Published in cooperation with the
Program in Science and Technology for International Security
Massachusetts Institute of Technology

Review of U.S. Military Research and Development 1984

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Pergamon Press Offices:

U.S.A. Pergamon-Brassey's International Defense Publishers,
1340 Old Chain Bridge Road, McLean, Virginia, 22101, U.S.A

Pergamon Press Inc., Maxwell House, Fairview Park,
Elmsford, New York 10523, U.S.A.

U.K. Pergamon Press Ltd., Headington Hill Hall,
Oxford OX3 0BW, England

CANADA Pergamon Press Canada Ltd., Suite 104, 150 Consumers Road,
Willowdale, Ontario M2J 1P9, Canada

AUSTRALIA Pergamon Press (Aust.) Pty. Ltd., P.O. Box 544,
Potts Point, NSW 2011, Australia

FRANCE Pergamon Press SARL, 24 rue des Ecoles,
75240 Paris, Cedex 05, France

FEDERAL REPUBLIC OF GERMANY Pergamon Press GmbH, Hammerweg 6,
D-6242 Kronberg-Taunus, Federal Republic of Germany

Library of Congress Cataloging in Publication Data
Main entry under title:

Review of U.S. Military research and development, 1984.

"Published in cooperation with the Program in Science and Technology for International Security, Massachusetts Institute of Technology."
1. Military research–United States–Addresses, essays, lectures. 2. United States–Armed Forces–Procurement–Addresses, essays, lectures. 3. United States–Armed Forces–Weapons systems–Addresses, essays, lectures. I. Tsipis, Kosta. II. Janeway, Penny.
III. Massachusetts Institute of Technology. Program in Science and Technology for International Security.
IV. Title: Review of US military research and development, 1984. V. Title: Review of United States military research and development, 1984.
U393.R48 1984 355'.07'0973 84-16560
ISBN 0-08-031622-0

Printed in the United States of America

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TECHNOLOGY OF BALLISTIC MISSILE REENTRY VEHICLES

Matthew Bunn

INTRODUCTION

The flight of a long-range ballistic missile can be divided into three distinct phases. First is the boost phase, during which the main rockets lift the missile out of the atmosphere and give it the velocity required to reach its intended target. Once out of the earth's atmosphere, the warhead (or warheads) separates from the rocket and coasts through the earth's gravity field, until it reenters the atmosphere and ultimately detonates over the target. Thus, the three distinct phases of the flight are the *boost phase*, lasting 3–5 minutes, the *free-fall phase*, covering the long central portion of the flight, and *reentry* through the atmosphere, which requires only the last minute or two of the missile's flight.

In order to survive the rigors of reentry, the nuclear warhead is protected by the *reentry vehicle*, or RV. Most of the significant technological issues concerning reentry arise from the simple fact that when the RV enters the atmosphere, it is travelling at enormously high speed. An RV from an intercontinental ballistic missile (ICBM), for example, might travel roughly 10,000 kilometers from its launch site to its target; it would then enter the atmosphere at a speed of approximately 7,200 meters per second at an angle of approximately 22 degrees from the horizontal.[1]

Such speeds are far beyond those meant by the term supersonic; they are referred to as *hypersonic*. The flow of air over an object traveling through the atmosphere at hypersonic speeds is extraordinarily complex and does not obey the same basic principles as do flows over objects travelling at lower speeds. Indeed, much of the early research on reentry was devoted more toward gaining a basic physical understanding of hypersonic flow than to development of particular vehicles.

As a result of their extreme speed, RVs experience aerodynamic forces much greater than those experienced by any other type of vehicle in the atmosphere. Principal among these forces is the force of aerodynamic drag, the slowing force caused by friction with the atmosphere: typical RVs experience drag decelerations of more than 50 gravities.[2] (One gravity is the rate at which a marble or cannon ball dropped from a height would accelerate toward the ground.) This friction with the atmosphere will also subject the forward tip of the RV to pressures hundreds of times as great as normal atmospheric pressures and willl heat the RV to thousands of degrees centigrade. As a result, until moments before it hits the ground the RV is enveloped in a glowing ionized gas called a plasma, giving it the appearance of a meteor as it streaks across the sky. Plasmas are opaque to nearly all forms of electromagnetic radiation, making it extremely difficult for the RV to transmit or receive any information from the outside world through the plasma.

The nuclear weapon within the RV must be protected from these extremely high temperatures in order to function properly. To dissipate the heat, most modern reentry vehicles rely on a process known as *ablation*. The RV is coated with a material which will burn away at the temperatures encountered during reentry. The process of changing this material from a solid to a gas uses up most of the heat of reentry, thus preventing the heat from raising the temperature of the warhead inside the RV. Generally the nosetip of the RV encounters the most severe heating. In addition the shape of the nosetip determines many of the aerodynamic properties of the RV. Thus, as we shall see subsequently, the nosetip is one of the RV's most crucial components, and the focus of much of the current research on reentry.

In addition to protecting the nuclear warhead from burning up while reentering the atmosphere, the reeentry vehicle has an important effect on the *accuracy* with which the warhead can be delivered to its target. Other significant areas of RV research include *survival of hostile reentry environments*, such as heavy rain or the clouds of dust raised by earlier nuclear explosions, and *penetration of anti-ballistic missile systems* (ABMs), should such systems be deployed. These three concerns are the focus of much of the reentry research in the United States.

There are two types of reentry vehicles: *ballistic* and *maneuvering*. A ballistic RV is not guided or controlled as it falls through the atmosphere. After the end of the boost phase, when it is released from the main rocket which houses the guidance system, such an RV coasts onward, unpowered and unguided, much like an artillery shell. Maneuvering reentry vehicles, or MaRVs, *are* guided during reentry and are capable of changes in direction, rather than simply falling straight through the atmosphere. (This is a quite different concept from the MIRV, which stands for multiple independently-targetable reentry vehicle: that a missile is MIRVed merely means that it carries several RVs, which could be either ballistic RVs or MaRVs.)

Because the issues that arise with respect to the three areas of concern mentioned above differ for the two types of RV, we will first discuss all three with reference to ballistic RVs, and then with reference to MaRVs.

BALLISTIC REENTRY VEHICLES

Modern ballistic reentry vehicles have a number of common characteristics. Externally, ballistic RVs are slender cones with rounded nosetips. Inside, they contain, of course, a nuclear warhead, but this is only a portion of the total volume and weight of the RV. In addition to the warhead, the RV contains complex electronic arming and fusing mechanisms to detonate the warhead at the appropriate place, and a variety of other electrical and mechanical systems having to do with spinning the RV for stabilization during reentry or communicating with the missile before the RV is released. Figure 6.1 is a simplified diagram of a typical ballistic RV.[3] This section will discuss in turn how such RVs address the three issues identified at the beginning of this chapter: accuracy, reentry through hostile environments, and ABM penetration.

Accuracy

Since ballistic RVs are not guided, they cannot correct for any of the errors that may arise during reentry. Therefore, no missile armed with ballistic RVs can ever be perfectly accurate, even if there are no errors whatsoever in the guidance system of the missile. Indeed, it is unlikely that it will be found economical to pursue total-system accuracies greater than 50–70 meters with missiles equipped with ballistic RVs.

There are three main sources of inaccuracy that arise during reentry: atmospheric variations, such as winds and variations in atmospheric density, variations in the RV itself, such as asymmetric ablation of the nosetip, and errors in the fusing mechanism which determines when to detonate the warhead.

Atmospheric Variations. The behavior of the atmosphere is complex and difficult to predict. In order to place a ballistic RV on the appropriate

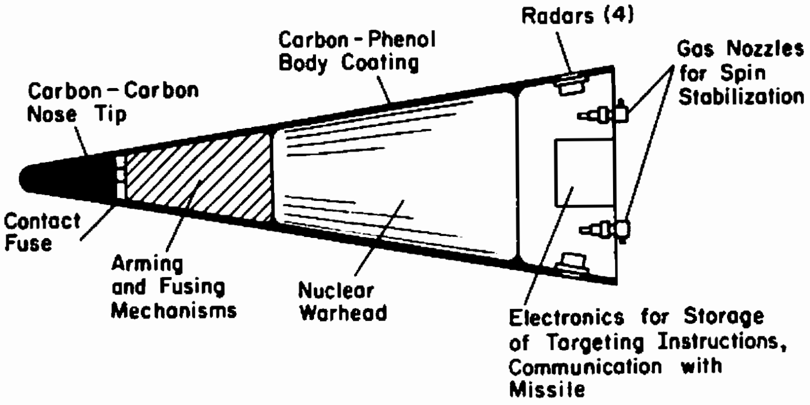

FIGURE 6.1. Typical Ballistic RV

trajectory to reach its intended target, the probable effect of winds and atmospheric density on the RV must be programmed into the missile's guidance computer before launch. This can never be done with perfect accuracy, as the winds and density throughout the many layers of the atmosphere change rapidly and unpredictably with the weather. The impact errors resulting from these variations can amount to several tens or even hundreds of meters, depending on the type of RV and the magnitude of the variations.

