicle have been studied, from gas-jet propulsion, to stubby wing flaps, to bent noses that can be rolled to turn the vehicle in different directions. Two basic types of reentry vehicle guidance systems can be envisaged: self contained inertial guidance, much like that now used for the first stage of flight, or guidance that relies on information from outside the RV, such as RVs that "home in" on the target's optical, infrared, or radar signature. In addition to these different maneuvering and guidance technologies, maneuvering reentry vehicles (MaRVs) have two different missions, which require somewhat different technologies: to improve accuracy, and to evade anti-ballistic missile systems.

Inertially guided reentry vehicles offer the prospect of reducing errors attributable to reentry, both those resulting from atmospheric variations and those resulting from imperfections of ablation, to near-zero levels. The U.S. has two inertially-guided MaRVs under development. The Mk. 500 RV developed for the Trident missile is designed for simple maneuvers to evade ABMs; its guidance system is a rather rudimentary one, and its accuracy is less than that of the ballistic Mk. 400 also developed for the Trident (Fu15). The Advanced Maneuvering Reentry Vehicle (AMARV) research program represents much more advanced technology, but AMARV is not under full-scale development for any current missile system. AMARV is designed to provide both maneuvering capability and high accuracy; it is the first operationally sized RV with a complete three-dimensional inertial guidance system (Fu16). Three flight tests have been conducted so far, and the technology is now being refined (Fu17).

The inertial sensing requirements for MaRVs are significantly different from those for boost-phase guidance, as the instruments must be small, light-weight, and able to withstand much more severe acceleration and vibration environments; nosetip and heatshield requirements are also increased. Acceleration environments are especially extreme in the case of MaRVs designed for ABM evasion, which requires sharp, high acceleration turns.

While inertially-guided MaRVs will help to eliminate reentry errors, they will not remove the other errors of inertially guided systems; terminally homing MaRVs, on the other hand, offer at least the theoretical possibility of CEPs of essentially zero. In concept, a terminally homing MaRV is simply one that receives some outside information as to its location relative to the target, allowing it to find the target more or less exactly. We have already discussed one theoretical possibility for such a MaRV, in the discussion of the Global Positioning System. However, no current U.S. strategic missile development program relies on satellites, because of their inherent vulnerability: most current efforts in this area center, instead, around receiving electromagnetic signals from the target area. The U.S. has been investigating these technologies for several years, under the aegis of the Precision Guided Reentry Vehicle (PGRV) program; it is intended that these technologies be incorporated into AMARV at some later stage of development (Fu18).

Most of the technologies currently being investigated involve active radar sensing of the target terrain: these include the terrain recognition system developed for the cruise missile (TERCOM), which compares data from a radar altimeter with maps of ground features stored in the missile's on-board computer, and more complex radar image systems similar to those to be used on the Pershing II IRBM (Fu19). These concepts represent a great number of potential difficulties; as is widely known, the guidance systems for both the cruise missile and the Pershing II have encountered problems in development and testing. If either of these systems were to be used on an intercontinental-range MaRV, the RV would have to be slowed down substantially before it reached the target, as current RVs travel through the atmosphere so rapidly that they are enveloped in ionized plasma until just before they reach the ground, making radar guidance impossible; the design requirements for radars to survive both the acceleration and the plasma environments are quite severe.

Perhaps more importantly, any system which utilizes radar is potentially vulnerable to jamming and other electronic countermeasures. If terminal homing MaRVs capable of destroying high-value hardened targets are deployed, the target superpower is likely to give high priority to electronic countermeasures against them: whether a system of this type can be developed that is essentially invulnerable to such efforts remains an open question.

Should such a system be developed, however, the door would lie open to extremely high accuracies, which would enable an attacker to destroy hardened silos with weapons of low yield, minimizing the number of civilian casualties that would be inflicted. Such a situation would reduce the chances that a countersilo attack would escalate to all-out war, increasing the possible temptation to launch such an attack, especially in a crisis when the attacker's own weapons were similarly threatened. In the absence of arms-control limitations on the technological developments we have described, the development of such a dangerously unstable situation cannot be ruled out.

2.8 CONCLUSIONS

As we have discussed in the last several sections, any large-scale countersilo attack would be subject to a number of uncertainties: the CEP, destructiveness, and reliability of strategic weapons missiles can be estimated only with some uncertainty, because of the basic limitations of peacetime testing; the hardness of the target silos is extremely difficult to predict, as a result both of the fact that no silo has ever experienced a nuclear blast, and because of the difficulty of obtaining reliable intelligence as to the design features of target silos; the precise effects of fratricide are difficult to predict, and can never be tested, as a result of the Partial Test Ban Treaty; and the possibility of systematic biases large enough to have some significance, arising from gravitational errors, targeting uncertainty, and atmospheric variations, cannot be ruled out.

As a result, the outcome of such an attack is essentially impossible to predict; given the capabilities of current weapons, it would be extremely difficult even to determine whether the percentage of targets destroyed would be as low as 50 or as high as 90 per cent. The common practice of stating the probable outcome of such attacks to two significant figures, on the basis of extremely simplified calculations, is therefore misleading, and should not be the basis for major policy decisions concerning nuclear weapons. Indeed, given the complexity of an attack involving hundreds of intercontinental missiles delivering thousands of thermonuclear warheads over variable ranges to more than a thousand separate targets, it is hardly surprising that a modeling method involving only four variables has proved to be inadequate.

In addition to the technical problem of predicting how many ICBM silos would be destroyed in the event of such an attack, there would be even larger political uncertainties. If, for example, the defender chose to launch his weapons on warning of the attack, the attack would be fruitless, regardless of the number of empty silos destroyed; it would amount to an act of national suicide. Even if the defender chooses not to launch on warning, the response to such an enormous attack, possibly involving millions of civilian casualties, is difficult to predict: the punishments that could easily be inflicted with the defender's remaining weapons would be completely unacceptable to any rational attacker. (A longer discussion of the political problems associated with such an attack can be found in Appendix A).

However, in the absence of significant restraints on nuclear weapons technology, many of the technical uncertainties will evaporate over the coming years. Once intercontinental ballistic missiles are twice as accurate as is necessary to ensure destruction of the target, variations of 10 or 20 per cent in such parameters as accuracy, yield, and silo hardness will no longer be of much importance, and the purely <u>technical</u> feasibility of such an attack will be much increased.

In the longer term, it is conceivable that supremely accurate maneuvering reentry vehicles can be developed that are essentially invulnerable to countermeasures; such weapons could destroy hardened silos with weapons of much smaller yield, which could mitigate some of the <u>political</u> risks of such an attack as well. In our view, such a development would be profoundly destabilizing, and would represent a significant decrease in the security of both the United States and the Soviet Union.

APPENDIX A: OTHER PROBLEMS OF COUNTERFORCE SCENARIOS

For the last several years, the driving force behind most strategic debate in the United States has been the conception that the Minuteman force is vulnerable to Soviet attack, and that this, in and of itself, constitutes a major problem which must be solved by the deployment of an accurate land-based missile. This argument is based on the following premises:

I. Soviet ICBMs have the technical capability to destroy essentially all of the U.S. land-based ICBM force in its silos, in a first strike.

II. Since the U.S. ICBM force is the only portion of the U.S. force capable of responding in kind by an attack on Soviet silos, a Soviet strike that destroyed the U.S. ICBMs would leave the U.S. with no choice but to surrender or to escalate to attacks on cities.

III. The collateral damage caused by such a strike would be small. As a result, the U.S. could reliably be expected not to escalate to attacks on cities, because such attacks would only draw equivalent retaliation against American cities. The Soviet leaders could have complete confidence that U.S. leaders would continue to behave "rationally." Thus, the Soviet Union would not be deterred from launching such a strike.

IV. Thus, as a result of such a strike, the U.S. would thus be left with no choice but to concede whatever demands the Soviets made.

V. Even if such a strike were never launched, the perception of its possibility would weaken American resolve in international crises, and weaken the confidence of American allies in the U.S. nuclear guarantee, while emboldening the Soviet Union.

VI. The appropriate response to this problem is to deploy a new ICBM in a survivable land-based basing mode, with the requisite accuracy to ride out such a Soviet attack and respond in kind with a strike against the remaining Soviet ICBMs. By sparing cities, such a strike would reduce the chance that the conflict would escalate, thus providing a more credible threat; by destroying ICBM silos and command bunkers, it would attack those targets the Soviet leaders value most, and is therefore the only sure way to deter them from launching such a strike.

In our view, all of these premises are dubious in the extreme. This report has addressed the purely technical part of the question, premise one; in this appendix, we will briefly deal with some of the issues raised by consideration of the other premises.

Premise two is simply incorrect; a moment's thought will reveal that within the territory of any nation, there are a wide variety of possible targets that are neither cities nor ICBM silos. Many crucial economic targets, such as oil refineries, are usually separated from cities (or "non-collocated", in the jargon of the trade); similarly, many important military targets, whether they be troop concentrations, air bases, or logistics "choke points" are neither hardened nor in the vicinity of Soviet cities. In fact, as we discuss below, there are only three broad classes of targets that are sufficiently hardened to require an accurate ICBM: ICBM silos, command bunkers, and nuclear weapon storage sites. Both nuclear weapon storage sites and command bunkers could be destroyed by the surviving portion of our land-based bomber force, although it would take some hours; essentially any other target within the Soviet Union could be successfully attacked by the surviving SLBMs, amounting to some thousands of warheads, each considerably larger than those that leveled Hiroshima and Nagasaki. Thus, a wide range of flexible retaliatory options would remain, even in the absence of surviving ICBMs. The main difficulty in implementing a policy of "flexible response" is not the availability of weaponry, but the requirements for complex and survivable command and control.

It is not clear what the Soviet Union would have gained militarily by such an attack: U.S. counterforce capability would be destroyed, but Soviet counterforce capability would no longer be useful, since there will be no U.S. "force" left to "counter". Both sides will retain the capability to wreak unheard-of devastation on the other.

Indeed, the idea that an attack on the ICBMs would deprive the U.S. of an important counterforce capability is somewhat curious, because many of those who make this argument also argue that the current U.S. ICBM force is not adequate to attack Soviet silos; if the latter argument is true, then nothing has changed militarily as a result of such an attack, except that each nation has considerably fewer warheads available. However, statements that the Soviets possess some sort of "counterforce monopoly" are grossly misleading. In fact, even if Soviet silos are hardened to 3500-4000 psi, a U.S. Minuteman III, with a CEP of .1 nautical miles and a yield of 350 kilotons, would have almost exactly the same kill probability against a Soviet silo as would the warhead from an SS-19 Mod against a U.S. Minuteman silo. While the U.S. does not have enough warheads to attack all of the Soviet ICBMs, the vast majority of the Soviet ICBM force is concentrated in a few hundred MIRVed missiles, to which U.S. ICBMs pose a threat similar to that which current Soviet ICBMs pose to the U.S. land-based force. Indeed, the Soviets keep none of their bomber force on alert, and only 15% of their strategic submarines at sea; as a result, the Soviet Union would have enormously fewer surviving warheads after an American first strike than the U.S. would have after a Soviet first strike.

The third premise, that the collateral damage from such an attack would be low, involves even more enormous uncertainties than calculating how many silos would be destroyed in the attack. The Congressional Office of Technology Assessment recently estimated that a purely counterforce attack on the United States would cause between 20 and 45 million casualties. The current Air Force estimate is similar (1A). Even these terrifying estimates generally include only the casualties due to short-term fallout: in the longer term, the possibility of massive environmental damage and widespread epidemics cannot be dismissed. Much of the agricultural land of the United States would be contaminated with fallout, raising the possibility of world-wide famines. The lower bounds of these estimates are an order of magnitude larger than the total of number of American combat deaths in all previous wars combined.

The simple fact is that with current nuclear weapons technology, there is no such thing as a "precision" nuclear strike; it is inconceivable that U.S. leaders would not launch a devastating retaliation to an attack on such a scale. Thus, the implausibility of premises two and three makes premise four, that the U.S. would respond by granting whatever demands the Soviet Union made, seem ludicrous.

The fifth premise, that even in the absence of the attack, the perceived ability to execute such a strike would make a decisive difference in world affairs, has two variants. The more extreme variant holds that the Soviets could extract political concessions from the U.S. in international crises by merely threatening such an attack. This seems to us quite silly; should such an explicit threat be received, the U.S. nuclear force would be put on alert. Any Soviet attack occuring after such a threat would probably lead the U.S. to launch on warning, regardless of what the U.S. declaratory policy had been. Certainly the Soviets could not be sure that this would not be the case. A large-scale countersilo attack is thus only plausible <u>outside</u> the context of a severe international crisis: if, for instance, fighting were occurring in Europe, Soviet planners could not possibly have confidence that the U.S. would not launch their ICBMs when they detected a Soviet launch of several thousand warheads.

The more subtle and plausible variant is that the perceptions of the strategic balance that might be created by a Soviet ability to destroy hardened silos would have a debilitating effect on the conduct of U.S. foreign policy, even in the absence of an attack or threat of an attack. U.S. confidence in its ability to maintain "escalation dominance" would be eroded, the Soviets would be emboldened, and U.S. allies would lose faith in the U.S. nuclear guarantee; the erosion of NATO confidence in U.S. willingness to use its strategic weapons in the defense of Western Europe is the most frequently cited example. On closer examination, it is our view that this erosion has little to do with the technical characteristics of the weapons involved: it is not a function of nuclear <u>superiority</u>, but of functional nuclear <u>parity</u>. As long as each superpower is perceived as being able to wreak unacceptable destruction on the other in retaliation for a first strike, sensible Europeans will have little faith that U.S. strategic nuclear weapons would be called into play in any European conflict. Indeed, it is our view that this functional parity will largely decouple strategic weapons from the conduct of international affairs. While international perceptions of power are undeniably important to the successful conduct of foreign policy, most world leaders have only the most impressionistic sense of the technical details of the superpowers' strategic arsenals; if there is anything approaching a universal impression, it is that both superpowers have far more nuclear weapons than could conceivably be needed. Indeed, a recent Brookings Institution study, commissioned by the Defense Department, found that "the data do not support propositions as to the importance of the strategic balance. It was not true that positive outcomes were proportionally less frequent, the less the U.S. advantage vis-a-vis the Soviet Union in the number of either nuclear warheads or delivery vehicles...our data would not support a hypothesis that the strategic weapons balance influences the outcome of incidents in which the United States and the U.S.S.R. are involved." (3A).

The enormous resources to be devoted to countering this perceived imbalance might well be better spent on forces that can actually be effectively brought to bear in a specific area of interest; it is these forces, combined with intangibles such as economic, diplomatic, and political power, that are more likely to be the determining factors in the perceptions of the various national "players" in international affairs. Indeed, it is interesting to note in this respect that while the vulnerability of U.S. strategic forces is a frequently-discussed topic in the United States, and is frequently asserted to be a primary issue in the defense of the NATO alliance, the vulnerability of our tactical nuclear forces, which have a much more immediate role in the defense of Europe, is rarely discussed.