The degree to which an RV is affected by atmospheric variations is largely determined by its *weight-to-drag ratio*, or *ballistic coefficient*. This if often referred to as the *beta* of the vehicle, and is generally expressed in pounds per square foot, rather than in metric units. The drag deceleration which an RV experiences as it travels through the atmosphere is proportional to the density of the air, and to the square of the RV's velocity; it is inversely proportional to the beta of the RV.[4] Thus, RVs with high betas experience less deceleration and fly through the atmosphere much more rapidly than do those with low betas. As a result, a high-beta RV spends less time in the atmosphere, and is less affected by atmospheric variations; other factors being equal, an RV with high beta is much more accurate than one with low beta. Figure 6.2 shows an estimate of the errors resultng solely from atmospheric variations, as a function of the beta of the vehicle in question. The reader is cautioned that while the shape of this curve is correct, the specific values at various points are only extremely rough ballpark estimates.[5]

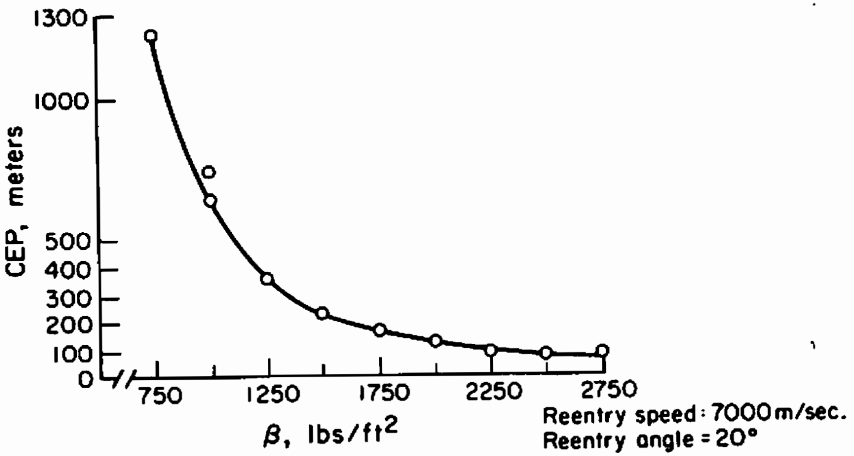

FIGURE 6.2. Atmospheric Contribution to CEP vs. Beta

The betas of both U.S. and Soviet RVs have improved significantly over the last 10-15 years. The beta of the Mark (Mk) 4 RV developed for the Trident I missile is approximately 1800 lbs/sq. ft., while the beta of the Mk. 12A warhead now deployed on the Minuteman III is of the order of 2000 lbs/sq. ft. Soviet RVs are generally several years behind their U.S. counterparts; current Soviet RVs are thought to have betas in the range of 1500-1800 lbs/sq. ft.[6] The improvement in the betas of RVs has depended primarily on improvements in nosetip and headshield technology, since passing through the atmosphere more rapidly means more heat that must be dissipated by ablation.

Vehicle Asymmetries. In addition to inaccuracies caused by atmospheric variations, there are a variety of other sources of error in a ballistic RV. Most of these arise from forces which are asymmetric. When a force on one side of the RV is not equal to that on the other, the force in question will turn the direction of the RV's travel.

If such asymmetric forces went uncompensated, they could cause the RV to veer far off its original course. In order to prevent this, the RV is stabilized by spinning it, much as a football is spun when it is thrown. Since such asymmetric forces are usually fixed with respect to the RV, spinning the RV will also spin the forces: one moment, the asymmetric force will be pointing to the right, and the next it will point to the left. If the asymmetric forces and the rate of spin remained constant throughout the flight, the effect of the asymmetries would average out to essentially zero. But of course it is not that simple; neither the asymmetric forces nor the rate of spin remain constant, with the result that asymmetric forces do have a very significant effect on the accuracy of ballistic RVs.

The two most significant forces of this type are the aerodynamic lift that arises from *asymmetric ablation* of the nosetip, and the forces that arise from a process known as *flow transition*. These two phenomena are closely related.

When the RV first encounters the thin air of the upper atmosphere, the air will flow over it in a smooth and continuous way, even though the speed at which it is traveling is more than seven kilometers per second. Such flow is referred to as *laminar* flow. As the RV encounters denser air, the flow will eventually become *turbulent*; this process is referred to as *flow transition*. When the flow is laminar, the forces and heating rates are much different from those that occur when the flow is turbulent. Until the early 1970's, the complexity of the flow transition that takes place during reentry was not fully understood; since then, it has been discovered that some areas on any given RV experience flow transition before others, creating unpredictable asymmetries in the forces acting on the RV. This process is still not well understood, and a significant part of current flight-testing efforts are devoted to a better understanding of flow transition.

It is currently believed that microscopic variations in the roughness of the RV determine the progress of flow transition.[7] Just as a stick in a river will cause a V-shaped eddy downstream, so a rough spot on the RV can cause a region of turbulent flow extending back up the RV from the rough spot, away from the nosetip. When a *transition front* forms around the RV, the flow is still laminar forward of the front, toward the nosetip, while behind the front, the flow is turbulent. Typically, the transition front will move slowly from the back of the RV toward the nosetip. This front first forms at high altitude, but does not reach the nosetip until the RV has completed most of its reentry.[8] It is thought that the front "jumps" forward from one rough spot to the next; since the rough spots are by no means arranged in perfect circles around the RV, the front at any given time is likely to be considerably farther forward in some areas than it is in others. (See Figure 6.3.) The result is a significant increase in aerodynamic forces and heating in those areas in which the flow is turbulent over those in which the flow remains laminar. The resulting asymmetric forces are one of the most significant error sources in current ballistic RVs, often accounting for some tens of meters of error.[9] As we shall see, the asymmetric heating has an equally significant effect on the ablation of the nosetip.

Current research on flow transition includes a variety of activities. First, considerable effort is being devoted to simply developing a better understanding of what factors affect the onset of transition. Measuring how the transition front moves over the surface of an RV during reentry is in itself extraordinarily difficult, as the sensors required are difficult to develop and if exposed on the surface might themselves trigger transition. Considerable effort is being devoted to this problem both in laboratory tests and flight tests.[10] Concurrent with such practical experiments is a significant effort to model the effect mathematically. So far, adequate correlation of actual test-flight data on flow transition with the roughness of the RV has not been possible. While it is clear that some correlation exists, the exact relation remains in doubt.

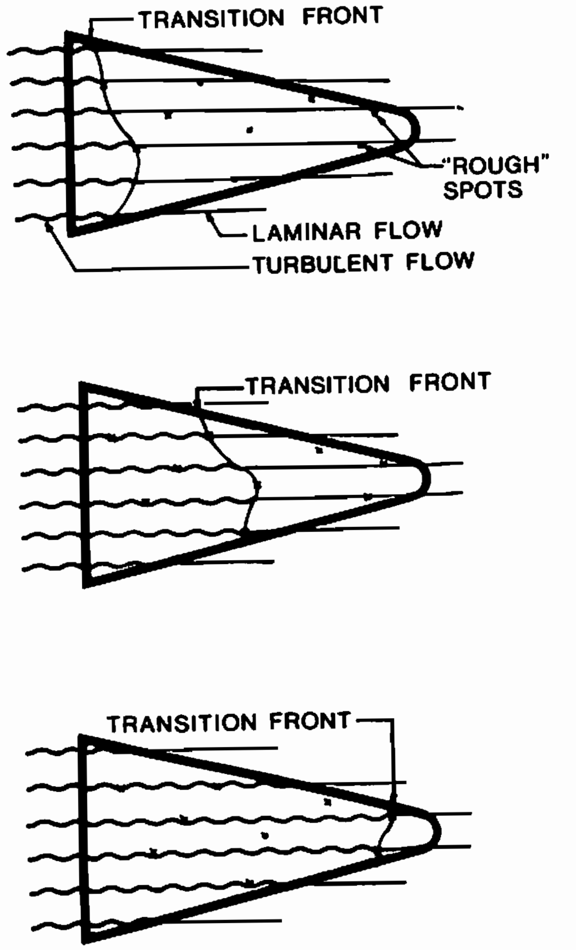

FIGURE 6.3. Progress of Laminar-to-Turbulent Flow Transition

Not surprisingly, another area of current research effort centers on improving the smoothness of the RV. If RVs can be developed that are close to being perfectly smooth not only when they first enter the atmosphere, but after considerable ablation as well, the onset of turbulent flow can be delayed until very late in the flight of the RV. This would result in significantly smaller errors resulting from both flow transition and nosetip ablation.

As the RV passes through the atmosphere, the nosetip erodes through ablation, changing shape drastically. Figure 6.4 shows a progression of nosetip shapes for different altitudes, beginning with a typical hemispherical shape, and finally eroding to a much more pointed shape.[11] Since it is the first point at which the flow of air contacts the RV, the nosetip's shape is an important determinant of the RV's aerodynamic characteristics. Any change in its shape has a significant effect on the RV's flight path. As a result, uncertainties concerning the rate at which the nosetip ablates can cause errors in estimating the final impact point of the RV.

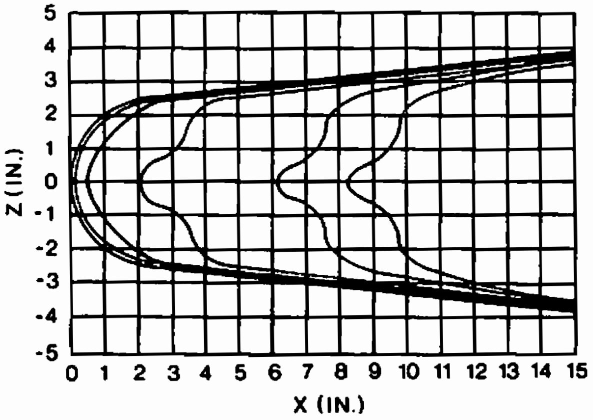

FIGURE 6.4. Nosetip Shape

There is another, even more significant phenomenon associated with nosetip ablation. As with flow transition, nosetip ablation generally does not take place symmetrically. In fact, these two asymmetries are intimately related. Those areas in which the flow is turbulent will experience greater rates of heating; thus, as the uneven transition front moves forward over the nosetip during reentry, some areas of the nosetip will ablate more rapidly than others. Typically, a dozen or so deep gouges will develop, running from the back of the nosetip toward a central tip, which is itself offset from the original center, often by as much as 10 or 20% of the original radius of the nosetip.[12] Figure 6.5 is a photograph of a test

FIGURE 6.5. Recovered Nosetip

nosetip which was recovered after reentry, showing the gouges and the offset of the central point.[13]

These asymmetric gouges have pronounced effects on the aerodynamics of the RV. Even when the RV is spinning rapidly, asymmetric ablation of the nosetip is often the largest single contributor to the inaccuracy of a ballistic RV.[14] Although considerable research has been devoted to the problem, predicting the exact features of the gouges, and hence their precise effect on the RV's flight path, has so far been impossible.

In addition to these nosetip ablation asymmetries, some asymmetries develop in the ablation of the rest of the RV's heatshield as well. Sometimes, for example, strange cross-hatchings and spiral patterns develop over the surface of the RV. These can also have some effect on the RV's accuracy, but they are generally less important than nosetip ablation.

Warhead Fusing. The requirements for the RV's warhead fuse depend on the specific mission of the RV. In some cases, the weapon is meant to be burst on the ground, and essentially a simple contact fuse can be used. More often, however, the weapon is meant to be detonated in the air, and more complex fusing systems are required.

There are two main types of fuses for air-burst warheads. The first is the *path-length* fuse, which in concept is simply an accelerometer in the nose of the RV. The path-length fuse measures how far the vehicle has traveled over its entire trajectory, and when the distance travelled equals the distance to the desired detonation point, the fuse detonates the warhead. Such fuses are not perfectly accurate; typically they might have inaccuracies amounting to 20-50 meters. Since the RV is reentering at an angle of 22 degrees to the horizontal, this error in measuring the path length would result in a somewhat smaller range error on the ground, and an error in height of burst of only 7-20 meters. (Errors in burst height are important in attacking soft targets such as cities, where detonations at the optimum height of burst cause much more damage than detonations at other heights; errors in range are important for attacking hard targets such as missile silos.)

The other main type of fuse for an air-burst warhead is the *radar altimeter*. In this concept, radars mounted on the RV measure the distance between the RV and the ground, and then detonate the RV at the appropriate height. This can only be done in the final seconds of the RV's flight, when the RV has slowed sufficiently so that it is no longer covered by a radar-blinding sheath of plasma. Indeed, one significant area of reentry, research centers around the development of *antenna windows* for RVs, which need to be able to withstand the heat of reentry in the same way as the RV's heatshield, but must also be transparent to radar. Of course, antenna windows are also necessary for other uses of radar by RVs, such as precision guidance and jamming of ABM radars.

Radar altimeters can be designed which are somewhat more accurate than path-length fuses, but unless the radar is very carefully designed, it may be possible for a defender to cause the RV to fail to detonate (or detonate at the wrong altitude) by jamming the altimeter. One approach that is currently being used is to have both types of fuse on a single RV, for improved accuracy and resistance to jamming.

In addition to accuracy, the size and weight of fusing mechanisms is extremely important, as any weight in the RV devoted to fusing is weight taken from the warhead itself. Much of the research on fusing mechanisms centers on miniaturization.

Survival in Hostile Reentry Environments

There are two major types of hostile atmospheric conditions that an RV may have to pass through. The first is heavy weather, such as thick clouds, snow, rain, or hail; the second is the dust clouds raised by nuclear detonations. Both nuclear detonations and heavy weather have large and unpredictable effects on the winds and density of the atmosphere, which degrade the accuracy of entering RVs. Their most significant effect, however, is the erosion of the RV's nosetip caused by the particles in the clouds.

When an RV travels through a cloud, whether it is of water droplets, ice crystals, or dust particles, the tiny particles erode the surface of the RV, especially the nosetip. Since the RV is generally travelling at several kilometers per second, the effect of passage through such clouds of dust is similar to exposure to a sandblaster of extraordinary power. In addition to increasing the speed with which the nosetip burns away, such particles can also change the ablation pattern, as a particle which penetrates the flow of air around the RV and actually hits it will create a tiny rough point, possibly triggering the transition from laminar to turbulent flow at that point. The exact effects of such clouds on the RV are not well understood. While in the past, reentry flight tests have been skewed toward days with good weather, considerable effort is now being put toward flight testing a variety of different types of nosetips under different weather conditions.

How much the nosetip will erode depends on a variety of factors. Clearly, the size and density of the cloud are important, as is the size of the particles involved. Another important factor is the *height* at which the RV passes through the cloud; the effect of a collision with a particle is roughly proportional to the *square* of the RV's velocity, so clouds at high altitudes where the RV has not yet been slowed down by the atmosphere are more important than similar clouds at lower altitudes. These factors raise a number of questions which are the subject of current research: What is the average thickness of the different types of clouds? What are the sizes of the particles within them? How often do they occur, at what heights, and in what areas of the world? In the case of heavy weather, it has been estimated that 2% of the time the cloud cover or rain is heavy enough to degrade the total accuracy of an ICBM by 25%, which means roughly a doubling of the inaccuracy of the RV.[15] In severe cases, the nosetip can erode away completely, exposing the RV to high temperatures which may cause it to burn up in the atmosphere.[16]

Degradation or destruction of RVs by passage through a nuclear dust cloud is referred to as "fratricide," since it is one nuclear warhead which is destroying another. For an understanding of fratricide, a specific case will serve as an example, one which is often debated in the United States: an attack by Soviet ICBMs on the 1000 U.S. Minuteman silos.[17]

To achieve a reasonable probability of destroying the U.S. ICBMs, two SS-19 or SS-18 warheads would have to be targeted on each U.S. missile silo. Such an attack would probably be scheduled in two waves, separated by more than ten minutes, in order to allow the largest particles raised by the detonations of the first wave to fall back to the earth. By this time, the clouds formed of the remaining small particles and dust will have stabilized in height; their top will be at an altitude of roughly 18 kilometers, and they will be roughly 8 kilometers thick. The diameter of the cloud from each of the detonations of the first wave will be so large that by 10 minutes after the first wave, the clouds will have merged into essentially one large dust blanket covering the entire field.[18] Thus each RV of the second wave will have to pass through the dust cloud.

What effect might this have on the effectiveness of the second wave of the attack? It is known that a groundburst of a half-megaton nuclear device will raise nearly 200,000 tons of dust, and thus the dust blanket over a field of 150 silos attacked by a first wave of 150 such warheads would contain many millions of tons of dust. It is possible to decrease drastically the amount of dust raised by bursting the weapon above the ground; however, a first wave of 150 warheads would still raise more than a million tons of dust, even if they were burst at the highest altitude possible for an attack on silos hardened to 2000 psi.[19] The RV will enter this dust cloud at a speed of approximately 6 kilometers per second, and will pass through more than 20 kilometers of it. As a result the RV will encounter more particles, and at higher speeds, than it would even under severe weather conditions. Whether an RV equipped with a standard ablative nosetip would survive such a passage is an open question; it cannot be realistically tested, as the Partial Test Ban Treaty of 1963 forbids detonating nuclear weapons in the atmosphere. It seems certain, however, that the accuracy of the RVs of the second wave would be severely degraded, drastically reducing their effectiveness.

Research on developing RVs which can survive passage through such hostile environments has centered on developing erosion-resistant nosetips; it is to nosetip research that we now turn.