The sixth premise, that the appropriate response to the perceived threat is to deploy an accurate missile, is perhaps the most dubious and pernicious of all. The basic question arises: what purpose would such a missile serve? As we pointed out above, there are only three main classes of targets that an accurate missile can destroy, which an inaccurate one cannot: ICBM silos, command bunkers, and nuclear-weapon storage sites. It can be assumed that in preparation for, or concurrently with the execution of a major nuclear first-strike, the Soviet Union would remove those weapons it considered necessary from their storage sites and disperse them to the military forces that would use them in any conflict that might ensue. Thus, the value of striking nuclear storage sites after the conflict has begun is likely to be marginal at best. The problem with a counterforce second-strike is similar: after launching a counterforce first-strike, the Soviet Union would surely have placed its remaining force on alert, and when Soviet radars detected the approach of several thousand

U.S. warheads targeted on their remaining ICBM silos, it is hard to believe that they would not simply launch their weapons; the U.S. counterforce second-strike would then destroy only empty silos, while bringing down an additional strike on the United States. It is thus unclear that an effective countersilo second-strike is a possibility; countersilo attacks may be, by definition, "useful" only in initiating a nuclear war.

It should be pointed out, as well, that a large proportion of Soviet ICBMs are based within the ethnic Russian heartland, with several bases immediately around Moscow; it is not clear that in the aftermath of an attack on these targets, Soviet leaders would continue to act "rationally", and avoid escalating the conflict to more destructive levels, as the effect of such an attack may seem similar to that of a counter-city attack. Again, there is no such thing as a "precision" strike, given current weapons technology. Thus, the argument that a retaliatory strike against ICBM silos is less likely to escalate to an all-out exchange than other types of attacks does not seem to be well-grounded in logic; as described above, it would provide powerful incentives for the Soviets to launch their remaining ICBMs, and would devastate much of the Russian heartland.

The last set of targets, command bunkers, also presents some difficulty. Firstly, our bombers could destroy such command bunkers within several hours; it is not completely clear why we would need to destroy them sooner, since the portion of the Soviet attack requiring extensive coordination is assumed to have already taken place. More disturbing, however, is that the destruction of these bunkers would remove any possibility of negotiating an end to the conflict, ostensibly one of the chief reasons to acquire accurate weapons in the first place; if the Soviet leadership is destroyed, then there is no one left who might be able to cease the carnage. Again, the assumption that accurate weapons are better able to prevent the conflict from escalating out of control does not seem to be grounded in logic: once the Soviet leadership was destroyed, "out of control" is exactly what the conflict would become.

We should point out, moreover, that the deployment of accurate weapons not only does not seem to provide the tangible benefits that have been assigned to it, but would actually help cause what we would regard as a significant decrease in U.S. security. In the current situation, the Soviet Union can be confident that any possible strike by the United States would leave them with considerably more than a thousand warheads with which to retaliate. Given the fact of American anti-submarine warfare superiority, both in geographic and technical terms, the most secure of these warheads are those on the land-based ICBMs. If an accurate American weapon were deployed, this would threaten those remaining warheads, reducing the force that could be reliably expected to survive a U.S. first strike to less then 5-10% of the original nuclear force. While it is difficult to imagine a situation in which initiating a nuclear war would be the most attractive policy option available, a crisis in which the Soviets had a considerable expectation that the U.S. might launch such a preemptive strike would be as close to such a situation as we can imagine. In that case, the only way the Soviets could insure their ability to retaliate would be to strike first; if the accurate U.S. weapon is based in a vulnerable basing mode, as is currently proposed, this would exacerbate this crisis instability still further.

A much more likely scenario is that the Soviet Union would choose either to put its nuclear force on a launch-on-warning posture, or to develop new types of weapon systems. Neither of these options would be favorable to the security of the United States: the first would put the fate of the world in the hands of Soviet computers (a situation no sane person could desire), while the second would greatly increase the strategic threat that the U.S. must face, and if Soviet "solutions" to the problem are similar to those that have been pursued in the United States, might greatly complicate the process of arms control. In the face of the American intention to deploy the MX, Soviet spokesmen have explicitly threatened to take both of these policy options. Thus, a policy of acquiring accurate ICBMs to counter Soviet accurate ICBMs is simply not a logical response to the problem, if there is one: such a deployment would decrease U.S. security rather than increasing it.

To conclude, it is our view that every one of the fundamental premises of the arguments concerning "the window of vulnerability" is incorrect. Specifically, we believe that the deployment of a counterforce-optimized weapon such as the MX would provide little useful additional capability for U.S. strategic forces, and would greatly increase the danger of nuclear war, especially if it is placed in a vulnerable basing mode. We regard it as a depressing comment on the state of strategic analysis in this country that the arguments outlined above have been successfully used to justify the expenditure of tens of billions of dollars.

APPENDIX B: TRAJECTORY OF A BALLISTIC MISSILE

A. THE EQUATIONS OF MOTION

To describe the motion of a ballistic missile, it is helpful to make several simplifications: first, we assume that the earth is a perfect sphere, with uniform density, and hence fulfills Newton's inverse-square gravity law; second, that it is non-rotating; and third, that it has no atmosphere. Equations based on this "simplified earth" give a good appoximation of the actual relationships between the variables in a ballistic trajectory (1B, 2B). Such a simplified description of the trajectory begins with two equations of motion (3B), the first derived from the forces acting on the missile:

(1B) $$\ddot{r} - r\dot{\theta}^2 + \frac{GM}{r^2} = 0$$

and the second derived from conservation of angular momentum:

(2B) $$\frac{d}{dt}(r^2\dot{\theta}) = 0$$

This second equation is equivalent to:

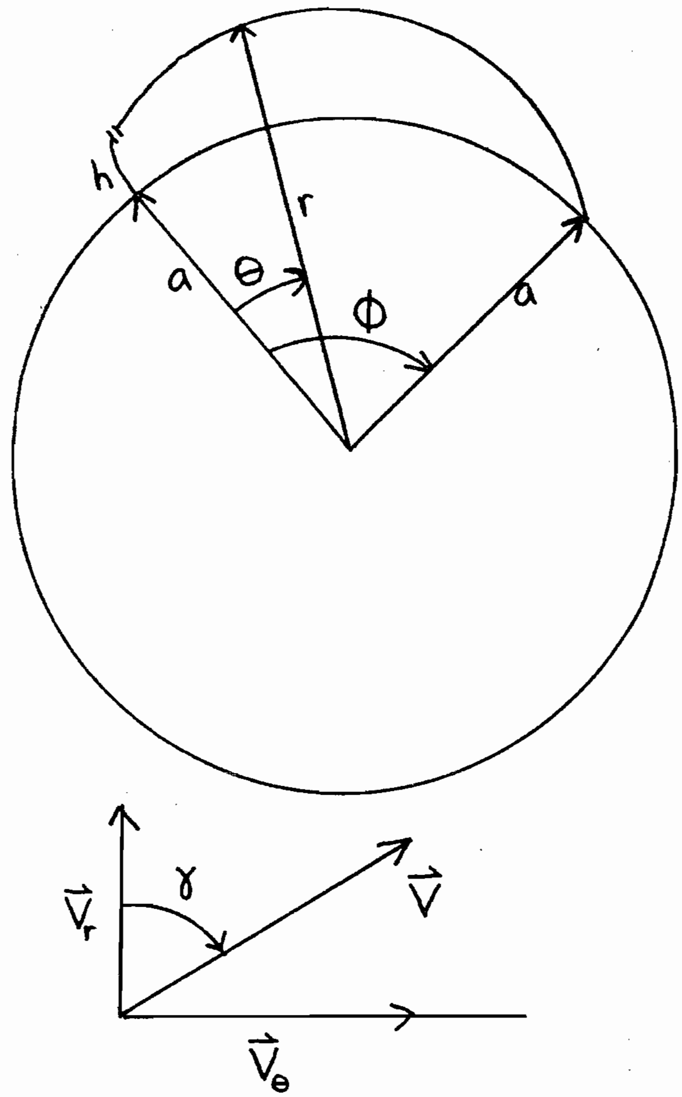
(3B) $$r^2\dot{\theta} = p$$

The constant p can be calculated using the initial values of the orbit variables:

(4B) $$r^2\dot{\theta} = r_0{}^2 \frac{V_\theta}{r_0} = r_0 V_\theta = r_0 V \sin\gamma = p$$

These variables are defined in Figure IB: Note that here, and for the rest of this discussion, we will use the variables that are directly controlled by the missile's guidance system, such as the burnout height, velocity, and angle (measured from the vertical), rather than more standard orbit parameters such as the eccentricity and the inclination; while this complicates the derivation, the resulting equations give good descriptions of the task facing the guidance system, which cannot be assessed using the more standard variables. Note also that:

(5B) $$r_0 = a + h \approx a$$



Equation (3) offers a simple way to convert between time derivatives and derivatives with respect to theta:

(6B) $$\frac{d}{dt} \equiv \frac{d\theta}{dt}\,\frac{d}{d\theta} = \frac{p}{r^2}\,\frac{d}{d\theta}$$

Equation (1B) can then be converted to a relationship between r and theta, without time, by first combining equation (1B) and equation (2B), and then converting to theta derivatives:

$$(7B)\quad \frac{p}{r^2}\frac{d}{d\theta}\left(\frac{p}{r^2}\frac{dr}{d\theta}\right) - \frac{p^2}{r^3} + \frac{GM}{r^2} = 0$$

B. THE HIT EQUATION

If we now define

$$(8B)\quad u = \frac{1}{r}$$

so that

$$(9B)\quad \frac{du}{d\theta} = \frac{-1}{r^2}\frac{dr}{d\theta}$$

we find:

$$(10B)\quad p^2u^2\frac{d}{d\theta}\left(-\frac{du}{d\theta}\right) - p^2u^3 + GMu^2 = 0$$

A rearrangement of this equation yields:

$$(11B)\quad \frac{d^2u}{d\theta^2} + u = \frac{GM}{p^2}$$

A simplification that will soon become useful can be made by defining:

$$(12B)\quad \eta = r_0 V^2/GM$$

Recalling equation (4), this gives:

$$(13B)\quad \frac{d^2u}{d\theta^2} + u = \frac{1}{\eta r_0 \sin^2\gamma}$$

Solving equation (13) yields:

$$(14B)\quad u - \frac{1}{\eta r_0 \sin^2\gamma} = A\sin\theta + B\cos\theta$$

where A and B are functions of the initial conditions. B can be found by remembering that:

(15B) $u(0) = 1/r_0$

Combining this with equation (14) yields:

(16B) $B = \frac{1}{r_0} - \frac{1}{\eta r_0 \sin^2\gamma}$

To find A, we notice that:

(17B) $\cot\gamma = \frac{V_r}{V_\theta}$

which is equivalent to saying that

(18B) $r_0 d\theta = \frac{V_r\, dt}{\cot\gamma}$

If we now cancel the time terms and replace r with u, we find our second initial condition:

(19B) $\left.\frac{du}{d\theta}\right|_0 \doteq \frac{-1}{r_0}\cot\gamma$

Combining this with equation (14) gives us A in terms of the burn-out variables:

(20B) $A = \frac{-1}{r_0}\cot\gamma$

Equation (14) can then be rewritten as:

(21B) $u - \frac{1}{\eta r_0 \sin^2\gamma} = \frac{-\cot\gamma \sin\theta}{r_0} + \left(\frac{1}{r_0} - \frac{1}{\eta r_0 \sin^2\gamma}\right)\cos\theta$

Rearrangement and the use of a double-angle trigonetric identity simplifies this to:

(22B) $ur_0 = \frac{1-\cos\theta}{\eta \sin^2\gamma} + \frac{\sin(\gamma-\theta)}{\sin\gamma}$

This equation defines the possible ballistic trajectories. For ballistic missiles, it is necessary to control the burnout variables so that the missile will fly a certain distance, passing through a given geocentric range angle and then landing on the earth's surface. Thus, our equations have a final condition as well as initial conditions:

(23B) At $\theta = \phi$, $r = a$

Combining this with equation (22) yields what is known as the "hit equation":

(24B) $$\frac{r_0}{a} = \frac{1-\cos\phi}{n\sin^2\gamma} + \frac{\sin(\gamma-\phi)}{\sin\gamma}$$

This equation describes the possible combinations of speed, angle of motion, and burnout height required for a missile to impact at a given range. The trajectories described by this equation take the form of Keplerian conic sections; there are, of course, an infinite number of such trajectories connecting any two points on the earth's surface. To specify a particular desired trajectory, it is necessary to specify one additional paramter, related to how high or low the missile will fly.

C. THE MINIMUM-ENERGY TRAJECTORY

There exists a single trajectory for a given range that requires less energy than any other, reaching the longest possible range for a given payload and quantity of propellant. The energy of a missile depends on both its velocity and its height; however, in most cases, the burnout height will be quite small in relation to the radius of the earth, so the minimum-energy trajectory is quite closely approximated by the minimum-velocity trajectory. To find this trajectory, we solve equation (24B) for the velocity:

(25B) $$V^2 = \frac{GM}{r_0}\,\frac{1-\cos\phi}{\sin^2\gamma + \sin(\phi-\gamma)\sin\gamma}$$

To find the value of gamma which requires the least velocity, we differentiate with respect to gamma, and set the result equal to zero:

(26B) $$\frac{d(V^2)}{d\gamma} = \left[\frac{GM(1-\cos\phi)}{r_0}\right]\left[\frac{1}{(\sin^2\gamma + \sin\gamma\sin(\phi-\gamma))^2}\right]$$
$$[2\sin\gamma\cos\gamma + \sin(\phi-\gamma)\cos\gamma - \cos(\phi-\gamma)\sin\gamma] = 0$$

Since neither of the first two terms will equal zero except in trivial cases, we can ignore them, and simplify the third with trigonometric identities:

(27B) $$\sin2\gamma + \sin(\phi-2\gamma) = 0$$

If we expand the second term of this equation, and simplify the result, we find an equation for the minimum-velocity burnout angle for any given geocentric range angle:

(28B) $$\tan 2\gamma_{min} = \frac{\sin\phi}{\cos\phi - 1}$$

This can be simplified to give:

(29B) $$\gamma_{min} = (\phi + \pi)/4$$

D. THE HEIGHT OF APOGEE

Apogee is defined as the highest point in a ballistic trajectory. If we simplify the situation by considering the burnout height to be essentially zero, in comparison to the radius of the earth, then by symmetry, apogee will occur mdiway between the launch point and the target. To calulate the height at this point, we use our relation between r and theta, equation (24B), setting theta equal to half the total geocenctric range anle through which the missile will fly, so that the value for r will correspond to the mid-point of the flight:

(30B) $$\frac{r_0}{r_{max}} = \frac{1-\cos 1/2\phi}{\eta \sin^2 \gamma} + \frac{\sin(\gamma - 1/2\phi)}{\sin \gamma}$$

E. THE TIME OF FLIGHT

From equation (4), we find that:

(31B) $$dt = \frac{r_0}{V_\theta} \left(\frac{r}{r_0}\right)^2 d\theta$$

If we now define:

(32B) $$\langle (r/r_0)^2 \rangle$$

as the average value of that ratio, the time of flight is given by

(33B) $$T = \frac{r_0 \phi}{V_\theta} \langle (r/r_0)^2 \rangle$$

Of course, to find that average value requires an integration; in this case, the integration is extremely messy and tedious (4B). A rough approximation can be made using an average height that is simply the midway point between the apogee height and the burnout height:

$$(34B) \quad T \simeq \frac{r_0\phi}{V_\theta}\left(\frac{r_0 + r_{max}}{2r_0}\right)^2$$

This approximation is reasonably accurate for the minumum energy trajectory and lower trajectories, but less so for higher trajectories.

F. ERROR ANALYSIS

From equation (24B), it is possible to calculate the error in range for a given small variation in any of the other parameters. We begin by taking the total differential, remebering the definition; If

$$(35B) \quad f(r_0,\gamma,V,\phi) = 0$$

then

$$(36B) \quad df = \frac{\partial f}{\partial r_0}dr_0 + \frac{\partial f}{\partial \gamma}d\gamma + \frac{\partial f}{\partial V}dV + \frac{\partial f}{\partial \phi}d\phi = 0$$

Taking the necessary partial derivatives, we find:

$$(37B) \quad \frac{\partial f}{\partial V} = \frac{-2}{V}\frac{(1-\cos\phi)}{\eta\sin^2\gamma}$$

$$(38B) \quad \frac{\partial f}{\partial r_0} = \frac{-1}{a} - \frac{(1-\cos\phi)}{r_0\eta\sin^2\gamma}$$

$$(39B) \quad \frac{\partial f}{\partial \phi} = \frac{\sin\phi}{\eta\sin^2\gamma} - \frac{\cos(\gamma-\phi)}{\sin\gamma}$$

$$(40B) \quad \frac{\partial f}{\partial \gamma} = \frac{-2\cot\gamma(1-\cos\phi)}{\eta\sin^2\gamma} + \frac{\cos(\gamma-\phi)}{\sin\gamma} - \frac{\sin(\gamma-\phi)\cos\phi}{\sin^2\gamma}$$

Combining these and rearranging slightly yields:

(41B) $$\left(\frac{-2(1-\cos\phi)}{V\eta\,\sin^2\gamma}\right)dV - \left(\frac{1}{a} + \frac{(1-\cos\phi)}{r_0\eta\sin^2\gamma}\right)dr_0 + \left(\frac{\cos(\gamma-\phi)}{\sin\gamma} - \frac{2(1-\cos\phi)\cot\gamma}{\eta\,\sin^2\gamma} - \frac{\sin(\gamma-\phi)\cos\phi}{\sin^2\gamma}\right)d\gamma = \left(\frac{\sin\phi}{\eta\sin^2\gamma} - \frac{\cos(\gamma-\phi)}{\sin\gamma}\right)d\phi$$

By most standards, this is a messy and unwieldy equation. Its usefulness lies in the fact that it is possible to find the error in range caused by an error in any single variable, holding all other variables constant; when this is done, all terms but the two terms of interest go to zero. In order to derive the errors in range that would be caused by small variations in any of the above variables, it is necessary to remember that an error in range dR is related to variations in phi by the following equation:

(42B) $$dR = a\,d\phi$$

G. BURNOUT SPEED ERROR

If the direction of motion and the height at burnout are held constant, the error in range caused by a given error in speed will be given by:

(43B) $$\frac{\partial R}{\partial V} = \frac{-2a}{V}\,\frac{(1-\cos\phi)}{\sin\phi - \eta\sin\gamma\cos(\gamma-\phi)}$$

This equation can be simplified by solving equation (24B) for nu, and plugging in the result:

(44B) $$\eta = \frac{(1-\cos\phi)}{\sin\gamma[\sin\gamma - \sin(\gamma-\phi)]}$$

(45B) $$\frac{\partial R}{\partial V} = \frac{-2a}{V}\,\frac{(1-\cos\phi)[\sin\gamma - \sin(\gamma-\phi)]}{\sin\phi[\sin\gamma - \sin(\gamma-\phi)] - (1-\cos\phi)\cos(\gamma-\phi)}$$

If we now expand the double-angle terms and work through the ensuing algebra, we find our simplified solution:

(46B) $$\frac{\partial R}{\partial V} = \frac{2a}{V}\,[\sin\phi + \tan\gamma(1-\cos\phi)]$$

H. BURNOUT ANGLE ERROR

If we hold the velocity and the height constant, and allow small variations in the burnout angle, we find the following:

$$\frac{\partial R}{\partial \gamma} = a\left[\frac{\eta\sin\gamma\cos(\gamma-\phi) - \eta\cos\gamma\sin(\gamma-\phi) - 2\cot\gamma(1-\cos\phi)}{\eta\sin\gamma\cos(\gamma-\phi) - \sin\phi}\right] \quad (47B)$$

If we again substitute for nu, expand the double-angle terms, and simplify, we eventually find:

$$\frac{\partial R}{\partial \gamma} = 2a\left[1 + \frac{\sin(\phi-2\gamma)}{\sin 2\gamma}\right] \quad (48B)$$

I. VERTICAL VELOCITY ERROR

Often it is useful to express the burnout velocity errors in terms of error in vertical velocity and error in horizontal velocity, rather than errors in speed and burnout angle. A given error in vertical velocity can be expressed as a combination of an error in speed and an error in direction:

$$dV_r \approx dV + V\,d\gamma \quad (49B)$$

From geometry, we get three simple relations interrelating these variables:

$$dV = dV_r\cos\gamma \quad (50B)$$

$$V d\gamma = dV_r\sin\gamma \quad (51B)$$

$$d\gamma = \frac{\sin\gamma}{V}\,d\,V_r \quad (52B)$$

Combining the last four equations, we find:

$$\frac{\partial R}{\partial V_r} = \frac{2a\cos\gamma}{V}\left[\sin\phi + \tan\gamma(1-\cos\phi)\right] + \frac{2a\sin\gamma}{V}\left[1 + \frac{\sin(\phi-2\gamma)}{\sin 2\gamma}\right] \quad (53B)$$

J. HORIZONTAL VELOCITY ERROR

The situation with regard to horizontal velocity errors is very similar:

(54B) $dV = dV_{\theta} \sin\gamma$

(55B) $d\gamma = \frac{\cos\gamma}{V} dV_{\theta}$

These two become:

(56B) $$\frac{dR}{V_{\theta}} = \frac{2a}{V}[\sin\phi + \tan\gamma(1-\cos\phi)]\sin\gamma + \frac{2a}{V}[1 + \frac{\sin(\phi-2\gamma)}{\sin 2\gamma}]\cos\gamma$$

K. BURNOUT HEIGHT ERROR

The range error caused by a small variation in the altitude of the missile at burnout is given by:

(57B) $$\frac{\partial R}{\partial h} = \frac{\eta \sin^2\gamma + (1-\cos\phi)}{\eta \sin\gamma \cos(\gamma-\phi) - \sin\phi}$$

This can be simplified in a manner similar to the previous cases, giving:

(58B) $$\frac{\partial R}{\partial h} = 2 \tan\gamma - \frac{\sin(\gamma-\phi)}{\cos\gamma}$$

L. HORIZONTAL IN-PLANE POSITION ERRORS

An error in horizontal position within the plane of the trajectory at thrust termination will cause an identical error in range at the target, since it simply rotates the trajectory around the earth:

(59B) $$\frac{\partial R}{\partial D} = 1$$

M. OUT-OF-PLANE POSITION ERROR

So far, we have considered only those errors caused by variations within the plane of the trajectory, a plane defined by the launch point, the target, and the center of the earth. Such errors, we found, caused errors primarily in range (in fact, if we remember the rotation of the earth, these errors also cause small cross-range errors, since they cause some variation in the flight time, and the target will move westward during that incremental time).

In practice, the missile will also experience position and velocity errors perpendicular to this plane. Using spherical trigonometry, it can be shown that the cross-range (or track) error caused by a postion error out of the plane of the trajectory is given by:

(60B) $$\frac{\partial L}{\partial n} = \cos\phi$$

N. OUT-OF-PLANE VELOCITY ERROR

The error caused by spurious out-of-plane velocity can be found by integrating the position error. First, we remember that:

(61B) $$V_\theta = V\sin\gamma = \frac{a\,d\theta}{dt}$$

Since the increment in out-of-plane position will be the velocity times the incremental time, we find:

(62B) $$\partial n = \frac{\partial V_n\, a d\theta}{V\sin\gamma}$$

Combining this with equation (61), and integrating to find the total effect of the small increments in out-of-plane position, we find:

(63B) $$\frac{\partial L}{\partial V_n} = \frac{a}{V\sin\gamma}\int_0^\phi \cos\theta\, d\theta = \frac{a\sin\phi}{V\sin\gamma}$$

O. TWO SPECIFIC CASES

Since both the U.S. and the U.S.S.R. cover large geographic areas, the range from a specific launcher in one country to a target in the other will vary, depending on the locations of the launcher and the target. Some of these ranges will be of the order of 8,000 km or less, while an attack launched from or against the ICBM fields along the Trans-Siberian railway in the southern portion of the Soviet Union would involve a range of the order of 10,000 km or more, or a geocentric range angle of 90 degrees. If we plug the appropriate figures for this latter case into our trajectory equations, we find the following, for the minimum-energy trajectory:

(64B) $$\gamma = 67.5°$$

(65B) $V = 7.19 \times 10^3$ m/sec

(66B) apogee = 1320 km

(67B) Time $\simeq$ 30 minutes

(68B) $\frac{\partial R}{\partial V_r}$ = 2,300 m/m/sec

(69B) $\frac{\partial R}{\partial V_\theta}$ = 5,600 m/m/sec

(70B) $\frac{\partial L}{\partial n} = 0$

(71B) $\frac{\partial L}{\partial V_n}$ = 960 m/m/sec

(73B) $\frac{\partial R}{\partial h}$ = 5.8 m/m

Another case of interest is to compare these error partials at thrust termination with those that would be experienced on the shorter range the Soviets fly the majority of their tests over (5B); this is a range angle of the order of one radian. Since we are interested only in determining the order-of-magnitude of the changes in errors, we will make the simplifying assumption that the warhead is released at essentially the same flight angle:

(73B) $\gamma \simeq 68°$

(74B) $V \simeq 6400$ m/sec

(75B) $\frac{\partial R}{\partial V_r}$ = 740 m/m/sec

(76B) $\frac{\partial R}{\partial V_\theta}$ = 3400 m/m/sec

(77B) $\frac{\partial L}{\partial V_n}$ = 910 m/m/sec

Here, we have included only the more significant error partials; as can be seen, this difference in range has a large effect on the resulting error partials.

P. THE BOOST PHASE TRAJECTORY: AN APPROXIMATION

The acceleration history during the boost phase will vary greatly; no general solution is possible. However, calculation of the velocity error at thrust termination caused by certain types of guidance errors requires a specific model of the boost phase trajectory. We have therefore made a very rough approximation to real boost phase trajectories; the reader should keep in mind the real variations among thrust histories, which will cause significant differences in the resulting errors.

Our approximation begins with two simple observations. First, efficient rocket operation requires nearly constant thrust. Second, if a rocket is being driven by a constant thrust, its acceleration will be constantly increasing, because of the decrease in mass; since the thrust is constant, this decrease in mass can be modeled by a linear decline.

Berfore going further with our approximation, it must be remembered that the accelerometers of the guidance system do not measure the force of gravity; thus, the "accelerometer-sensed" acceleration will differ from the "real acceleration." Since the former quantity is that which effects the guidance system, our approximation will ignore the effect of gravity. Although the missile does experience significant aerodynamic forces when rising through the atmosphere, we have neglected these as well, to simplify the problem. The thrust is then the only significant force acting on the missile; since, to first order, the thrust is constant, and the mass is linearly decreasing, the acceleration will be given by:

(78B) $|a| = \frac{k}{m_0 - ct}$

This approximation is only reasonable during the firing of one specific stage of the rocket. An ICBM will typically ahve three main stages; each one will probably have a different thrust and a different fuel consumption rate. However, we have further simplified the problem by assuming that each stage is essentially identical in these respects, so that the above equation holds over the entire flight.

To complete the expression, it is only necessary plug in values for the magnitude of the final acceleration, the initial acceleration, and the amount of time the boost phase comprises. In most missile systems, peak accelerations are of the order of 100 m/secu2d; we use this value for the final acceleration. The initial acceleration we take to be 25 m/secu2d; since the missile is also experiencing roughly 10 m/secu2d of gravitational acceleration, this means that the real acceleration at that point is of the order of 15 m/secu2d. Current U.S. Minuteman missiles have burning times of the order of 180 seconds (6B), so we have used this value for the length of the boost phase. The expression for the magnitude of the acceleration then becomes:

(79B) $$|a| = \frac{25}{(1 - \frac{t}{240})}$$

This expression is graphed in Figure 2B. We have divided this acceleration into X any Y components, and modeled the change in these components with 3 linear segments of decreasing length, as follows:

From t=0 to t=90:

(80B) $$a_y = 25 - .0236t$$

(81B) $$a_x = .387t$$

From t=90 to t=150:

(82B) $$a_y = 22.88 - .215(t-90)$$

(83B) $$a_x = 34.8 + .518(t-90)$$

From t=150 to t=180:

(84B) $$a_y = 37.67 + .63(t-150)$$

(85B) $$a_x = 55.0 + .92(t-150)$$

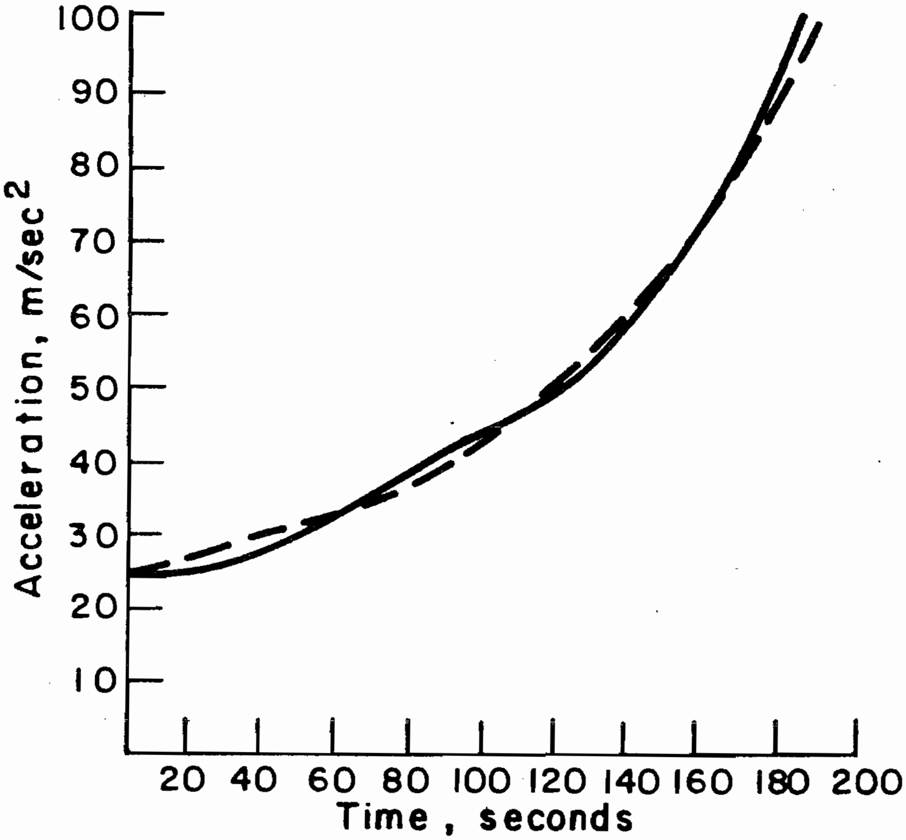


Fig. 2B Boost-Phase Acceleration

As can be seen, this approximation shows an abrupt change in the direction of acceleration at t=150. The reason for this is simple; if the rocket is still going through large changes in direction at thrust termination, imperfections in the control of rocket torque can introduce error, so we decided arbitrarily to have the missile's final direction of motion achieved at t=150, after which the acceleration changes to a direction parallel to the direction of motion.