Types of Reentry Vehicle Nosetips

We have seen that the RV nosetip is the determining factor in many of the performance parameters of the RV. The beta of the RV cannot be significantly increased without a nosetip capable of withstanding greater heating. Asymmetric ablation of the nosetip is perhaps the largest single contributor to inaccuracy, and the RV cannot survive reentry through hostile environments without a nosetip capable of withstanding severe erosion. It is not surprising, then, that the preponderance of reentry vehicle research and development currently under way in the United States is concerned with the problem of improving nosetip performance.[20]

A material intended for use as an RV nosetip must fulfill a variety of requirements. First, since the purpose of the nosetip is to use up the heat of reentry by slowly turning from a solid to a gas, the material's melting and boiling temperatures must be within the range of temperatures encountered during reentry. If the material does not burn away sufficiently rapidly at reentry temperatures, not enough heat will be used up, and the heat of reentry will get through to the warhead, and possibly damage it. Conversely, it is better not to have the nosetip burn away too rapidly. The more rapidly it burns away, the more it will change shape during reentry and the more uncertain its final shape—and thus its accuracy—will be. Indeed, one of the most important characteristics of a nosetip material is that it burn away evenly and predictably, so that it is possible to predict the RV's flight path reasonably accurately. Another important feature of an RV material is strength; a material that cracks or bends at high temperatures would obviously be unsuitable.

Most ablative nosetip materials have been made out of carbon or carbon compounds, as carbon tends to form strong solids that burn away slowly at high temperatures. The early choice was a substance called carbon phenol. Although carbon phenol was superior to many others (silicon compounds, for example, which had also been tried), by today's standards it was not very satisfactory. Carbon phenol nosetips ablated quite rapidly and somewhat unpredictably, causing inaccuracy, and they were subject to mechanical fractures at high temperatures. During the late 1960's, nosetips were developed made of graphite, another carbon compound; these ablated much more slowly and evenly, and hence RVs equipped with them were capable of greater accuracy. However, graphite nosetips were also subject to structural stress at high temperatures; as a result, long graphite nosetips could not be used without risking fractures. With a short nosetip, an increased rate of ablation, such as would be encountered flying through dust clouds or rain, might erode the nosetip away entirely, causing the RV to burn up in the atmosphere. Thus, most types of graphite nosetips do not perform very well in heavy weather.

More recently, nosetips have been developed that are composed of a very fine three-dimensional weave of carbon fibers. These nosetips maintain the desirable ablative properties of graphite but do not have similar stress problems at high temperature. Thus, nosetips of 3-D weave carbon-carbon can be much longer than those of graphite, resulting in a better "all-weather" capability for the RV.[21]

This description of the different types of ablative nosetips ignores the very significant differences that can exist between nosetips made of the same material. The specifics of the manufacturing technology used are themselves a significant determinant of the performance of a nosetip, and manufacutrers such as Avco and Fiber Materials devote considerable research effort to improving the performance of nosetips of a given type. Indeed, there remain differences of opinion as to the relative advantages and disadvantages of the materials described: while the U.S. Air Force has decided to equip the Advanced Ballistic Reentry Vehicle (ABRV) for the MX missile with a 3-D weave carbon-carbon nosetip developed by Avco, the U.S. Navy still prefers graphite nosetips, about which more is known. The Navy is currently exploring the possibility of graphite nosetips with considerably improved response to heat stresses.[22]

Another possibility for an ablative nosetip capable of surviving reentry through heavy weather is to back up an ordinary graphite or carbon-carbon weave nosetip with a tungsten interior. Under ordinary circumstances, the nosetip would not ablate sufficiently for the tungsten to be exposed, and the nosetip would behave like an ordinary nosetip. However, if the RV encountered a severely erosive environment, such as passing through a nuclear dust cloud, the ordinary nosetip material would quickly be worn away, exposing the tungsten. Tungsten is much more resistant to erosion than most other materials. It is so resistant to heat that it would not burn away significantly even at extremely high temperatures. Therefore, once the tungsten is exposed, the heat of reentry will no longer be used up by ablation. If the ablative front of the nosetip were to wear completely away while the RV was still at high altitude, this might result in the warhead getting hot enough to fail to detonate, but if this erosion occurred at the low altitudes typical of many natural clouds, it would not be a significant problem.

Recently, an entirely different nosetip concept has been developed, one that does not rely on ablation to carry away the heat of reentry. This is the *liquid-cooled* nosetip. A liquid (or a gas) is carried inside the RV to be forced out through the nosetip at high pressure; as a result, the temperature at the nosetip never gets high enough to cause the nosetip to burn away, and the nosetip does not ablate. Since liquid-cooled nosetips rely on actively pushing liquid out through the tip, rather than simply allowing the tip to be slowly burned away, they are sometimes called *active* nosetips, as opposed to the *passive* ablative nosetips.

Liquid-cooled nosetips have a number of distinct advantages. First, much larger quantities of heat can be dissipated without degrading the nosetip, which is important in a number of situations. For example, as we mentioned above, the beta of RVs, and hence their ability to avoid deflection by atmospheric winds and the like, is limited largely by the capability of the nosetip to withstand the higher temperatures of a faster transit through the atmosphere. To give another example, it is sometimes desirable to loft an RV so that it flies on a higher trajectory than usual. A lofted RV reenters the atmosphere faster, at a steeper angle, and hence requires a nosetip able to dissipate more heat. For maneuvering reentry vehicles (which will be discussed in the next section), a coolable nosetip is even more important because their high speed maneuvers within the atmosphere result in increased heating rates. In fact, the particular needs of maneuvering reentry vehicles have provided most of the impetus for the development of liquid-cooled nosetips.

A second advantage of active nosetips is that, since the nosetip does not ablate, the problem of asymmetric nosetip ablation is essentially eliminated. This significantly improves the accuracy of the RV, and could improve it even further when combined with the dramatically higher betas that might conceivably be achieved with the use of this technology. Finally, it is believed that active nosetips will be significantly less susceptible to erosive environments than are even tungsten-backed ablative nosetips, although this has not yet been confirmed by flight testing. Active nosetip technology is still in its infancy; it has been developed largely for maneuvering reentry vehicles, and has yet to be applied to ballistic RVs on a significant scale. In this regard, it is worth noting that active technology is much more complex and more expensive than the technology of passive nosetips.

Three types of liquid-cooled nosetips have been considered. See Figure 6.6.[23] The single port nosetip is the simplest: in this case, a gas has been found to be a more practical coolant than liquid, so this nosetip is often referred to as a *gas-jet* nosetip. The gas is forced out through the central port at high pressure; it then passes over the rest of the nosetip, absorbing the heat of reentry. Different rates of heating can be accommodated by varying the flow of gas out from the nosetip; however, the flow cannot be directed to specific areas of the nosetip to correct for asymmetric heating. It is thought that the gas-jet, being the simplest of the three types of nosetips, would be significantly cheaper to implement than the others.

Another active nosetip concept is the *porous matrix* nosetip. These nosetips are permeable to liquids, much as a sponge is, and the liquid used for cooling the nosetip is forced out through the material that comprises the nosetip itself. This concept is somewhat more complex than the gas-jet nosetip, but it still does not allow fine control of the flow; it has now been largely abandoned.[24]

The most complex of the three active nosetips that have been investigated is the *discrete matrix* nosetip. This nosetip, rather than simply being porous, has a large number of tiny "canals" for the fluid to exit from. Using this method, not only can the rate of the flow be controlled, but the coolant can be directed to specific areas of the nosetip that sensors show to be experiencing higher rates of heating. This concept and the gas-jet nosetip are still being investigated. Whether the fine control of the former will win out over the simplicity of the latter remains to be seen.

Penetration of Anti-Ballistic Missile Systems

Another important focus of reentry research is the development of means to penetrate a defense of anti-ballistic missiles (ABMs). While there is currently a treaty limiting ABM systems to the defense of only one site in the U.S. and one site in the U.S.S.R., research on overcoming such sys-

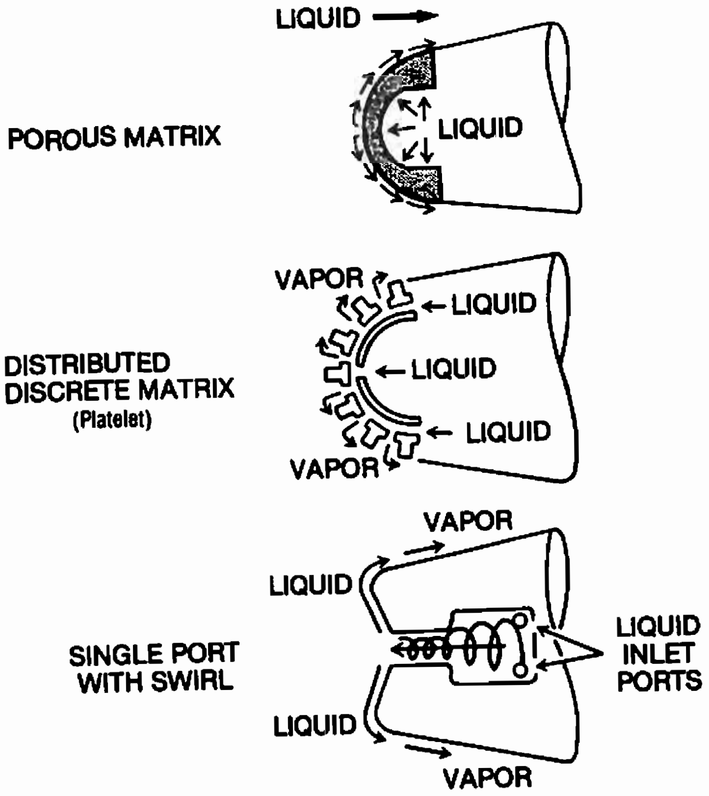

FIGURE 6.6. Liquid-Cooled Nosetips

tems continues, as a hedge against possible Soviet abrogation of the ABM treaty.