The total magnitude of acceleration given by these equations is the dotted line in Figure 2B; as can be seen, they match the analytical approximation of equation (79B) quite well. At the end of 180 seconds, the sensed velocity will be 8060 m/sec, at an angle 34.4 degrees from the horizontal; to find the actual velocity, we subtract from the sensed Y acceleration that portion which goes to counteracting the effect of gravity, and we find that the real final velocity is 7200 m/sec, at an angle 22.7 degrees from the horizontal, putting the warhead approximately on the appropriate trajectory.

APPENDIX C: TESTING OF BALLISTIC MISSILES

It is impossible to make any realistic assessment of the strategic balance, to plan forces, or to consider strategic arms control without accurate assessment not only of the numbers of strategic weapons possessed by each side, but also of their qualitative characteristics. Specifically, the construction of operational attack plans such as the U.S. Single Integrated Operational Plan (SIOP) requires detailed knowledge of the technical capabilities of the weapons involved, including accurate assessments of their accuracy, yield, reliability, range, and so forth. The acquisition of such information depends in large measure on testing of the weapons involved and of their components.

The testing of the nuclear warhead itself has been discussed at some length in the popular literature, in the context of the various proposed treaties limiting nuclear tests, and we will not discuss it here, except to say that there remains some uncertainty in predicting the operational yield and reliability of a given warhead design. For example, the original warhead design for the new Mk. 12A warhead recently deployed on the U.S. Minuteman III ICBM failed to achieve the yield that had been predicted for it: in all three of the weapon's first tests, the yield demonstrated was considerably below that which had been expected. The design was then modified, resulting in a more successful fourth test. Similarly, in the early 1960s, it was discovered that a safety feature on the Polaris A1 warhead which had worked well in development and test frequently jammed in operational situations, with the result that three out of four of the warheads were considered potential duds (1C). While these are extreme examples, they are illustrative of the simple fact that with the wide range of limitations on peacetime testing of nuclear explosives (including considerations of safety, cost, political and environmental impact, instrumentation difficulties, and treaty obligations), some uncertainty in estimates of their performance will remain into the foreseeable future.

Instead, in this appendix, we consider in some detail the testing of intercontinental ballistic missiles and their components, from which estimates of the missiles' accuracy and reliability are derived. Such testing includes both full-system tests and more limited tests of individual components; it begins with the development of individual system components and continues throughout the operational life of the system. We begin with a brief discussion of the early stages of testing, and continue with a more extensive discussion of operational testing. We conclude with a section discussing U.S. efforts to monitor Soviet tests.

A. PRE-DEPLOYMENT TESTING

A modern ballistic missile is an extremely complex technical device, comprising hundreds of smaller subsystems. The rigorous testing of each of these components is an integral part of their development: typically, detailed specifications of the total allowable error and failure rate are included in the contract to develop the component, and each compnent undergoes very extensive testing, to verify that the basic physical principles on which the new design is based have been successfully incorporated into an operational device that performs in accordance with the contract requirement.

Once the individual components have been developed, prototype missiles can be produced. Full-system testing of these missiles is essential to the development of any new system; while improved simulation and analysis techniques have greatly increased both the amount of information that can be predicted before full-system tests begin, and the amount of information that can be garnered from each test, it is impossible to develop a new system as complex as an ICBM without an extensive series of full-system tests. Otherwise, it is simply not possible to have high confidence in assessments of the complex meshing of the hundreds of subsystems that comprise the total missile. In the U.S., these pre-deployment tests are divided into two categories: research and development tests, which serve as the basis for modifications of the initial design, and Initial Operational Test and Evaluation (IOT&E) which serves to confirm hardware performance before the beginning of full-scale production.

Modern ICBMs generally undergo fewer pre-deployment flight tests than did earlier systems; currently, both the U.S. and the Soviet Union typically perform of the order of 20-30 tests of a new system before full-scale production begins (2C). Details of the testing process and testing instrumentation are discussed below.

While these initial tests provide invaluable information concerning the performance of missile hardware and software, they do not necessarily indicate the accuracy and reliability that will be achieved by operational missiles, as both the test environment and the production techniques for prototype ICBMs are likely to differ substantially from those that obtain for operational, mass-produced missiles. As one standard textbook on testing puts it (3C):

"It is evident, however, that there is still a considerable gap between meeting the detailed specifications and actually functioning in an operational environment in which the equipment must interact with men and peripheral equipment...It is thus apparent that developmental test and evaluation by itself does not give a complete or accurate picture of system operational performance...If an attempt is made to dispense with operational test and evaluation, as often occurs when budget constraints must be contended with, unpleasant surprises are in store for the system operators when the the system is deployed and begins actual operation."

As a result, testing of the operational mass-produced missiles is perhaps the most important part of the testing process; the testing of operational missiles is described below.

B. OPERATIONAL TESTING

Once a new ICBM has been produced and deployed, the first task is to perform a number of operational tests large enough to provide statistical confidence in estimates of the accuracy and reliability of the deployed weapons. These initial tests will also serve to detect any problems that have arisen in the transition from limited production of prototypes to mass production. In the U.S., these tests are referred to as Phase I of Follow-on Operational Test and Evaluation (FOT&E); in order to maintain the statistical comparability of the sample, data from tests of prototypes are generally discounted in developing these estimates, although in recent U.S. test experience, test performance of operational ICBMs has generally been as good as the performance of prototypes in the IOT&E tests (4C). In the case of the U.S. Minuteman II and Minuteman III missiles, roughly forty such tests were conducted in the initial years of deployment (5C).

Testing of an ICBM does not by any means end once these initial estimates of system performance have been developed. Throughout the life-cycle of the missile, both subsystem tests and operational full-flight tests continue, as well as additional R+D tests to validate modifications to the system hardware and software that are developed over its roughly 20-year operational life.

The kind and frequency of tests of individual subsystems depends, of course, on the technical specifics of the subsystem. Rocket motors, for example, have two characteristics that discourage frequent testing: first, a realistic test requires a static firing of the rocket, and this expends the engine, requiring that it be replaced. Second, the performance of a solid-fueled rocket engine does not usually change drastically through time; a small number of static firings will serve to determine whether chemical changes resulting from prolonged storage are degrading the performance of the engines in the operational missiles. Such static firings of randomly selected rockets are performed at regular intervals.

By contrast, the guidance system of an ICBM is capable of being tested non-destructively, and has a variety of performance characteristics that have been known to change unpredictably after prolonged operation. The latter results from the simple fact that in order to keep the system on constant alert, the guidance system must be kept up and running continuously; thus, for example, the high-speed gyroscopes that make up the core of the inertial measurement unit must be kept spinning for tens of thousands of hours, posing extreme operational requirements for the bearings involved. These factors suggest both the possibility and the necessity of frequent testing of operational guidance sets, and in fact, such frequent testing does occur. While the operational missiles are in their silos, the guidance systems undergo nearly constant test and evaluation, communicating with a large underground computer which continuously monitors such parameters as the drift rate of the gyroscopes in the inertial measurement unit and the voltages across certain key points within the electrical system (6C). In addition, the system undergoes a "simulated flight test" and extensive calibration and realignment every 30 days (7C).

Despite these extensive subsystem tests, continued full-system flight testing remains necessary throughout the life-cycle of an ICBM, to monitor any changes in the accuracy or reliability of the full system that may result from prolonged operation and storage, and to maintain full confidence in initial estimates of system accuracy and reliability. In the U.S., this phase of flight testing is referred to as Phase II of FOT&E; the U.S. typically conducts 5-10 such tests of a given ICBM each year (8C). The Soviet Union conducts a substantially larger number of total operational tests than the U.S., as is discussed below. In addition to these flight tests of operational missiles, R+D flights to verify incremental changes in hardware and software typically continue at least as long as the ICBM in question remains one of the top-of-the-line systems; for example, the U.S. conducted an average of roughly four R+D tests of the Minuteman III each year throughout most of the 1970s (9C).

Each flight test of a ballistic missile costs from millions to tens of millions of dollars; the need to stay within a limited testing budget is thus in frequent conflict with the desire to test a large enough sample of missiles to provide high statistical confidence in estimates of their accuracy and reliability. Thus, an effort is made to maximize the amount of information available from any one test: for this reason, most of the ICBM flight tests conducted by both the U.S. and the U.S.S.R. take place over heavily instrumented test ranges. With careful monitoring, a given ballistic missile flight test will provide extensive information not only concerning how far the weapon landed from its target (or whether it failed), but also precisely what factors contributed to any errors or failures. The U.S. ICBM flight tests are launched from Vandenberg Air Force Base in California, and are targeted on the lagoon of Kwajalein Atoll in the Pacific Ocean; both Vandenberg and Kwajalein have telemetry equipment, radar, and other instrumentation with which to monitor the progress of the test. Since essentially the entire flight is over the ocean, the safety hazards are minimized.

Similarly, the Soviet Union conducts the majority of its ICBM flight tests from two major test sites. The first of these, although usually referred to in Soviet literature as the "Baikonur Cosmodrome," is in fact 370 kilometers southwest of Baikonur, near Tyuratam (45 degrees 6' North, 63 degrees 4' East). This center includes 18 ICBM test silos, and is also the center of much of the Soviet space program. From here, ICBMs are fired into a heavily instrumented range on the Kamchatka peninsula, and occasionally at longer range into the Pacific Ocean. The second ICBM test center is at Plesetsk (62 degrees 8' North, 40 degrees 1' East.), and serves mainly for testing of intermediate-range ballistic missiles.

While both superpowers have tested ICBMs over several other ranges (the U.S., for example has flown ICBMs from Cape Canaveral in Florida to Ascension Island in the Atlantic), both the number of tests over other ranges and the number of different trajectories flown has been quite limited. This is not true of SLBM testing, but the differences in error budgets and the specifics of operational launches between SLBMs and ICBMs are so large as to make it difficult to usefully compare data between the two types of testing.

The testing sequence for U.S. FOT&E flight tests is as follows (10C):

<u>I</u>. A missile is selected at random, from the operational ICBMs in the silo fields.

<u>II</u>. While still in its original silo, with its original crew, the missile is brought to alert status, ready for immediate firing. This procedure is intended to test the condition of the silo, the crew, and auxiliary electronics. If the missile fails to come to alert properly, it is listed as a failure, and not tested further. The problem is then checked out, and the system repaired.

<u>III</u>. The live reentry vehicles are removed from the missile. The reentry vehicles are then shipped to a special facility in Texas, where the weapon is removed from each reentry vehicle, and replaced with telemetry equipment to monitor the missile flight.

<u>IV</u>. The missile is taken from its silo, and shipped to Vandenberg Air Force Base in California, where it is placed in a test silo. The only major differences between this silo and an operational one are the design of the silo cover, which on the test silo is reusable, and the fact that the test silo is covered with a protective substance so that it will not be severely damaged by engine firing, and can be readied for additional tests with reasonable rapidity. The test silo is manned by randomly-selected crews from the operational missile fields, who are transported to the test site for this purpose.

Air Force spokesmen insist that no extraordinary maintenance, or "gold-plating" of the missile takes place. There are two changes to aid the testing process: first, as was mentioned above, the reentry vehicles are no longer "live," but contain only telemetry equipment; second, for safety reasons, the missile is "wired" so that it can be destroyed should it go awry. Neither of these changes should have any effect on the missile's flight path or reliability.

V. The missile's guidance system is aligned and calibrated, as described in an earlier section. This is done every 30 days at the operational silos; in test, the missile is aligned and calibrated soon after its arrival at the test silo, and then launched 15 days later, in order to get an average result. This assumes, of course, that the decay of calibration and alignment with time will be reasonably linear.

VI. The missile is again brought to alert. If it fails to come to alert now, having succeeded in its original silo, the problem is investigated. If the failure is clearly attributable to a problem within the test silo, it is listed as a failure. If no such error can be found, the problem is attributed to damage incurred during transportation of the missile, and the event is not listed as a test failure.

VII. The missile is then fired from Vandenberg to Kwajalein lagoon, in the Pacific, a distance of about 8000 km. The ranges missiles would fly in wartime would vary considerably, depending on the location of the target and the launcher, but many significant targets would require ranges more of the order of 9-10,000 km. Maximum range of the Minuteman III missile is reported to be of the order of 13,000 km. The main Soviet ICBM test range is shorter still, of the order of 6500 km. The implications of this are discussed below.

Telemetry equipment installed on-board the missile monitors the performance of each subsystem throughout the flight, measuring fuel consumption, vibration, performance of the guidance system components, identifying sources of failure, and so on. This information is then broadcast to ground stations, where it is collected and stored for analysis. The missile's course is carefully monitored by ground-based radars and sometimes by satellite as well. Performance of the RV is monitored by large radars and optical telescopes based on Kwajalein, as well as by instruments on board the RV itself. Development tests of RVs also take place on a variety of surrogate launch vehicles.

There are two types of issues which frequently recur in discussions of the adequacy of operational testing of ICBMs; as is the case with most judgements regarding the effectiveness of weapon systems, both issues are controversial. The first issue surrounds the question of whether the current number of tests is enough to provide reasonable statistical confidence in estimates of system performance; the second issue is whether the tests are realistic enough for these estimates to be valid in estimating the probable performance of ICBMs in actual attacks.

The task of assessing the number of full-system flight tests required to achieve a given level of confidence in assessments of accuracy and reliability is not as simple as it might seem. In particular, one cannot use simple chi-square models of the accuracy uncertainty after a given number of tests, or simple binomial calculations of the reliability uncertainty after a given number of tests; these models assume that no information is available concerning system performance except a simple success/failure and an impact point, ignoring the wealth of information available from telemetry analysis, simulation, subsystem testing, tests of similar systems, etc. This wealth of information, if properly utilized, will greatly reduce the number of full-system tests that are required.

On the other hand, it should be pointed out that since each system is continually undergoing modifications of its hardware and software, the number of tests of any single guidance arrangement is often quite small. A spokesman for the Air Force has been quoted as saying "a half dozen, or a dozen in one case I'm aware of, would represent the kind of numbers we're talking about. It would more frequently be six than 12." (11C). Even considering all of the other available sources of information, and the extensive post-flight engineering analysis that is conducted, this is an extremely small number of flight tests on which to base statistical estimates of the accuracy of an ICBM equipped with a given guidance arrangement.

Concerns about the realism of operational testing of ICBMs have been summed up by then-Secretary of Defense James Schlesinger, who has argued that "the parameters of the flight from the western test range are not really very helpful in determining those accuracies to the Soviet Union...The effect of this is that there will always be degradation in accuracy as one shifts from R+D testing, which is essentially what we have at the western test range, to operational silos..." Indeed, Schlesinger was of the opinion that the uncertainties resulting from this problem were so large that he could "publicly state that neither side can a acquire a high-confidence first-strike capability."

Concerns about the realism of operational tests can be divided into two general categories: first, questions of possible changes in accuracy in shifting from the test trajectory to operational trajectories, and secondly, questions concerning the realism of the test sequence itself. We briefly address each of these issues in turn.