There are three basic types of ABM system, corresponding to the three stages of a ballistic missile's flight: there are those that aim to destroy the missile during the boost phase, before it releases its warheads; those that aim to destroy the reentry vehicles outside the atmoshere, during the free-fall phase; and those that aim to destroy them during reentry. The penetration of boost-phase ABMs depends on the missile, not on the reentry vehicle. ABMs which attack during the latter two stages of flight are the ones that are of interest in reentry vehicle research and development. ABMs which attempt to destroy the RV outside the atmosphere are referred to as *exoatmospheric*, while those which aim to destroy the

RV during reentry through the atmosphere are referred to as *endoatmospheric.*[25]

To cope with ABM systems, ballistic reentry vehicles rely on a wide variety of objects referred to collectively as *penetration aids*, which include facsimiles of the RV (decoys), clouds of metal shards or beads (chaff and aerosols), and interfering with the ABM sensors themselves (jamming). The purpose of penetration aids is to confuse the sensors guiding the ABM system: if the sensors are unable to distinguish the real reentry vehicles, then the ABM system cannot function effectively. The sensor's task of finding the real RVs among the penetration aids is referred to as *discrimination*.

Research and development of penetration aids currently accounts for one of the largest shares of reentry research expenditure in the United States.[26] However, this is one of the most highly classified areas of all strategic weapons programs, so public information on the subject is scanty. (The reason for this is plain to see: if the Soviet Union knew what types of penetration aids were being developed by the United States, it would greatly aid any of their efforts to develop sensors which could discriminate the real RVs.)

There are three key performance issues relating to penetration aids. First, the penetration aid must be able to confuse a wide range of possible sensors that the defender might use as part of his ABM system. Second, it must be very light, to minimize the amount of the missile's payload that must be devoted to penetrating the ABM rather than to destroying the target. And third, it should be able to protect the RV for as much of the flight as possible.

Developing exoatmospheric penetration aids is relatively easy. Outside the atmosphere, any objects which are launched together at the same speed will travel together indefinitely, and there is no way of telling which of a group of objects is the heaviest. As a result, penetration aids for use outside the atmosphere can be simple and light.

The simplest type of penetration aid is referred to as *chaff*. At the same time that the missile releases its RVs, it can spew out a cloud of tiny metal fragments, perhaps strips of metal foil. To most radars, the chaff would seem like one large object and they could not detect the reentry vehicles within the cloud. Chaff is very light and can effectively confuse most radars, but it can be compensated for by using other types of sensors such as infrared detectors.

A more sophisticated approach is for the booster to release a very large number of objects that would each appear to an ABM's sensors to be a real RV. For example, either radar or visual sensors would have great difficulty discriminating between a real RV and a metallized balloon of the same shape. Alternatively, one could encase the RVs themselves in balloons and accompany them with a large number of empty balloons. If sufficient ingenuity and expense were devoted to the design of heaters for such decoys, it could be made essentially impossible for any electromagnetic sensor to discriminate between them. The more capable the decoy, however, the more complex, heavy, and expensive it becomes.

While both of these approaches can be used to penetrate exoatmospheric ABM systems, neither will provide any camouflage once the RV has begun to enter the atmosphere. Since the chaff or decoys are much lighter than the RV, they will slow down much more rapidly in the upper atmosphere, allowing ABM sensors to pick out the RV easily as it leaves its penetration aids behind.

As the RV passes through the atmosphere, ground-based radars can assess not only its ballistic coefficient but its weight. Thus, to protect the RV all the way to the ground, a penetration aid would have to be as heavy as the RV itself, and might as well simply be another RV. This, in fact, was the genesis of the idea of MIRVing (having more than one RV on each missile). MIRV was originally designed primarily as a device to overwhelm ABM systems.

It is possible, however, to design penetration aids which will be difficult to discriminate at least through the upper reaches of the atmosphere. The simplest type of upper-atmosphere decoy is one which looks something like the antenna on a television set, with a heavy dart where the two rods come together. The rods give the illusion that the decoy is roughly the same size as an RV, while the heavy dart can give it a similar ballistic coefficient without making it as heavy as the RV. (See Figure 6.7.) Two more sophisticated approahces are now under development. One is intended to create an ionized wake similar in size to that left by a much larger object, such as an RV: the idea is for the penetration aid to pump out some ionizing material (such as salt) as it falls through the atmosphere. An even more complicated approach that is currently under development would involve the decoy's sensing the beam of the ABM radars that are looking for it, calculating how a real RV would look to such a radar, and then beaming a signal to match the reflection from a real RV, all within microseconds. This requires a microcomputer and a small radar on the penetration aid, but it is reported that the prototype is only the size of a half-gallon milk carton. It is likely that such high-performance penetration aids will be effective down to an altutide of 40-80 kilometers.[27] Another approach is for the RVs themselves to carry radars capable of jamming the defending ABM radars; in this case, if the jamming was successful, it could protect the RVs all the way to their impact points.

If the interceptors of the ABM system are fast enough so that the system can wait until all penetration aids can be discriminated from the RV before launching the interceptors, then ballistic RVs arriving one at a time will have a rather limited ability to penetrate. This is because the RV is ballistic: since it is simply falling and cannot maneuver, its path can be predicted almost exactly and interceptors can be directed to it with reasonable confidence. Although the problem has been described as one of "hitting a bullet with a bullet," it is not as difficult as that metaphor makes it seem, since the position of the RV is quite predictable. Most current ABM systems would, however, have difficulty with more sophisticated attacks involving several RVs.[28]

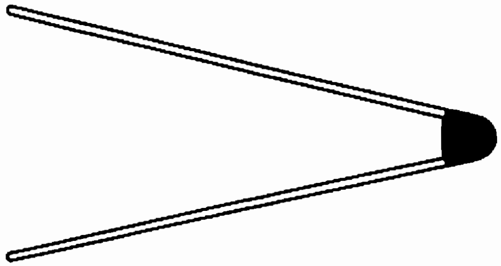

FIGURE 6.7. A Penetration Aid for the Upper Atmosphere

Testing of Reentry Vehicles and Materials

As with many military systems, reentry vehicle research and development depends heavily on testing, which consists of both laboratory testing and flight testing. Without such testing, further development of reentry vehicle technology would be essentially impossible.

Both ballistic and maneuvering RV prototypes, as well as materials for nosetips, heatshields and antenna windows, are subjected to extensive laboratory testing to verify their properties under conditions similar to those of reentry. The most difficult part of such testing is creating an environment in a laboratory similar to the extremely high temperatures, pressures, and winds experienced during reentry. Three main methods have been used to accomplish this task.

The first such method is to put the RV in the exhaust of a powerful rocket motor. This creates pressures and temperatures similar to those experienced during reentry, allowing an assessment of the behavior of materials under these stresses. However, a material's ablation cannot be determined accurately with this technique, because the chemical reactions that take place between the RV materials and the rocket exhaust are much different from those which would take place between the RV and the air.

Another technique to simulate the extremely high temperature of reentry, and the sheeth of ionized air that forms around the RV as a result, is to place the RV in an arcjet. This is an extremely powerful electric arc, much like an arcwelder, which heats the air to thousands of degrees centigrade. The ablation of nosetips under such an arcjet is at least qualitatively similar to that under actual reentry conditions.

Perhaps the most successful ground-testing technique is the use of high-velocity wind-tunnels. By creating winds travelling at many times the speed of sound, these tunnels simulate the conditions the RV will encounter as it travels through the atmosphere.

In the end, however, there is no substitute for actual flight testing. None of the laboratory testing techniques yet developed have succeeded in simultaneously simulating all the aspects of actual reentry. As a result, flight testing continues to be the most important (and the most expensive) part of the U.S. reentry research and development program. Since full-system flight testing is so expensive, with a single booster costing several millions of dollars, ground testing techniques serve to weed out undesirable materials and RV shapes before they reach the flight testing stage. Ground tests also serve to make preliminary assessments of the aerodynamic properties of new RVs and to make predictions of what factors ought to be looked for in flight testing. Flight tests are still required to validate the performance of RVs and materials in realistic reentry environments.

Even once the process of flight testing begins, there are several stages below full-range testing which can provide some useful information at less cost. RVs are tested over short ranges from a testing range at Wallops Island and another at White Sands.