The most frequently mentioned source of concern regarding the lack of testing over the trajectories that would be flown in war-time is the possibility of significant biases arising as a result of gravitational variations and other geophysical factors that change from one trajectory to another. As we have argued in sections 1.5 and 1.7, gravitational uncertainties are likely to be a small, though certainly not insignificant, portion of the total error budget; most other geophysical factors that have been suggested as possible sources of error are likely to be negligible. However, there are some significant variables would be likely to be quite different in the case of an actual attack than they would be in test. For example, RVs in most U.S. tests reenter over Kwajalein lagoon, an area where the atmosphere is as placid as it is anywhere in the world; the types of atmospheric conditions encountered in an actual attack on the Soviet Union would be very different. In addition, as we argued in sections 1.6 and 2.3, atmospheric variations in an actual attack would tend to act as a source of systematic bias, whereas in test, when a small number of RVs are tested at any one time, atmospheric variations tend to be random from one test to the next, contributing to the CEP.

Another issue concerns the comparison of the range of test trajectories and operational trajectories. As noted above, the length of the main Soviet test range is of the order of 6500 km. Most trajectories between the U.S. and the U.S.S.R. are at least 7-8000 km in length, and many of the most important trajectories, such as that between the SS-18 silos along the Transiberian Railway in the southern U.S.S.R and the U.S. Minuteman silos, are of the order of 10,000 km or more. Figure C1 shows the result of recalculating the error sources of Figure 1.8.1, which was calculated assuming a 10,000 km range, for a 6500 km range (12C).

Figure C1

Error Source	Miss Effect: Range	Miss Effect: Track
Initial Position and Targeting	0	0
Accelerometer Non-orthogonality	4	0
Initial Alignment - Vertical	27	5
Initial Alignment - Azimuth	0	65
Accelerometer Bias	24	6
Accelerometer Scale Factor	20	0
Gyroscope Bias Drift	32	10
Gyroscope Acceleration - Sensitive Drift	40	20
Guidance Computation	8	4
Thrust Termination	25	0
Gravity	0	0
Reentry	110	75
Fusing	40	0
RSS:	137	102

CEP = $.5887\ (\sigma_x + \sigma_y) = 143$ m $\approx$ .077 n. mi.

As can be seen, this change in range has a significant effect on almost every error source in the system; in general, the appropriate correction factor is different for every type of error. Thus, making corrections for variations in range requires an extremely detailed model of the sources of error of a guidance system. The difficulty of constructing such a model was discussed by J. B. Walsh, then Deputy Director for Strategic and Space Systems, Defense Research and Engineering, in 1976 (13C):

"For each year I show the theoretical accuracy, not measured accuracy, because in general the measured accuracy has been poorer than theoretical for operational degradation, mistakes, and so forth...In 1971, the gravity and geodesy term decreased significantly and the accuracy was reduced [sic]. Notice at the same time our understanding of the guidance and control got better, which showed we had a greater guidance and control error----that in 1970 we were just wrong. You see that effect later. In 1973 we took out some of the mistakes we had made in 1970 and the guidance and control error went down, and the total error went down. But now look: As these other large terms go down we began to wonder how to account for the error we were observing, and concluded the reentry dispersion was probably greater than we previously thought. In 1973 the reentry error was carried as a larger number. We felt we had to put in better instruments to measure that error, and we did, and found in fact that there was a new phenomenon we do not understand..."

While U.S. modeling of the various contributors to strategic missile error has improved significantly since that testimony was given, it remains the case that a considerable additional increment of uncertainty in estimates of the CEP of a given ICBM is introduced by the need to extrapolate from the ranges flown in test to probable operational ranges. Again, this uncertainty will be larger in the Soviet case, since they lack the main factor which has dramatically improved U.S. estimates in this area: the availability of an inertial guidance system much more precise than that used on the missiles being tested. Recent U.S. tests of Minuteman missiles have utilized the AIRS guidance system to be used on the MX to provide extremely detailed monitoring of the performance of the less accurate Minuteman guidance system. The uncertainty added to U.S. estimates of Soviet ICBM accuracy by the fact of tests over shorter ranges is likely to be very large indeed, as the U.S. is unlikely to have as accurate and detailed a model of the functioning of Soviet guidance systems.

However, the Soviets do conduct some tests at full range, with the RVs reentering over an area of the Pacific several hundred kilometers north of the U.S. test area at Kwajalein. For this purpose, the Soviets typically send out heavily instrumented boats similar to the "fishing trawlers" they use to monitor U.S. tests, and issue a warning to clear several hundred square miles of ocean, in order to avoid hazard to international shipping in the area. The latter is fortunate for U.S. monitoring efforts, since it allows the U.S. to send instrumented ships and aircraft into the region where the RVs will enter, to monitor the latter stages of the test. It should be noted, however, that the number of these full-range tests is often quite small; generally 3-5 full-range tests of a given system are conducted before deployment begins (14C).

The last remaining set of issues concerns the realism of the testing sequence itself. While less is known (at least at the unclassified level) concerning Soviet testing procedures, it is clear from the discussion given above that in the U.S. a great effort is made to provide the greatest possible realism in the ICBM test process: the missile is selected randomly from among the operational missiles, no modifications to it are made except those absolutely necessary to the testing process, it receives no extraordinary maintenance, and it is fired from a test silo as close as possible to operational silos, by a randomly-selected crew transported from the operational silo fields.

However, some potentially significant differences between the test sequence and operational launch sequence remain. Firstly, U.S. tests not only take place in an area with a naturally calm atmosphere, but are skewed toward days with good weather; since atmospheric errors are one of the most significant errors in the system, this could potentially have a noticeable effect on CEP estimates (15C).

Perhaps more importantly, there remains the fact that no full-scale test from an operational silo has ever been conducted by the United States; since such tests would have to fly over considerable portions of the continental United States, Congress has been reluctant to authorize them, because of safety concerns. There remains considerable controversy over whether this fact throws uncertainty into estimates of operational reliability. Much of this controversy surrounds the anecdotal evidence provided by the rather ill-starred history of U.S. attempts to conduct tests from operational silos.

In the mid-1960s, the U.S. Air Force did attempt to conduct four ICBM tests from operational silos; three of the four failed to leave their silos, and the fourth failed soon after. Air Force spokesmen have argued that the failures resulted from the very substantial modifications of the missiles that were made for safety reasons (in at least one of the tests, the missile contained only seven seconds of fuel and was tethered to the ground). However, one Pentagon analyst familiar with the cases has asserted that the failures were attributable to the launch control electronics; further, he argued that current U.S. tests do not adequately test the reliability of this subsystem: "you can't go down a launch countdown sequence without going through with it. You end up taking irreversible steps. But if you don't do those, you don't have a real countdown." He pointed out that the launch computer at Vandenberg, which does go through the whole countdown, does so every few weeks, and can therefore be expected to do so successfully with higher confidence than those in the operational silos: "a computer system that's used once a year---or never---is going to be a disaster." (16C). Air Force spokesmen, on the other hand, have argued that the current testing process, which includes preparing the ICBM for immediate launch in its operational silo, adequately tests all of the launch silo electronics.

More recently, in the mid-1970s, the Air Force decided to try a more realistic test---a complete flight of an unaltered Minuteman II from an operational silo. The plan was eventually canceled, as a result of safety concerns. The Air Force argument in favor of conducting this test was that the Vandenberg/Kwajalein tests "have yielded valuable data on weapons system performance, but test conditions there do not exactly duplicate those found at inland operation facilities...With any weapons system, it is important to demonstrate its capabilities under the most realistic conditions possible." (17C).

It is frequently pointed out that the Soviet Union, in contrast to the United States, frequently conducts tests from operational silos. However, many of these tests are primarily for crew training, and involve flight tests of older missiles with little or no telemetry; such tests provide much less information than fully-instrumented tests. For example, when a silo holding an old-model missile is to be rebuilt for a new type of ICBM, the old missile will generally be fired from the silo; in 1974, when SS-11 silos were to be rebuilt to hold the first SS-19s, the Soviet Union conducted more than 70 operational "tests" (disposals might be a better word) of the SS-11, all described as primarily for crew training (18C).

Thus, in the cases of both the United States and the Soviet Union, relatively small numbers of flight tests are conducted of any single ICBM system, and these tests are performed under conditions that in some significant respects are different from those that would obtain in an actual countersilo attack. We therefore believe that our estimates of uncertainties of 10% in both CEP and reliability are extremely conservative. In congressional testimony, Defense Department officials have shown graphs of the result of operational CEPs a factor of two larger than expected, as an illustrative example of the types of possible variations (19C).

C. U.S. MONITORING OF SOVIET ICBM TESTS

The monitoring of ICBM flight tests is an essential source of intelligence information, providing invaluable details concerning the capabilities and design of the opponent's weapons, as well as aiding in the verification of arms control agreements. Because of the disputes over verification of SALT that have taken place in the U.S., a much larger quantity of information is available concerning U.S. capabilities in this area than is available concerning parallel Soviet activities; hence, we will concentrate on a discussion of U.S. monitoring of Soviet tests. The U.S. utilizes a wide variety of techniques to monitor Soviet flight tests, including radars, telemetry interception, and optical and infrared tracking. We will discuss these in "chronological" order, beginning with systems capable of monitoring the boost phase, and ending with systems designed to assess Soviet reentry vehicles.

The first stage of a missile's flight, and the stage which provides the greatest wealth of information concerning its design characteristics, is the boost phase. During this phase of flight, Soviet ICBMs broadcast telemetry information to the ground on 50 separate channels: this telemetry includes detailed reports of the performance of all guidance components, thrust and fuel consumption of the rocket engine, rotation and vibration of the rocket, and so on. The interception of this information is perhaps the single most crucial phase of the monitoring of Soviet tests; successful telemetry interception should provide accurate information concerning all of the sources of error prior to thrust termination, which the possible exception of pre-launch errors. Indeed, the CIA is reported to have developed detailed computer simulations of the performance of Soviet guidance systems, based on telemetry information, although the modeling accuracy that could be achieved with the information available is open to doubt, as discussed above (20C).

Until 1979, the primary radars and electronic intelligence equipment used to intercept telemetry were stationed in northern Iran, only 1000 km from the Soviet launch sites at Tyuratam. These stations were lost as a result of the Iranian revolution; as a temporary measure, increased reliance was then placed on electronic intelligence stations in Turkey, which had previously been used to monitor intermediate-range launches from the Plesetsk launch area. However, these stations were much less useful than the Iranian stations: they are considerably farther from Tyuratam than were the Iranian stations, meaning that the curvature of the earth made it impossible to monitor the telemetry until the ICBM reached an altitude of some 250 km, and the intervening Caucasus mountains also interfered with the field of view (21C).

As an additional temporary measure, the TR-1 reconnaissance aircraft was equipped with telemetry equipment for the first time in early 1979 (22C). The disadvantages of telemetry monitoring from aircraft are even more manifest than those from Turkish sites, however: the aircraft must loiter for long periods near Soviet borders for a few minutes of telemetry information; continuous coverage cannot be provided without a very large number of aircraft; aerodynamic and weight considerations limit the receptivity of the antennas that can be used; there are considerable political problems associated with the requirement for frequent overflights of Turkish and Pakistani territory; and last but not least, even the aircraft could not intercept telemetry information below an altitude of roughly 65 km (23C). More recently, the United States has reportedly begun monitoring Soviet tests from Chinese soil.

In addition to ground stations and aircraft, some telemetry information can be picked up by satellite. Two general classes of satellites are used for this purpose: low-flying "ferret" satellites, and satellites stationed in geosynchronous orbit. Ferret satellites have the advantages of being high enough to be able to monitor telemetry all the way to ground, yet operating at a low enough altitude to insure that most telemetry information can be intercepted: however, since they operate in low orbits, they cannot remain stationary over the launch site, and a large number of satellites would be required to provide continuous coverage (24C).

Geosynchronous satellites, by contrast, remain stationary over their target, but their orbital position is so far away (more than 36,000 km from the launch site) that it is extremely difficult for them to pick up telemetry signals, especially if these are broadcast at low power. The U.S. Rhyolite intelligence satellites are geosynchronous platforms, intended both to provide notice of Soviet launches using infra-red sensors to detect the rocket exhaust, and to monitor telemetry from Soviet ICBMs. The first such satellite was launched in 1973; two more were placed in orbit in 1977, and a fourth in early 1978. Two of these satellites are reported to be stationed over the Horn of Africa, to monitor ICBM tests from Tyuratam, while two more are stationed farther east, to monitor intermediate-range tests from the launch site at Plesetsk. The latter are also monitored by ground stations in Norway (25C).

The problems associated with attempting to monitor telemetry from a range of 6,000 km were dramatically demonstrated not long after the Rhyolite satellites were launched. In the spring of 1977, Christopher Boyce was convicted of espionage, for having provided the Soviet Union with technical data on the Rhyolite program (26C); in early 1978, the Soviets reduced the output power of their telemetry signals (27C). The inference is manifest that the Soviet Union reduced the output power specifically to deny this source of information to the U.S. It is interesting to note in this respect that the first of a new series of more advanced geosynchronous intelligence satellites, the Chalet, was launched by the U.S. in late 1979 (28C). This action was also, in part, a reaction to concerns regarding the effect of the loss of U.S. stations in Iran on SALT verification.

All forms of telemetry interception are vulnerable to the encryption of the telemetry information. The unratified SALT II treaty contains limits on telemetry encryption, but it only prohibits encryption that would inhibit verification of the treaty provisions; this leaves considerable ambiguity as to what is and is not permitted. In 1979, the U.S.S.R. began extensive encryption of telemetry information; U.S. officials protested, and the encryption was discontinued (29C). In more recent tests, large fractions of the telemetry information have been encoded, again raising questions concerning compliance with the treaty, as well as U.S. ability to monitor design changes in the absence of this important source of information.

It is interesting to note that all three of the major decreases in U.S. monitoring capability discussed above (the loss of the Iranian sites, the reduction in output power of Soviet telemetry transmitters, and the 1979 encryption efforts) occurred immediately after the initial tests of the SS-18 Mod 4 and the SS-19 Mod 3, the most threatening Soviet weapons, which occurred in late 1977 and 1978. As a result, the uncertainties in U.S. estimates of the accuracy of these systems were larger than usual during this period: for example, for several years the most common estimates of the CEP of the most advanced Soviet ICBMs was roughly 200 meters; more recently, this estimate has been revised upward to between 250 and 300 meters, an upward revision of 25-50% (30C).

The next stage of monitoring of a Soviet ICBM test is the tracking of the missile by radar. This monitors primarily the post-boost portion of the trajectory, providing valuable information concerning the design and performance of the post-boost vehicle which puts each of the reentry vehicles on its separate trajectory. The radars of the U.S. Ballistic Missile Early Warning System (BMEWS) are used to track some portions of the missile's flight, but the most important radars in this respect are the Cobra Dane radar based on Shemya Island in the Aleutians, and ABM testing radars on Kwajalein Atoll, each of which was designed specifically to track RVs.

Cobra Dane is a huge phased-array radar system which first became operational in 1977. It is reportedly capable of tracking a basketball-sized object at ranges of 3,000 km, and of simultaneously tracking up to 100 such objects (31C). However, for the majority of Soviet ICBM tests, which impact on the Kamchatka peninsula some 720 km away, Cobra Dane cannot track the RV below an altitude of roughly 140 km, and therefore cannot monitor the reentry process (32C). Full-range Soviet tests to the Pacific can be monitored by the Altar and Tradex radars on Kwajalein: the former is capable of tracking up to 14 separate objects at ranges of more than 2000 km; it can determine the position and velocity of an RV to within 5 meters in range, 250 microradians in angle, and .1 m/sec in velocity. The Tradex radar, while somewhat more limited in range than the Altar, provides better accuracy in determining the position of the RV, and an order of magnitude greater precision in estimating its velocity (33C). With this degree of precision in measuring the RVs velocity, it should be possible to make very accurate estimates of the ballistic coefficient of Soviet RVs. In addition to the radars, the Kwajalein facility includes optical telescopes, which are also used to track and record the reentry process.