When an RV in development is to be tested to full range, it is usually launched from an old Minuteman I booster from the test silos at Vandenberg Air Force Base in California. Depending on the size of the RV, such a booster typically carries from one to four or five RVs, and possibly penetration aids as well if they are also being tested. The RVs and penetration aids then reenter over Kwajalein Lagoon in the Pacific Ocean, some 8000 kilometers away. At Kwajalein, there is an elaborate facility to monitor the reentry of these test vehicles, both to provide information on their performance during reentry, and to serve as a test-bed for ABM sensors. These facilities include both the Altar and Tradex radars, and optical telescopes which can be linked with the radars to observe the RV and its wake continuously as the RV reenters. The Tradex radar, the more accurate of the two, can simultaneously track six RVs, determining their position to within three meters and their velocity to within 0.01 meters/sec at ranges of 1,400 kilometers. The Altar radar can track 14 RVs at longer ranges.[29]

Until recently it was extremely difficult to collect data on the progress of nosetip ablation during reentry flight tests. Sensors implanted in the nosetip to measure the progress of ablation may themselves affect ablation and the onset of turbulent flow; more important, since high-performance RVs are still travelling at 2–3 kilometers per second when they hit the water of Kwajalein Lagoon, the nosetip itself is utterly destroyed and cannot be examined after flight.

Several years ago, however, techniques were developed to enable researchers to recover undamaged nosetips from RV flight tests. At the stage of flight at which it is desired to examine the state of the nosetip, the RV is decelerated by jettisonning its back portion, cutting its weight and thereby drastically decreasing its beta (the weight-to-drag ratio). This slows the RV sufficiently to deploy a parachute specially designed for extremely high velocities, which acts as a brake, cutting the velocity enough so that the nosetip is not significantly damaged by the RV's impact on the water.[30]. The recovery of flight test nosetips using this method should greatly improve the understanding of the ablative properties of advanced nosetip materials, possibly leading to significantly improved nosetip technology.

Summary of Ballistic Reentry Vehicles

Ballistic RVs are unguided and cannot maneuver. As a result, they can never achieve perfect accuracy, even if delivered by a missile with a perfectly accurate guidance system. The greatest sources of error in ballistic RVs are atmospheric variations, uneven flow transition, asymmetric nosetip ablation, and fusing difficulities. Each can contribute some tens of meters of inaccuracy in current systems. While foreseeable improvements in nosetip technology may significantly improve the accuracy of ballistic RVs, it is unlikely that intercontinental ballistic missiles equipped with ballistic RVs will achieve accuracies greater than 50-70 meters, because of irreducible error sources of the reentry vehicle and the missile's guidance system. While current RVs would be severely degraded or destroyed by passage through extremely severe weather or nuclear dust clouds, tungsten and active nosetip technologies may mitigate this problem. Lastly, because of their predictable trajectories, ballistic RVs may be vulnerable to endoatmospheric ABM systems.

Maneuvering reentry vehicles can be both more accurate and better able to penetrate ABM systems than ballistic RVs; it is to MaRVs that we turn in the next section.

MANEUVERING REENTRY VEHICLES

Maneuvering reentry vehicles, or MaRVs, have been under development in the United States since the early 1960's. The current Advanced Maneuvering Reentry Vehicle is the third generation of MaRVs developed by Advanced Strategic Missile Systems (ASMS, formerly Advanced Ballistic Reentry Systems, or ABRES), a tri-service program managed by the U.S. Air Force that is responsible for the bulk of the advanced reentry research in the United States. It remains the case, however, that all of the reentry vehicles *currently deployed* on U.S. ballistic missiles are themselves ballistic, as are all of those planned for the immediate future. The single exception is the MaRV deployed on the intermediate-range Pershing II missile.

The reason for this is simple: MaRVs are significantly heavier, more complex, and more expensive than ballistic RVs, which are quite capable of carrying out all of the roles currently assigned to strategic missiles. As we saw in the discussion of ballistic RVs, the two main areas in which MaRVs might have an advantage are the penetration of ABM systems and the achievement of extreme accuracy. Because of the ABM treaty of 1972, the Soviet Union has not yet made any significant deployment of anti-ballistic missiles, so MaRVs have not been required to evade ABMs. Similarly, the accuracy achievable with ballistic RVs is more than sufficient to destroy essentially any target in the Soviet Union, provided that warheads in the range of hundreds of kilotons are used. Thus, for the present, widespread deployment of MaRVs is not strictly necessary. Research and development of MaRVs, however, has continued essentially unimpeded until quite recently; this research has been justified as a hedge against possible future developments.

In order to perform the maneuvers which are their raison d'etre, MaRVs require several technologies beyond those of a ballistic vehicle. Basically, they must have some method of controlling their flight paths, such as small rockets or wings, and a guidance system to direct the maneuvers. The types of guidance necessary to achieve pinpoint accuracy are somewhat different from those required for ABM evasion; this has resulted in two overlapping areas of MaRV development, which will be discussed separately. However, for *any* RV, the three issues identified at the beginning of this chapter—accuracy, survivability in hostile environments, and survivability against ABMs—remain significant issues. The question of accuracy remains relevant for MaRVs designed primarily to evade ABMs, as does the evasion ability of MaRVs designed primarily for high accuracy. However, it should be noted that since MaRVs are guided through the atmosphere, such effects as unexpected atmospheric winds or unexpected lateral forces can be measured and compensated for by the guidance system; thus, many of the factors affecting the accuracy of ballistic RVs are much less important with respect to maneuvering vehicles. With respect to the third issue, reentry through hostile environments, the problems are fundamentally the same for both types of MaRVs as for ballistic vehicles: surviving reentry through heavy weather and nuclear dust clouds requires that the heatshield and especially the nosetip of the RV be capable of withstanding severe erosion.

Evading MaRVs

As has been discussed above, MaRVs are necessary to overcome only *endoatmospheric* ABM systems. Exoatmospheric ABM systems can be confused by chaff and decoys. However, because they weigh less, these penetration aids will become distinguishable from the RV as they pass through the upper atmosphere. In the case of ballistic RVs, with their predictable trajectories, it is theoretically a simple matter for the ABM computer to dispatch interceptors to meet and destroy them. In practice, however, most ABM systems designed so far have encountered a number of serious problems, some of which are discussed elsewhere in this volume.[31]

Evading MaRVs, by contrast, are able to swerve and duck at extremely high speeds, making it impossible for ABM computers to predict their course and direct interceptors to meet them. There are, of course, some limits as to how sharply the MaRV can turn and to how fast it can go; thus, the ABM computer will know that the MaRV will be *somewhere* within a given "area of uncertainty" when the interceptors sent to destroy it arrive. If enough interceptors are sent to destroy any vehicle within the entire area of uncertainty, it would be possible to destroy the MaRV. One of the primary development goals for evasion MaRVs is to make the number of interceptors required to do this very large, thus exhausting the defense. The number of interceptors required depends on the size of the "kill radius" of the interceptors and on the size of the area of uncertainty. The kill radius depends on both the hardness of the MaRV and the size of the ABM warhead; the size of the area of uncertainty depends on how sharply the RV can turn, how fast it can go, and how fast the interceptors can get to the area. (See Figure 6.8.) Thus, the most important features of a MaRV intended for ABM evasion are its nuclear hardness, the sharpness of the maneuvers it can execute, and its ability to maintain high speed throughout reentry. A high-performance MaRV could make the task of an endoatmospheric ABM essentially impossible.

Another possible approach for an ABM system intended to overcome MaRVs is the use of *homing interceptors*, which could conceivably outrun the RV one-on-one.[32] Such interceptors would have to be capable of extraordinarily high speeds and high accelerations, however, since a high-performance MaRV might still be travelling at more than 1000 meters per second throughout its atmospheric flight. It would be difficult for such a homing interceptor to chase a MaRV successfully until the atmosphere had substantially slowed it from its original speed of some 7,000 m/sec, for the pursuer would have to achieve speeds comparable to, if not greater than, the MaRV itself. At speeds of more than 2700–3000 m/sec, the interceptor would become encased in a plasma, which is opaque to most forms of electromagnetic radiation; it would then be difficult if not impossible for the interceptor to continue to sense and follow the MaRV, or to receive instructions from the ground. Thus, the critical feature of a MaRV intended to overcome a homing interceptor, as with more traditional ABM systems, would be the speed and maneuverability that the MaRV could maintain throughout its flight.

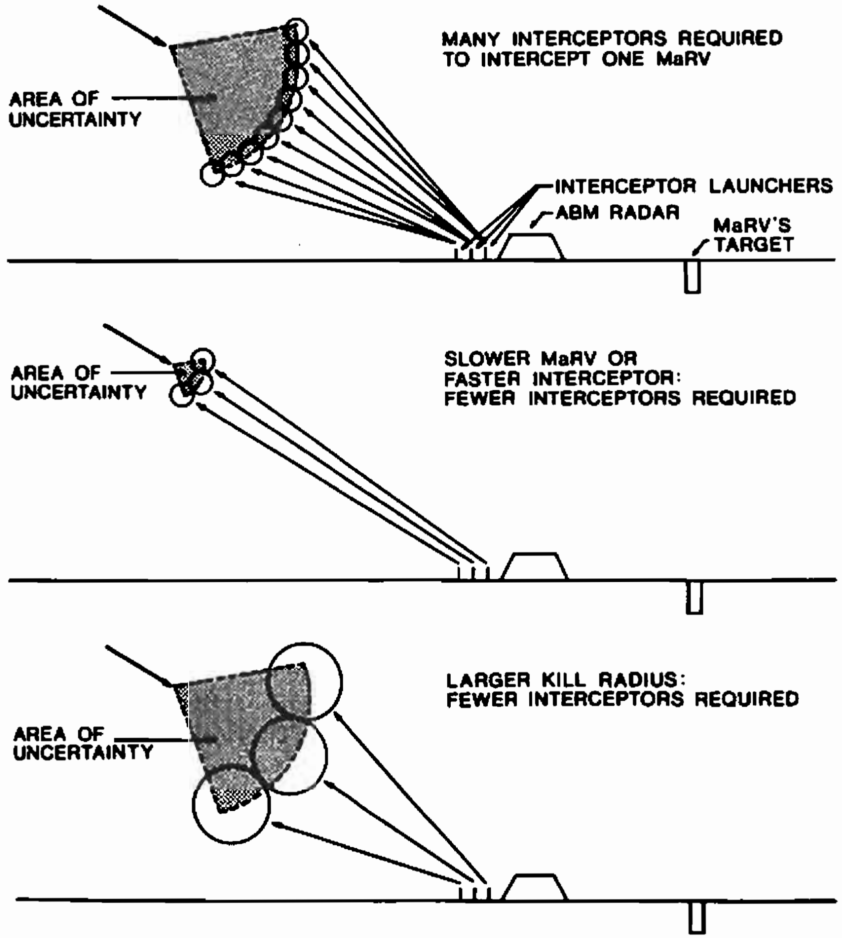

FIGURE 6.8. MaRVs and ABM Interception

To execute sharp turns at high speeds, the MaRV's control system should be able to provide accelerations of tens of gravities in the desired direction. To perform such maneuvers with rockets would require large amounts of fuel on the RV, posing an unacceptable cost in RV weight. The solution has been for MaRVs to rely on aerodynamics to provide the necessary forces. As noted above, the force of aerodynamic drag reaches magnitudes of the order of 50 gravities. By the use of various types of control surfaces, MaRVs can create aerodynamic lift forces of similar magnitude, enabling them to execute the maneuvers required. It should be noted, however, that relying on aerodynamic maneuvers means that the RV cannot begin to maneuver before it is well into the atmosphere, when the aerodynamic forces will have built up to large magnitudes. MaRVs cannot maneuver effectively, therefore, at altitudes above 60 kilometers.[33]

Thus, like ballistic RVs, MaRVs require penetration aids in order to overcome exoatmospheric ABM systems. In the case of MaRVs, the complication is that most penetration aids become distinguishable from the RV at an altitude higher than that at which the MaRV can begin to maneuver effectively; thus, there will be a time period of the order of several seconds during which the MaRV, like a ballistic RV, is essentially undefended.[34] If this "window of vulnerability" is too large, it is at least conceivable that an ABM system could be designed that could destroy the incoming RV during this interval—although certainly no ABM currently under development in either the U.S. or the U.S.S.R. would have such a capability. As a result, the development of decoys capable of penetrating deeply into the atmosphere could potentially be a significant issue, even when MaRVs are available; research in this area is extensive and ongoing, but as mentioned before, this area is extremely highly classified.

Evading MaRVs: Guidance and Accuracy. The guidance method used for evading MaRVs is identical to that used to guide the rocket during the boost phase of the missile's flight; in the process known as *inertial guidance*, accelerometers and gyroscopes measure the forces acting on the RV, and a computer then uses Newton's laws of inertia to calculate its motion and direct it to the target. However, the technological difficulties involved in the development of inertial guidance systems for MaRV applications are considerably different from those involved in guidance systems for the rocket in the boost phase. The requirement that the RV must be able to execute maneuvers involving accelerations of tens of gravities means that the guidance components must be able to survive and continue to measure accurately in an environment of acceleration and vibration far more severe than that usually encountered during ballistic missile boost. Second, since the MaRV is intended to survive attack by ABM interceptors, which often employ nuclear warheads, the guidance system must be extremely resistant to nuclear effects. In addition, the guidance system must be as small and light as possible, in order to allow as much room as possible for the nuclear warhead within the RV.

Unlike those for the boost phase, however, the guidance components for an RV need not measure with extreme accuracy. Since the entire reentry process typically takes only 1–3 minutes, small errors in measuring the acceleration of the vehicle do not have enough time to propagate to significant impact errors. But equally, since there is so little time for guidance, the mathematical formulations used by the guidance computer (known as the *guidance laws*) must be able to correct for any errors the guidance components detect extremely rapidly. As a result of the extreme time constraints involved, the accuracy of an evasive MaRV is often more sensitive to the formulation of the guidance laws (the software of the guidance system) than to the accuracy of the guidance components (the hardware). The explication of guidance law issues requires complex mathematics far beyond the scope of this chapter.[35] One important fact concerning any kind of MaRV guidance laws which should be understood is that when formulating the guidance and control equations, the designer must have detailed knowledge of the aerodynamic properties of the particular vehicle in question, for which rigorous testing is essential.

In addition to maneuvering and guidance technologies, evasive MaRVs also require much better heatshield technology than do their ballistic counterparts. The high-g maneuvers and extended times spent in the atmosphere mean both higher heating rates and more total heat to be dissipated. In addition, if an ablative nosetip is used, and if it ablates unpredictably, then the aerodynamic properties of the vehicle will be different during flight from the expectations of the guidance computer, resulting in some inaccuracy. Nosetips, therefore, are one of the most crucial technologies for MaRV development, as they are for ballistic RVs.[36] The work on liquid-cooled nosetips described earlier has been done largely with MaRVs in mind, and several of the MaRVs which have been flight tested have been equipped with liquid-cooled nosetips.[37]

Two quite different evading MaRVs have been developed by the United States, the Mk 500 "Evader" vehicle developed by the Navy and the Advanced Maneuvering Reentry Vehicle (AMARV) of the Advanced Strategic Missile Systems office. We will discuss each of these in turn, showing how the characteristics of their maneuvering and guidance systems relate to their ability to evade ABMs, and to their accuracy.

The Mark 500 Evader. The simplest method to provide the lift necessary for evasive maneuvers is to bend the vehicle, with the forward portion pointing in a slightly different direction than the rear. This is the concept used on the Mk 500 MaRV developed by the U.S. Navy for possible deployment on the Trident missile. Figure 6.9 shows the basic shape of the Mk 500. Since the angle of the nose is fixed, the *magnitude* of the lift is fixed as well, but the *direction* of the lift can be changed by rolling the vehicle. Rolling the vehicle can be accomplished by moving a weight from side to side within the RV; rather than adding a dead weight for this purpose in the case of the Mk 500, it is the vehicle's electronics package which is moved.[38]

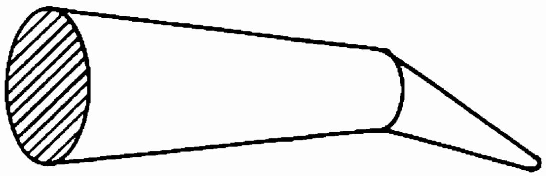

FIGURE 6.9. The Mk 500 "Evader"

Because the amount of lift remains fixed, the Mk 500 maneuvers constantly; it is incapable of flying in a straight line. Therefore, since the vehicle is continually expending energy to maneuver, by the time it reaches the ground it will be moving comparatively slowly. Since aerodynamic lift depends very strongly on velocity, this means that in the final moments of its flight it will no longer be capable of high-acceleration maneuvers.

Thus, high-performance interceptors could conceivably defeat the Mk 500. An extremely high-acceleration conventional interceptor could be launched in the very last moments of the RV's flight. Since the RV would be travelling rather slowly by this time, unable to maneuver at high accelerations, and the area of uncertainty would therefore be quite small, the MaRV could be destroyed by a small number of interceptors—possibly even one, if its kill radius were quite large. Similarly, a homing interceptor could intercept the RV without encountering serious plasma effects.[39] However, it should be emphasized that these types of interceptors are far in the future. The Mk 500 would be capable of overcoming all current and projected Soviet ABM systems.

In addition to the drawback of reduced speed during reentry, the bent-nose approach of the Mk 500 makes the vehicle inherently inaccurate. Since the amount of lift cannot be varied, there can be little fine control of the lift vector, making it impossible to execute maneuvers with the precision necessary for high accuracy. In addition, the guidance system used on the Mk 500 is a rather rudimentary one, consisting of a two-axis platform, rather than a full three-dimensional measurement unit. These two features, while allowing the Mk 500 to be smaller and less complex than most other types of MaRVs, make its accuracy inherently worse than that of the ballistic RV developed for the Trident missile, the Mk 4. The Mk 4 is the RV now deployed on the Trident, and there are no plans for further development or deployment of the Mk 500 unless the Soviet Union abrogates the ABM treaty of 1972 and deploys a major anti-ballistic missile defense.