In the case of Soviet full-range tests into the Pacific, of which warning is received, ship-borne and air-borne monitoring stations can also be used monitor the reentry process, with the advantage of being able to keep track of the RV all the way to the earth. Ship-borne radars suitable for monitoring of reentry include the new Aegis air-defense system, as well as the Cobra Judy radar now being developed specifically for tracking of ballistic missiles (34C). The most significant contribution of air-borne monitoring is the ability to record optical and infrared images of the RVs trail; spectroscopic analysis can provide valuable information concerning the materials of the RV's heatshield. In addition, airplanes can measure atmospheric variables such as wind and density, in the region through which the RV passes.

Thus, as long as telemetry information can be intercepted, and other monitoring techniques are not interfered with, it should be possible to acquire a considerable quantity of accurate information concerning the range, throw-weight, and fuel consumption of the missile, the performance of the guidance system during the boost phase, the technical characteristics of the MIRV bus, the number of RVs, and the ballistic coefficient and material composition of the RV. From this information, estimates of the reliability, accuracy, and other technical characteristics of Soviet ICBMs are developed. However, the uncertainties in estimating the accuracy of Soviet ICBMs will inevitably be considerably larger than the uncertainties associated with developing CEP estimates for U.S. ICBMs: intelligence information is simply not as detailed or as reliably available as is our own test telemetry. In particular, it is likely to be difficult to develop accurate models of the major contributors to Soviet ICBM error budgets, and such models are absolutely necessary for accurate extrapolation of accuracies from test ranges to longer operational ranges. In addition, since at least in U.S. testing practice, gravity and targeting errors are adjusted to essentially zero, since they are well known over the testing trajectories, it is likely to be extremely difficult to acquire intelligence as to the size of these error contributors for Soviet ICBMs.

Indeed, uncertainty in estimates of Soviet ICBM accuracy recently played a significant role in a major dispute over U.S. intelligence capabilities (35C). In 1976, after several years of conflict between the CIA, the Pentagon, and other agencies concerned with national security issues over what was alleged to be an "arms control bias" in CIA's estimates, the Ford Administration decided to set up a "competitive" analysis team to take the same data and determine if it could also support different conclusions. The so-called "B Team" was intentionally loaded with arch-conservative analysts, and was headed by Richard Pipes of Harvard. Not surprisingly, the B Team came to the conclusion that the situation was considerably more ominous than the CIA had estimated.

One of the two technical areas the B Team chose to investigate in detail was that of Soviet ICBM accuracy. They came to the conclusion that the CEP of Soviet ICBMs was essentially unknowable, and that there was little evidence to indicate that Soviet ICBMs were not considerably more accurate than CIA estimates indicated. As several analysts have pointed out, had there been a "C team" loaded with individuals more liberal than the CIA, they might well have come to the conclusion that there was equally little evidence that Soviet ICBMs were not less accurate than indicated by CIA estimates. The fact is that given current intelligence methods, considerable uncertainty as to the accuracy of Soviet ICBMs is inevitable; it should be remembered that any change in the estimate of the CEP of Soviet weapons would have a profound effect on estimates of outcome of a Soviet attack on U.S. ICBMs.

REFERENCES

Gu1. These issues will be discussed in detail in the second portion of this paper.

Gu2. Much of this discussion is based on David Hoag's classic paper, "Ballistic Missile Guidance," contained in B. T. Feld, et al., eds: Impact of New Technologies on the Arms Race, MIT Press, 1971. However, we have made substantial changes from Hoag's format, in addition to updating the magnitudes of error; as an example, Hoag changed his assumption as to the orientation of the accelerometers several times during the course of his discussion, while we choose a uniform orientation which we use throughout.

Gu3. Figure from Hoag, ibid.

Gu4. Figure from Hoag, ibid.

Gu5. Graph from A. Wheelon: "Free Flight of a Ballistic Missile," American Rocket Society Journal, December 1959.

Gu6. Extremely attentive readers will notice that the table of error partials given here differs from that given by Hoag; our value for the target miss caused by a given altitude error is correct.

Gu7. Graph from Wheelon, op. cit.

Gu8. Because it relates to intelligence gathering methods, targeting accuracy is an especially sensitive issue, and there is very little unclassified information. Hoag estimates 200 meters of targeting error about each axis as of 1970, but it seems clear from the context that this is only an order-of-magnitude estimate. Our estimate is based on informal conversations with NASA scientists.

Gu9. Many other gyroscope arrangements are possible. As an example, if two-degree-of-freedom gyroscopes were used, only two would be necessary, and one redundant signal would be available. Similarly, if three two-degree-of freedom gyroscopes were used, there would be three redundant signals, and the system could function even if one gyro failed completely. Current U.S. Minuteman missiles are said to employ two gyroscopes. See Gen. R. Marsh: "Missile Accuracy: We Do Know!" Strategic Review, Spring 1982.

Gu10. Alternatively, instruments conceptually similar to carpenter's levels can be used; this is the method used for current Minuteman alignment. C. Venegas: "Alignment Performance of an Inertial Navigation System in a Low Level Seismic Environment," paper presented to the 1977 Guidance and Control Conference of the American Institute of Aeronautics and

Astronautics (AIAA).

Gu11. J. Hopkins: "The Global Positioning System Versus Gravity Disturbance Modeling in an Inertial Navigation System," presented at the 19th AIAA Aerospace Sciences Meeting, 1981.

Gu12. Alternatively, azimuth determinations can be made by repeated stellar measurements. However, since these measurements can only be made at night, they are unable to account for possibly significant diurnal variations; they are also available only in good weather. They require as much as several months to develop an accurate data base, and error can be introduced by the refraction of the earth's atmosphere. J. Shearer and W. Atwill: "Description and Applications for an Automated Inertial Azimuth Measuring System," presented at the 1978 AIAA Guidance and Control Conference.

Gu13. At the latitudes of most U.S. Soviet ICBM silos, the azimuth error caused by a given tilt is nearly equal to the tilt itself. Ibid.

Gu14. It is of note that this error is the largest we have so far encountered; indeed, Shearer and Atwill (ibid.) point out that "Azimuth uncertainties now represent a substantial portion of the total ICBM weapons system Circular Error Probable (CEP) estimates."

Gu15. Lt. Col. Scanlon, Air Force Ballistic Missile Office. Private communication.

Gu16. J. Lukesh: "Characterization Testing of the MX AIRS," presented at the 1979 AIAA Guidance and Control Conference. Since calibration depends on alignment, and vice versa, both are carried out continuously, with a Kalman filter (employing a model of the behavior of the particular AIRS unit, updated continuously using the results of the calibration and alignment process) damping the resulting errors. Rather than adjusting the physical instruments themselves, the navigation algorithm is adjusted to account for the subsystem errors. As a result of this continuous filtered calibration, the stability of many error sources is more of an issue than their original magnitude.

Also, since the calibration is accomplished by a continuous tumbling of the sphere, the accuracy requirements for the instruments causing and measuring the tumbling are quite stringent. Lukesh states that "the most critical issue in the AIRS error budget" is "the stability of the gyro torquing electronics."

Gu17. Ibid. The MX AIRS employs a floated ball torqued by hyrdraulic forces, and so avoids this problem, which Lukesh describes as "a major source of error in such a system."

Gu18. Ibid.

Gu19. Hoag, op.cit.

G1. The standard text on this subject is Physical Geodesy, by W. A. Heiskanen and H. Moritz, W. H. Freeman and Company, 1967.

G2. W. M. Kaula: "Determination of the Earth's Gravitational Field," Reviews of Geophysics, Vol. 1, No. 4, November 1963, pp. 507-551.

G3. For a detailed mathematical method of comparing gravity models, see R. M. Edwards: Gravity Model Evaluation for Precise Terrestrial Inertial Navigation, AFAL-TR-79-1231, 1979.

G4. Graph is from M. M. Bennett and P. W. Davis: "Minuteman Gravity Modeling," presented at the 1976 AIAA Guidance and Control Conference. The vertical scale was absent in the original.

G5. J. Hopkins and D. A. Richardson: "Effects of Unmodeled Gravity Disturbance Components on Inertial Navigation Systems," presented to the 35th Annual Meeting of the Institute of Navigation (ION), June 1979.

G6. Figures drawn from Bennett and Davis, op. cit.

G7. Ibid. Since the trajectories of interest have never been flown, this graph represents only an estimate of the uncertainty, not actual flight test data.

G8. J. E. Anderson: "Properties of Intercontinental Ballistic Missile Trajectories With a View To Determination of Errors," unpublished, available from the author care of the Mechanical Engineering Department of the University of Minnesota.

G9. According to Gen. R. Marsh ("Missile Accuracy: We Do Know!" op. cit.), the average value of gravity is known to better than one part in 20 million; an error of this order would result in a completely negligible target miss.

R1. Beta is also a function of Reynolds number, but this is only significant at high altitudes, where the effect is quite small, and uncertainties in the drag coefficient are overshadowed by atmospheric uncertainty. F. M. Shinnick: "On the Linearized Atmospheric Contributions to Reentry Vehicle CEP," Master's thesis in Aeronautics and Astronautics, MIT, 1964.

R2. Graph from "Data for ICBM Reentry Trajectories," RAND memorandum RM-3475-ARPA, April 1963.

R3. Graph from "Data for ICBM Reentry Trajectories," ibid.

R4. "Based on a limited data base, we would expect that 2% of the time weather conditions will exist in the target area which dould increase total system CEP by 25% due to nose cone erosion." Testimony of Gen. Alton Slay, head of Air Force Research and Engineering, Department of Defense Authorization Hearings for Fiscal Year 1977, Senate Armed Services Committee, pt. 11, p.6529. "It is known to be possible to postulate a sufficiently heavy rain or snow environment to cause the demise of both Polaris and Poseidon reentry bodies...", information supplied by the Department of the Navy, Department of Defense Authorization Hearings for Fiscal Years 1976 and 197T, Senate Armed Services Committee, pt. 10, p. 5355-5356.

R5. The method used to derive this graph involved a great number of assumptions and simplifications; it provides only extremely rough order-of-magnitude estimates of the errors.

To derive these numbers, we developed a simple computer program which modeled the aerodynamic forces and gravity forces acting on the RV, in order to trace its path through the atmosphere. We assumed a non-rotating spherical earth, and a perfectly symmetrical RV with a beta that did not change as it ablated, entering with zero angle of attack, and experiencing no lift forces.

We then introduced a series of essentially arbitrary winds and density variations, and observed their effect on the RV's impact point. Fortunately, we had available an infinitely more rigorous treatment of the subject (Shinnick, op. cit.), with which we could compare our results. Shinnick analyzed only two values of beta, 1000 and 2500 pounds/sq. ft.; having made a rough estimate of the shape of the curve given, we used his value for the atmospheric contribution to the CEP of a vehicle with a beta of 2500 to set the vertical scale, and found that our estimate of the value for a beta of 1000 agreed reasonably well with Shinnick's. His value for the atmosheric CEP of a vehicle with a beta of 1000 is the uncircled point on the graph. Thus, the values of CEP given for beta=2500 and beta=1000 can be treated with considerably higher confidence than those between. However, the reader should remember that the graph represents only the contributions made by atmospheric variables, assumes zero asymmetries in the vehicle, zero trim angle of attack, and does not account for the fact that the beta of the vehicle may change as the nosetip ablates.

R6. Drawn from graphs in Shinnick, ibid.

R7. T. Greenwood: "Notes on Conversations with AVCO Personnel," 1975, unpublished. Greenwood describes the beta of the RV developed for the Trident 1 as being 1800 lbs/sq. ft., with the technology available to build an RV with a beta of 2000. Jim Miller, head of the Ballistic Missiles Systems Branch of the Defense Intelligence Agency, in testimony before the House Armed

Services Committee in 1979, described the beta of the Minuteman III RVs as being "up around 2000", while Soviet RVs were then much less capable, having betas of the order of 1500.

R8. J. P. Crenshaw, "Effect of Lift with Roll Rate Variation on Reentry Vehicle Impact," Journal of Spacecraft and Rockets, May 1971, and "Effect of Lift Variation on the Impact of a Rolling Reentry Vehicle," Journal of Spacecraft and Rockets, April 1972. Both of these effects, as well as the more extreme possibility that the roll rate might pass through zero, should be manageable by increasing the spin rate of the RV. D. H. Platus describes effects which are not in "Dispersion of Spinning Missiles due to Lift Nonaveraging," AIAA Journal, July 1977.

R9. B. F. Fuess: "Impact Dispersion Due to Mass and Aerodynamic Asymmetries," Journal of Spacecraft and Rockets, Nov. 1967.

R10. Crenshaw, op. cit.

R11. Ibid.

R12. R. B. Dirling, Jr.: "Asymmetric Nose-Tip Shape Change During Atmospheric Entry," presented at the 12th AIAA Thermophysics Conference, June 1977. The paper includes a photo of an RV nose-tip recovered from a flight test, which shows quite graphically the extent to which the ablation that occurs is rough and asymmetrical.

R13. Ibid.

R14. Fuess, op. cit., and Crenshaw, op. cit.

R15. Testimony of Gen. Alton Slay, FY1977 authorization hearings, op. cit., p. 6450. See also H. King: "Ballistic Missile Reentry Dispersion," Journal of Spacecraft and Rockets, May-June 1980, which identifies reducing dispersion attributable to the nosetip to a level comparable with that attributable to atmospheric variations as "a design goal."

R16. Dirling, op. cit.

R17. In fact, testing of RVs may be significantly skewed toward days with good weather. Private coummunication with researcher at the RAND corporation.

R18. S. Glasstone and P. Dolan, eds: The Effects of Nuclear Weapons, U.S. Department of Defense and U.S. Department of Energy, 1977, p. 111.

R19. Testimony of Richard Delauer, Undersecretary of Defense for Research and Engineering, Senate Armed Services Committee, Feb. 24, 1982.

O1. "A White Paper on RV Trajectory Deflection by the Earth's Magnetic Field," Paper no. AVSD-0567-81-PP, AVCO Systems Division, Wilmington MA., 1981.

O2. G. Bomford, Geodesy, Third Edition, Clarendon Press, 1971, p. 559.

K1. Testimony before the Senate Foreign Relations Committee, April 30, 1982.

K2. A particularly extreme example of this appeared in the Congressional Record (January 23, 1978, p. H99-H100), where the "confidence level" in the outcome of an attack was calculated, assuming that the kill probabilities of all the weapons in the attack were known precisely, and that they did not interfere with each other in any way. Given that most of the lack of confidence arises from precisely the uncertainties that this ignores, this calculation is not very useful.

K3. Glasstone and Dolan, op. cit.

K4. For more information, see K. Tsipis: Nuclear Explosion Effects on Missile Silos, MIT Center for International Studies, February 1978.

K5. This is the number that one finds in most sources; however, James Miller, head of the Weapons and Systems branch of the Defense Intelligence Agency, has stated that the number given to the intelligence community by the Air Force for official threat assessments is 2200 psi. Testimony before the Senate Appropriations Committee, June 16, 1981.

K6. In the DIA system, the vulnerability of a target is expressed by a "VNTK" number, where VN is a logarithmic transformation of the hardness of the target, T specifies whether the type of pressure referred to is overpressure or dynamic pressure, and the K is a measure of the target's sensitivity to pulse duration. See Mathematical Background and Programming Aids for the Physical Vulnerability System for Nuclear Weapons, DI-550-27-74, DIA November 1 1974, with Change 1 (August 1, 1976).

However, there is some dispute over the accuracy of this modeling of the effect. Indeed, B. Bennett has pointed out a seeming inconsistency in the DIA's formulation, concluding: "there appears to be a real problem somewhere in DIA's weapon radius formulation." The inconsistency appears to be a small one however, and applicable largely to very soft targets. See B. Bennet: How to Assess the Survivability of U.S. ICBMs, R-2577-FF, with Appendixes, R-2578-FF, RAND Corporation, Santa Monica, California, June 1980, Appendix B, page 9.

K7. Ibid., Appendices.

K8. For similar calculations, see K. Tsipis, Offensive Missiles, Stockholm Paper number 5, Stockholm International Peace Research Institute, 1974, and J. E. Anderson, "The Probability of Destruction of a Missile Silo," unpublished, available from the author, care of the Mechanical Engineering Department of the University of Minnesota.

K9. Bennett, op. cit., Appendixes, pages 20-21. Our calculations indicate that while this is true for most downrange biases of reasonable size, it is not true in the case of a large crossrange bias (that is, perpendicular to the semimajor axis of the distribution), but this is an unlikely event, as bias errors, like random errors, are more often downrange than crossrange.

K10. Tsipis, Missile Silos, op. cit., page 20.

K11. These are currently the most commonly cited figures on the technical performance of Soviet ICBMs; they are from Aviation Week and Space Technology. They are included in the fairly detailed description of much of the Soviet strategic arsenal given in the special issue on modernization of strategic forces, June 16, 1980, under the title "Soviets' Nuclear Arsenal Continues to Proliferate." The same figures are given in several subsequent articles; most recently, in an October 12, 1981 description of the "Soviet Military Power" section of the Fiscal Year 1983 Defense Posture Statement, under the title "Missile Deployment Increases Threat."

Slightly different figures were given by James Miller, chief of the Weapons and Systems Division of the Defense Intelligence Agency, in testimony before the Senate Appropriations Committee on June 16, 1981: he cited 245 meters (about .13 nautical miles) as the accuracy of the SS-19, but since he also gave a higher value for the hardness of the Minuteman silos than is usually used (2200 psi), the better accuracy gives roughly the same kill probability as do the numbers we use. (From the context, it would appear that the appearance of these numbers in the printed text was a slip-up in classification procedures). The most recent edition of the IISS Military Balance gives CEPs of .15 nautical miles, slightly larger than the numbers we use here: if these numbers were used, the kill probability of Soviet weapons would be significantly lower than that we calculate.

It should also be noted that the Soviets are currently testing a follow-on modification of the SS-18, the SS-18 Mod 5, which is estimated to have somewhat better accuracy than the Mod 4. It is estimated that intitial deployment of this modification will begin in 1985. In addition, the Soviets are currently testing two new ICBMs (one of which may be a modification of the old SS-13). As of this writing, it is too early to make any estimates of the accuracy of these systems: it is unlikely that either will be deployed before the late 1980s.

K12. Reliability is one of the "softest" numbers concerning Soviet capabilities; most discussions of the technical abilities of Soviet weapons ignore this issue entirely, and those estimates that are available in the unclassified realm range from 60% to 98%.

However, some basis for judgement is available. First, Soviet liquid-fueled ICBMs are widely regarded as being less reliable than their American solid-fueled counterparts; as an example, B. Schneider and S. Leader give figures of 75-80% for American ICBMs, and 65-75% for Soviet ICBMs. ("The United States-Soviet Arms Race, SALT, and Nuclear Proliferation," Congressional Record, June 5 1975).

Second, an ICBM is an extremely complex technical system; when reliability is defined as the ability to launch at any moment over thousands of hours with the extreme accuracy needed for a counterforce attack, it is simply unrealistic to expect reliabilties close to 100%. Albert C. Hall, one of the chief engineers for the Titan II, has indicated that it would be "extremely difficult" to engineer "a system as complex as an ICBM" with a reliability greater than 80%. ("The Case For an Improved ICBM," <u>Astronautics and Aeronautics</u>, February 1977).

Other reasonably current estimates of Soviet ICBM reliabilties that fall in this same range include Edward Luttwak's, who uses roughly 73% in <u>Strategic Power: Military Capabilities and Political Utility</u>, Center for Strategic and International Studies, Georgetown University, 1977, and that of the Congressional Budget Office, who give an estimate of 75% in "Counterforce Issues for the U.S. Strategic Nuclear Forces," January 1978, p. 16.

However, there are other estimates that are significantly higher: current estimates from the RAND corporation use 85% for both U.S. and Soviet systems, while Rep. Thomas Downey gave 85% for current Soviet weapons, and 90% for early 1990's systems, in "How to Avoid Monad---And Disaster," <u>Congressional Record</u>, September 20, 1976, p. S16211-S16212. A figure of 80% or 85% would increase the kill probabilities we calculate by several percent.

K13. Testimony of General John Vessey, Chairman of the Joint Chiefs of Staff, before the Senate Appropriations Committee, May 5, 1983, reported in the <u>New York Times</u>, May 6, 1983.

B1. One of the early articles on this subject was Andrew Cockburn and Alexander Cockburn's "The Myth of Missile Accuracy," <u>New York Review of Books</u>, Nov. 20, 1980. J. E. Anderson, a former inertial guidance specialist now at the University of Minnesota, then wrote three unpublished but widely-discussed papers on the subject, "Properties of Intercontinental Ballistic

Missile Trajectories With a View to Determination of Errors," "The Probability of Destruction of a Missile Silo," (both op. cit.) and "Are We Vulnerable To a First Strike?" More recently, his "First Strike: Myth or Reality?" appeared in the Bulletin of the Atomic Scientists, November, 1981. (Note letter by R. Speed in the April 1982 Bulletin, pointing out an error in Anderson's calculations). Other influential articles on the subject of bias have included A. Metcalf: "Missile Accuracy---The Need to Know," Strategic Review, Summer 1981 (with discussion from Anderson and Gen. R. Marsh, Spring 1982), and P. Mann: "Panel Reexamines ICBM Vulnerability," Aviation Week and Space Technology, July 13, 1981. In addition, James Fallows included some discussion of bias in his bestselling book, National Defense, pp. 139-170.

B2. This conflict of definitions has caused considerable confusion. For example, Fallows notes in his book that "Several men who have devoted large portions of their working lives to the details of missile technology patiently explained to me, over the course of many months, the concept of 'bias' I set out in the next few pages...Several other people of comaparable intelligence and integrity, who have been equally attentive to the details of nuclear policy, assured me that...a missile's 'accuracy'...really does measure how close its warheads would come to its intended target." In the exchange between Anderson and Gen. Marsh in Strategic Review, Marsh initially defines CEP as "the radius of a circle centered around the target area in which the impact is likely (50 per cent probability) to occur," but later concedes that Anderson's definition using the average point of impact is "a preferable mathematical construct."

B3. The Minuteman III is assumed to have a yield of 335 kilotons, and a CEP of .1 nautical miles. Both weapons are here assumed to have perfect reliability and to be attacking a target hardened to 2000 psi.

B4. Cockburn and Cockburn, op. cit.

B5. Fallows, op. cit.

B6. Testimony before the Arms Control Subcommittee of the Senate Foreign Relations Committee, March 4, 1974.

B7. Testimony before the Senate Foreign Relations Committee, April 30, 1982, op. cit.

B7. Testimony before the Senate Armed Services Committee, March 5, 1975.

B8. Mann, op. cit. This article includes several statements on both sides of the issue.

B9. Marsh, op. cit.

B10. Testimony before the House Armed Services Committee, 1979. As with most Congressional testimony, the passage is somewhat confusing; bias, after all, is an undefined concept for one test.

F1. This method is drawn from that in J. Romm and K. Tsipis: "Analysis of Dense Pack Vulnerabilities," Program in Science and Technology for International Security, Report No. 8, Massachusetts Institute of Technology, November 1982. This is perhaps the most detailed unclassified discussion of the problem of fratricide. For another interesting discussion of the subject see J. Steinbruner and T. Garwin: "Strategic Vulnerability: The Balance Between Prudence and Paranoia," International Security, Summer 1976. Bennett, op. cit., provides an interesting analysis of Steinbruner and Garwin's piece, refining some of the models used. Another analysis, more qualitatively than quantitatively oriented (perhaps because of the inherent limitations imposed by secrecy) is provided by Lt. Col. J. McGlinchley and Dr. J. Seelig: "Why ICBMs Can Survive," Air Force Magazine, September 1974. The title refers exclusively to the problem of fratricide.

F2. The calculation of the lethal radius for neutron flux was made using the kill criteria and neutron flux equations given by Romm and Tsipis, op. cit., p. 5.

F3. Glasstone and Dolan, op. cit., p. 28 and 70-71.

F4. H. L. Brode: "Nuclear Weapons Effects," Annual Review of Nuclear Science, 1968, Vol. 18, p. 176.

F5. Glasstone, p. 82 and 106-115.

F6. The rate of rise of the fireball at 10 seconds is roughly 100 m/sec, but the fireball has been rising somewhat faster previously (Glasstone and Dolan, op. cit., p. 28 and 31). It has therefore risen roughly 1000-2000 meters by this time. If we assume a height of burst of 200 meters, the fireball at 10 seconds is 1200-2200 meters from the ground, and has a radius of 1000 meters. As the fireball radius reaches several hundred meters within the first tenth of a second, the fireball remains in contact with the ground from immediately after the explosion until nearly 10 seconds later.

Several analysts have postulated the existence of a "window" through which a second RV could safely reenter, lasting from roughly 2 seconds after the first detonation to perhaps 7 seconds (see Steinbruner and Garwin, op. cit., and Bennett, op. cit.). We do not believe a significant window exists during this time period. Firstly, at least part of the fireball will remain in contact with the ground throughout this period, meaning that to attack the same target, a second RV would have to pass through an area where the temperature is several thousands of degrees centigrade, and the turbulent winds are of the order of 900 km/hr. In addition, since the density of the fireball is orders of magnitude less than that of the surrounding air within milliseconds after the detonation, the fireball begins to rise quite rapidly immediately after the detonation: the rise of the fireball creates strong vertical winds which entrain dust and debris, which in turn can easily be lethal to the entering RV. Even if none of these effects existed, the timing of an attack involving more than 1000 RVs each arriving within a 5 second window of its predecessor, over ranges ofthousandsof kilometers, would be a difficult project indeed.

F7. Glasstone and Dolan, op. cit., p.233.

F8. Brode, op. cit.

F9. Glasstone and Dolan, op. cit., p. 106-115.

F10. Ibid, p. 28 and 31.

F11. Cloud size information from Glasstone and Dolan, ibid, p. 34, 506-507, and 431.

F12. Map of Malmstrom Air Force Base taken from H. York: "Military Technology and National Security," Scientific American August 1969. The grey areas represent the clouds, while the black dots in the center are the cloud stems. For the purposes of this figure, the simplfying assumption was made that each detonation occurred directly over the silo. It should be noted that in those portions of the base not shown on this map, the silos are much more closely spaced than those shown in this picture, meaning that the coverage of the field by the dust cloud is even more complete.

F13. Bennett, op. cit., Appendices.

F14. Chart of fratricide effects presented by Gen. Alton Slay, head of Air Force Research and Engineering, in Hearings on Military Posture for Fiscal Year 1979, House Armed Services Committee, part 3, p. 335.

F15. The numbers on these figures are derived from Glasstone and Dolan (op.cit) and Brode, (op.cit.).

F16. This calculation is quite simple; if 25% of the warheads fail, then the effective reliability of an attack that targeted two warheads on each silo would be 94%, and it is this number by which the kill probability of the warheads is multiplied. These calculations assume zero bias, as do all the calculations in this section; the combined effect of uncertainties will be discussed in section 2.6.

F17. As mentioned above, particles weighing up to seven grams would still be falling out of the cloud up to twenty minutes after the detonations of the first wave. A collision with a particle weighin as much as seven grams would probably inflict severe damage on the RV.

F18. In making this graph, we assumed that since the dust clouds caused by the first wave of detonations are so large as to merge into one cloud, the most useful first approximation is to assume that fratricde effects are equal for all warheads in the second wave. Our chart shows the effect of both increases in atmospheric CEP, and the possibility of warhead destruction. To calculate the total CEP resulting from a given change in atmospheric CEP, we assumed that the atmospheric portion of the CEP of current Soviet weapons was .06 nautical miles (a conservative estimate for a system with a total CEP of .14 nautical miles), and used a standard root-sum-square approach to calculate the resulting new CEP for given increases in the atmospheric CEP.

The specific assumptions that correspond to a particular point on the graph are as follows:

(1) No fratricide effects.

(2). No RVs destroyed, reentry errors multiplied by 1.3

(3). 5% destroyed, reentry errors multiplied by 1.6

(4). 5% destroyed, reentry errors multiplied by 2.

(5). 10% destroyed, reentry errors multiplied by 2.2

(6). 10% destroyed, reentry errors multiplied by 2.5.

(7) 20% of second-wave RVs destroyed; reentry errors multiplied by 2.5

(8). 35% destroyed; reentry errors multiplied by 3.

(9). 50% destroyed; reentry errors multiplied by 3.5.

(10). 65% destroyed; reentry errors multiplied by 4.

(11). 80% destruction, reentry errors multiplied by 4.5.

(12). 100% destruction.

F19. As noted in the section on reentry, even heavy rain or snow can increase the total system CEP by roughly 25% (corresponding very nearly to a doubling of the reentry errors, as we calculate them above), and can destroy the RV outright under some conditions. The effect of passage through the nuclear dust cloud and disturbed atmosphere should be at least as severe.

F20. To calculate the result of such an attack, it is necessary simply to calculate the percentage of silos destroyed in the first wave, and the percentage of those missed in the first wave (excluding those at which the warhead failed) which would be destroyed by the second wave. For this type of calculation, it is often useful to construct an "event tree" which exhaustively lists all of the possibilities in a given situation, and the probabilities attached to each. Event trees for each of the calculations performed in this section are available from the authors.

F21. Richard Garwin, private communication.

F22. MX Missile Basing, report of the Congressional Office of Technology Assessment, September 1981, p. 156. F19. Note also that some of the weapons allocated to pindown role would fail: if the attacker believed that the command and control system of his opponent would be adequate to take advantage of the gap left by a failed missile, a much larger allocation would be required to insure against this possibility. It should be pointed out, however, that the weapons for pindown need not be accurate, so that weapons from older ICBMs or submarines could be used.

F23. The "attack ratio" or "exchange ratio" is the ratio of the resources the attacker expends in the attack to those the defender loses. In this case, an attack which destroyed 76% of the 2100-warhead Minuteman force, or 1600 warheads, would require 3000 accurate warheads. This is an exchange ratio of nearly 2-1 against the attacker, without counting warheads assigned to pindown roles. If the exchange ratio is measured in terms of equivalent megatons, or as a percentage of total deliverable warheads, the ratio in this case is even more unfavorable to the attacker.

It should be noted that if the 10-warhead MX is deployed in Minuteman silos, this argument will no longer hold; a 10-warhead missile represents a much more attractive target than does a 1 or 3-warhead missile, and is thus more vulnerable in the same basing mode, especially if the number of them deployed is small, so that the attacker can afford to devote a larger number of warheads to attacking those silos.

F24. The combined total of Soviet SS-18 Mod 4 and SS-19 Mod 3 warheads is estimated to be 2550. See "The Freeze and the Counterforce Race," H. Feiveson and F. von Hippel, Physics Today, January 1983.

F25. The "event tree" in this case is extremely complex, but the assumptions of this graph are the same as those of Figure 2.4.3, except for the following: since the reprogrammed warheads will be arriving after the detonations of two waves, rather than one, it is assumed that all of the reprogrammed warheads suffer 1.3 times as much fratricide as those which arrive in the second wave. It is assumed that reprogrammed warheads for the failures of both of the first waves are targeted to arrive at the same time, so that in a very small number of cases, two reprogrammed warheads arrive at a previously undamaged target; in these cases, only one warhead survives to detonate.

F26. See, for example, R. Garwin, "Effective Military Technology for the 1980's," International Security, Fall 1976.

F27. MX Missile Basing, op. cit., p. 126-127.

U1. A different approach can be found in Bennett, op. cit. The backbone of Bennett's paper is a statistical uncertainty analysis based on assumed probability distributions representing the uncertainty in various parameters; these probability distributions are then employed in Monte Carlo simulation to determine the total uncertainty in probability of kill. Our method is considerably simpler and less rigorous, as we felt the quantity of available information did not justify employing such a rigorous method.

In particular, Bennett treats the problem of uncertainty in CEP as essentially a chi-square impact distribution problem, much like assessing the CEP of a dart after a given number of throws; however, the CEP information derived from a series of tests is far more complex than simply a collection of impact points. For example, until several years ago, Navy SLBM tests were conducted on a simple "shoot and score" basis; the distance between the target and the actual impact point was measured, and little information was available as to what factors contributed to any errors. During the late 1970s, the Navy spent several hundreds of millions of dollars developing a monitoring capability similar to that available for land-based ICBM tests, which is capable of providing reasonably accurate estimates of the causes of particular impact errors. In general, such additional information can be extremely important, and can significantly decrease the number of tests required to achieve a given level of accuracy.

Bennett's paper is by far the best discussion of this subject we have come across; we recommend it highly.

U2. The effect of the shorter flight ranges is assessed in Appendix C.

U3. This chart was calculated assuming no fratricide and no bias; the same is true of the other similar charts we will present in this section.

U4. F. Hussain: "The Impact of Weapons Test Restrictions," Adelphi Paper 165, International Institute for Strategic Studies, Spring 1981, p. 29 and p. 51.

U5. Ibid, p. 32.

U6. Ibid. Hussain discusses this point in some detail; for methods of assessing system reliability which reduce the requirement for full-system flight testing, he cites R. Stevens: Operational Test and Evaluation: A System Engineering Process, John Wiley and Sons, 1979.

U7. R. Engelman: "Minuteman Misfire Deals Blow to Missile's Credibility," Kansas City Times, June 4, 1982.

U8. Glasstone and Dolan, op. cit., preface.

U9. Mathematical Background and Programming Aids for the Physical Vulnerability System for Nuclear Weapons, Defense Intelligence Agency, 1974. Page 35.

U10. See discussion in Bennett, op. cit., p. 22-23 and 35.

U11. H. L. Brode: "Height of Burst Effects at High Overpressures," RAND Corporation, 1970, prepared for the Defense Atomic Support Agency. A subsequent report by Brode and T.G. Lewis also reported substantial uncertainty in overpressures: see "Implications of Recent Airblast Studies to Damage of Hardened Structures," 1975.

U12. Ibid, p. 9. See also similar graphs p. 8, 11, and 12.

U13. Ibid, p. 14

U14. Ibid, p. 10.

U15. Bennett, op. cit., Appendices.

U16. Testimony in Department of Defense Authorization Hearings for Fiscal Year 1979, Senate Armed Services Committee, pt. 9, p.6476.

U17. Ideally, the combination of a variety of uncertainties is best assessed by Monte Carlo simulation; however, such simulation requires a specific probability distribution for each uncertainty, and as could be gathered from the previous section, it is simply not possible to create realistic distributions for each parameter from the information available in the unclassified literature. Therefore, we will simply show the effect of simultaneous unfavorable variations of the parameters. It is also perfectly possible for the attack to experience simultaneous favorable variations, but this is not germane to our question, which is, what is the level of destruction that the attacke can have some minimal confidence of achieving, even under unfavorable circumstances?

U18.

U19. This "light fratricide" calculation is identical to that performed in the section on fratricide: it assumes that the first wave will be timed adequately to experience no fratricide, and that 5% of the warheads in the second wave will be destroyed, and for those that survive, the portion of the CEP attributable to reentry errors (assumed to be .06 nautical miles for current Soviet systems) will be doubled.

U20. The unfavorable variations assumed in this row are the same as those described individually in the last section: a 10% degradation in CEP, silos 20% harder than expected, a 25% variation in yield and expected weapons effects, and a 10% degradation of reliability. These variations result in a system with a CEP of .154 n. mi., an effective yield of .41 MT, and a reliability of .675, attacking silos hardened to 2400 psi.

Fu1. See note K12.

Fu2. The Military Balance, 1982-1983, International Institute for Strategic Studies, 1982.

Fu3. See "Sizing up the SS-24," Newsweek, March 14, 1983.

Fu4. Lukesh: "Characterization Testing of the MX AIRS," op. cit.

Fu5. See discussion in the Senate Armed Services Committee hearings on the Deptartment of Defense authorization for appropriations for fiscal year 1983, especially testimony by James Wade, Deputy Undersecretary of Defense for Research and Engineering, and Richard Wagner, Assistant Secretary for Atomic Energy, on March 17, 1982.

Fu6. Edwards: Gravity Model Evaluation for Precise Terrestrial Inertial Navigation, op. cit.

Fu7. D. Shroeer: "Quantification of the Technological Imperative," in D. Carlton and Carlo Schaerf, eds., Reassessing Arms Control, forthcoming.

Fu8. While it would probably be possible to harden silos to survive pressures greater than 2000 psi, in order to maintain the same survivability through time, the hardness of the silos would have to increase by a factor of eight for every time the accuracy doubled, i.e., every seven years or so. While claims of everything from 5000 psi to 100,000 psi have been made for new silo designs in the debate over MX basing, these claims are largely based on very simplified calculations from scale model tests of conventional explosions, which cannot possibly model many of the synergistic effects of nuclear weapons. To these writers, it seems abundantly clear that it will be technically impossible for U.S. hardness improvements to successfully "race" Soviet accuracy improvements. Even a doubling of the hardness of all 1000 Minuteman silos would do no more than to delay the problem for a few more years.

Fu9. Shinnick (op. cit.) gives 60-70 meters as the atmospheric ontribution to CEP for a vehicle with a beta of 2500 lbs/sq. ft; vehicles with betas greater than 2500 are not enormously more accurate, as the curve gets quite flat in that region, and they are difficult to design as well.

Fu10. "Design Review of Navstar Block II Completed," Aviation Week and Space Technology, June 7, 1982. See also R. J. Milliken and C. J. Zoller: "Principle of Operation of NAVSTAR and System Characteristics," Navigation, Summer 1978.

Fu11. The Soviets first tested SIG on the SS-N-8 SLBM, in 1972. Hussain, op. cit., p. 51.

Fu12. The D5 missile as currently planned will utilize an improved SIG system, as well as a system of eliminating initial velocity errors by correlating measurements of the ocean floor with data stored on-board the submarine. See Aviation Week and Space Technology: "Trident Missile Capabilities Advance," June 16, 1980; "Emphasis Grows on Nuclear Defense," March 8 1982; and "Congress Questioning Viability of MX ICBM," March 22 1982.

Fu13. M. Gerber: "Gravity Gradiometry: Something New in Inertial Navigation," Astronautics and Aeronautics, May 1978.

Fu14. Ibid.

Fu15. B. Miller: "Advanced Reentry Vehicle Tests Planned," Aviation Week and Space Technology, May 24, 1976.

Fu16. Ibid. AMARV is roughly the same size as current U.S. Minuteman Mk. 12A RVs.

Fu17. Arms Control Impact Statements, Fiscal Year 1982, p. 18-19.

Fu18. Miller, op. cit.

Fu19. Ibid.

1A. MX Missile Basing, op. cit., p. 195. The OTA report estimated that an attack on current U.S. ICBM silos, MX missiles in multiple protective shelters, bomber bases, and submarine ports would total 25-50 million, while the added fatalities from the attack on the multiple protective shelters would cause from 1 to 5 million casualties. We have subtracted the upper bound of the MPS casualties from the total, to be conservative. The Air Force estimate was provided in testimony before the House Subcommittee on Public Lands, on May 13 1981 (citation provided by Richard Garwin).

2A. Estimate of combat deaths of less than one million taken from chart in F. Spinney, "Defense Facts of Life," December 1980,

NTIS publication AD/A111 544.

3A. B. Blechman, S. Kaplan, et. al.: Force Without War, Brookings Institution, Washington DC, 1978.

1B. Much of this derivation follows that given in A. Wheelon: "Free Flight of a Ballistic Missile," op. cit.

2B. Another useful derivation of some of these quantities is given by J. E. Anderson, in "Properties of Intercontinental Ballistic Missile Trajectories With A View To Determination of Errors," op. cit.

3B. See, for instance, Goldstein, Classical Mechanics .

4B. The correct integration is given in Wheelon, op. cit.

5B. This difference in ranges is discussed in some detail in Appendix C.

6B. See "Minuteman Gravity Modeling," op. cit.

1C. Both of these cases are described in Hussain, "The Impact of Weapons Test Restrictions," op. cit. Hussain provides an overview of controversies surrounding nuclear weapons testing and uncertainties in estimating weapons performance.

2C. Private communications with Lt. Col. Scanlon of the Air Force Ballistic Missile Office, and Sydney Graybeal, formerly a monitor of Soviet testing for the CIA, and subsequently first Commissioner of the SALT Standing Consultative Commission. See also Hussain, op. cit., who indicates that both the U.S. Minuteman III and the Soviet SS-18 underwent approximately 29 R+D tests before full-scale deployment.

3C. R. Stevens: Operational Test and Evaluation: A System Engineering Process, John Wiley and Sons, 1979, p. 6-7.

4C. Scanlon, op. cit.

5C. Hussain, op. cit.

6C. G. Houchens: "Missile guidance and control Subsystems 'think' Minuteman is constantly in flight," IEEE Spectrum, Oct. 1981, p. 64.

7C. Hussain, op. cit., and Scanlon, op. cit.

8C. Ibid.

9C. Ibid.

10C. Ibid.

11C. Lt. Col. Louis Montulli, quoted by P. Mann: "Panel Reexamines ICBM Vulnerability," Aviation Week and Space Technology, July 13, 1981.

12C. Although an ICBM flying over a range much shorter than the maximum would have considerable flexibility concerning the trajectory to be flown, we have made the simplifying assumption that the rocket would release the RV at an angle of 22.5 degrees, just as in the 10,000 km case, with the boost phase trajectory being identical to that described in Appendix B, except several seconds shorter. The same techniques were used to calculate this error table as were used for the original error derivations in the first half of this paper; the error partials at thrust termination for each case are derived in Appendix B. It should be noted that in this case we have assumed the targeting errors to be zero, since the test range will probably be surveyed extremely accurately. In addition, we have listed the gravity errors as zero: the same is done in Congressional testimony on ICBM testing, since in that case "we know that gravity well and can back it out precisely." See testimony of J. B. Walsh, Deputy Director for Strategic and Space Systems, Defense Research and Engineering, in Hearings on Military Posture for Fiscal Year 1977, House Armed Services Committee, part 5, p. 200.

13C. Walsh, op. cit., p. 198-199.

14C. Graybeal, op. cit.

15C. Private communication with researcher at the RAND corporation. See also Mann, op. cit., which quotes A. Battista of the the House Armed Services Committee as saying that the Soviets "have tested over a broader spectrum of possible operational conditions and adverse circumstances like bad weather."

16C. R. Engelman: "Minuteman Misfire Deals Blow to Missile's Credibility," op. cit. As is often the case, the analyst quoted is not named. Another interesting journalistic discussion of this subject is J. Marshall: "Missiles That Fizzle," Inquiry, March 1983. Marshall quotes yet another unnamed Pentagon analyst as arguing, in reference to Soviet ICBMs, that "it would be closer to call [80-85%] their unreliability."

17C. In-house publication cited by both Engelman and Marshall, ibid.

18C. Graybeal, op. cit., and Hussain, op. cit.

19C. This example of a possible operational degradation of CEP was provided by J. B. Walsh, Deputy Director for Strategic and Space Systems, Defense Research and Engineering, in Hearings on Military Posture for Fiscal Year 1977, House Armed Services

Committee, part 5, p. 202.

Bennett, op. cit., uses a chi-square analysis to estimate the uncertainty in CEP; the resulting uncertainty distribution is not symmetric, giving a higher probability that the system will perform significantly worse than expected than that it will perform significantly better. Although we do not believe that such a simple statistical analysis adequately models the uncertainty in CEP, we are inclined, by a healthy respect for the applicability of Murphy's Law to technical systems, to believe this assymmetry. Bennet estimates an upper 95% confidence interval roughly 40% greater than the expected value of the CEP, though he does not consider uncertainties introduced by lack of realism; our estimate of the plausible unfavorable variation in CEP is one-fourth this value.

20C. F. Moncrief: "SALT Verification: How We Monitor the Soviet Arsenal," Microwaves, September 1979. Another interesting and quite detailed discussion of the loss of the Iranian monitoring sites and the subsequent interim measures is provided in J. Prados: The Soviet Estimate: U.S. Intelligence Analysis and Russian Military Strength, 1982, p. 271-276.

21C. Ibid.

22C. Hussain, op. cit.

23C. Moncrief, op. cit.

24C. For a description of some U.S. ferret satellites, see ibid.

25C. Hussain, op. cit.

26C. "U.S. Monitoring Ability Impaired," Aviation Week and Space Technology, April 14, 1979.

27C. Moncrief, op. cit. He performs a rough calculation to indicate that the Rhyolite satellites were probably no longer able to receive telemetry data.

28C. Hussain, op. cit.

29C. Moncrief, op. cit.

30C. Until the last two issues, the estimate of the CEP SS-18 Mod 4 published in the semi-official Military Balance published by the International Institute for Strategic Studies was 600 feet. The more recent issues give 300 meters as the CEP of this system, while the recent Aviation Week articles cited in section 2.2 give an estimate of approximately 270 meters. We have used the more conservative value.

The Iranian monitoring sites were considered to be an especially great loss to U.S. ability to estimate the accuracy of Soviet ICBMs. Dr. William Perry, then Undersecretary of Defense for Research and Engineering, discussed SALT verification in testimony before the House Armed Services Committee during February of 1979: after a long deleted section assessing the impact of the impending loss of the Iranian sites, he simply said: "I would point out that we are not limiting accuracy in this treaty..."

31C. P. Klass: "USAF Tracking Radar Details Disclosed," Aviation Week and Space Technology, Oct. 25, 1976.

32C. Hussain, op. cit.

33C. Ibid.

34C. Ibid.

35C. Prados, op. cit., provides an excellent discussion of the B Team episode.