The Mk 500 has completed its flight test program.[40] It is now regarded as essentially "on the shelf" technology, available to counter any future Soviet abrogation of the ABM treaty. Should deployment of the Mk 500 become necessary, it is estimated that the lead-time for deployment would be approximately three and a half years, at a cost of $1-2 million per vehicle, in 1981 dollars.[41]

The Advanced Maneuvering Reentry Vehicle. The Advanced Maneuvering Reentry Vehicle (AMaRV) developed by Advanced Strategic Missile Systems is considerably more advanced than the Mk 500. However, it is also considerably heavier and more complex. Indeed, it is too large to be carried effectively on the Trident I missile for which the Mk 500 was designed and is intended for possible deployment on either the Minuteman missiles or the MX.[42]

Rather than a bent nose, AMaRV relies on a flap system to provide the lift necessary for maneuvers. (Figure 6.10 shows the basic shape of the AMaRV). There are two flaps on one side of the vehicle; raising or lowering them in tandem pitches the vehicle up or down, while raising and lowering them separately, in a scissors-like motion, turns the vehicle. Unlike the fixed nose of the Mk 500, these adjustable flaps allow fine control of both the magnitude and the direction of the lift, allowing much greater control over the maneuvers the vehicle can execute.

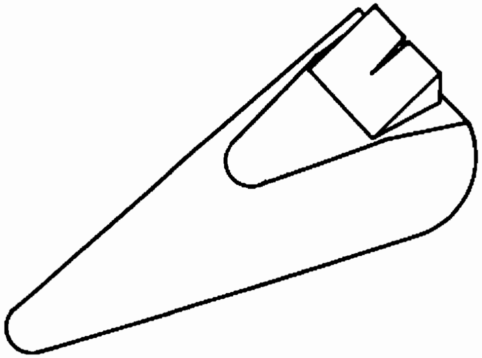

FIGURE 6.10. The Advanced Maneuvering Reentry Vehicle

This eliminates most of the possible vulnerabilities of the Mk 500. Since the AMaRV does not necessarily maneuver constantly, it can avoid expending its energy at high altitude. It could easily maneuver at high altitudes, fly straight for a time to conserve energy, and have enough speed left over to execute high-acceleration maneuvers in the last moments of flight, avoiding even the extremely capable interceptors postulated above as counters to the Mk 500. It is difficult to conceive of an endoatmospheric ABM which could defend against AMaRV-type vehicles at reasonable cost.

In addition, AMaRV is considerably more accurate than the Mk 500. Since the flap system allows fine control of the lift, it does not pose an obstacle to the accuracy of the vehicle. In addition, AMaRV has a sophisticated 3-dimensional inertial guidance system. Its accuracy would be somewhat dependent on the severity of the maneuvers it was required to execute during its flight. When performing the maximum maneuvers it is capable of, AMaRV would be somewhat less accurate than current ballistic RVs. On a trajectory involving minimal maneuvers, however, its accuracy would be significantly better, since its guidance would allow it to eliminate many of the errors associated with ballistic reentry. Between these extremes, it is believed that the accuracy of AMaRV on most maneuvering trajectories would be comparable to that of ballistic vehicles.[43]

The guidance system of the AMaRV is advanced in another respect as well. It is extraordinarily small and light, partly as a result of substituting laser gyro technology for more conventional inertial measurement devices. The inertial measurement unit weights only 14 kilograms and occupies less than .02 cubic meters,[44] an enormous improvement over current guidance systems for the boost phase. This allows more room and weight to be devoted to the warhead itself. In addition, laser gyros are much better able to withstand high acceleration and nuclear effects than are conventional inertial technologies; laser gyros have been successfully tested against nuclear effects in underground tests, and they have survived accleration tests of up to 280 gravities.[45] This increased nuclear hardness would reduce the kill radius of a nuclear interceptor used against the AMaRV vehicle.

The Advanced Maneuvering Reentry Vehicle has been tested three times, and like the Mk 500, is now regarded as essentially "on-the-shelf" technology, ready for the full engineering development and deployment whenever the situation seems to require such a vehicle. The lead-time on deployment would probably be similar to that for the Mk 500, while costs per vehicle would be likely to be somewhat more.

Summary of Evading MaRVs. Evading MaRVs are designed primarily to evade endoatmospheric ABM systems, should the ABM treaty ever be abrogated. By providing a capability to penetrate endoatmospheric ABM systems, evading MaRVs provide both a hedge for U.S. security and a deterrent against deployment of such systems, since they would negate any marginal benefits that might otherwise be had by abrogating the treaty.

Most types of MaRVs designed for this purpose are capable of overcoming any current or projected Soviet ABM interceptors; overcoming extremely advanced interceptors, however, would require a sophisticated MaRV capable of maintaining high speed throughout reentry, such as the AMaRV. The accuracy which can be achieved with evading MaRVs varies from somewhat less than current ballistic RVs to significantly more, depending on the sophistication of the particular MaRV design.

Accuracy MaRVs

The reentry vehicles we have been discussing so far are "blind"—they cannot actually "see" their target. Even the guided MaRVs discussed in the last section find their way to their targets solely by sensing their own accelerations and decelerations, and comparing that to a computer memory of the location of the target.

Another type of MaRV that has been investigated in the U.S. can receive information from the outside (such as examining the territory below with a radar) in order to guide the RV directly to its target. These are generally referred to as *precision-guided reentry vehicles*, or PGRVs. The only such vehicle currently deployed is the MaRV on the Pershing II intermediate-range ballistic missiles in West Germany. It is often said that in theory, such vehicles could reduce the inaccuracy of the system to zero; however, there are a variety of practical limitations that introduce some inaccuracy even for these precision-guided vehicles.

The concept of an extremely accurate PGRV has traditionally been closely related to the concept of limited nuclear war. More traditional RVs, such as the ballistic and evading RVs discussed above, can achieve sufficient accuracy to destroy even the hardest targets in the Soviet Union, provided the guidance system of the missile delivers them is itself sufficiently accurate and that warheads in the range of hundreds of kilotons are used. The use of such large warheads, however, means that even in an attack limited to military targets millions of civilian casualties would be unavoidable, increasing the probability of escalation to total war and the annihilation of both sides. If more accurate vehicles were available, smaller warheads could be used to destroy the same hardened targets, reducing the "collateral damage" (as civilian destruction is referred to in strategic jargon) and thereby, if the theory is correct, improving the chances that a limited war would remain limited. In the most extreme case, even hardened missile silos might conceivably be destroyed by *conventional* rather than nuclear weapons, reducing the collateral damage to almost zero. While it is difficult to imagine this being done with conventional high explosives, the necessary pressures could be created by the sophisticated use of fuel-air explosives.[46] However, this remains only a theoretical possibility for the rather distant future.

If there is a nuclear strategy that calls for limited strikes on hard targets with low levels of collateral damage—in short, a limited nuclear war-fighting scenario—then PGRVs would be useful. In the absence of such a strategy, there would be little point in developing PGRVs.[47] As a result, there was little serious work on precision guidance until James Schlesinger became Secretary of Defense. He was the first U.S. Secretary to emphasize limited nuclear options in the overall U.S. war plans.

It should be noted that while PGRVs would provide the possibility of greatly reduced collateral damage in a nuclear attack, they would not necessarily increase the *effectiveness* of the attack. Indeed, the probability of destroying a given target will often be lower with a PGRV than with a ballistic RV, because accuracies of missiles armed with ballistic RVs are likely to improve to the point that essentially every RV which arrives and detonates will destroy its target. Once such accuracies are achieved, the *reliability* of the missile becomes the important issue. Since PGRVs will be much more complicated than ballistic RVs, they are likely to be less reliable overall. There would then be a trade-off between *decreasing* the overall kill probability somewhat in return for reducing collateral damage in order to further a limited-war-fighting strategy.

The technological difficulties of producing a PGRV have proven to be considerably greater than the difficulties of producing an evading MaRV. The maneuvering requirements are similar, except that the accuracy mission requires fine control of the maneuvers (eliminating the possibility of using a Mk 500-type vehicle for a PGRV), and does not require such high-acceleration maneuvers (unless the accuracy goal is coupled with ABM evasion, which is also possible). The main additional requirements for a PGRV are the terminal sensors and the computing capacity to interpret the information they provide. Thus, the AMaRV could be made into a PGRV, and indeed, this is one of the long-range goals of the AMaRV program. As we saw earlier, however, the guidance and control systems even for comparatively simple vehicles like the Mk 500 and AMaRV take up significant portions of the RV's total volume and weight. In the case of PGRVs, the weight, volume and complexity of the guidance equipment are extremely serious development issues. In addition, since the guidance system of a PGRV relies on outside information for its accuracy, it may be susceptible to enemy interference with this information through a variety of possible techniques collectively known as *countermeasures*.

Terminal Guidance Techniques. Research and development of terminal guidance techniques for ballistic missiles has a variety of goals. Ideally, such a system should be extremely accurate; difficult for the defender to jam or confuse; able to function at night and in bad weather, smoke, or dust clouds; able to perform its task without sacrificing evasion capability;

and also be small, lightweight and reliable. This is a formidable list of demands for any designer, and no such "ideal" system yet exists; the systems that have been investigated represent trade-offs among these various goals.

There are two basic types of terminal guidance techniques. The first relies on receiving information transmitted from other systems to determine the position of the vehicle. A typical example would be a weapon which is guided to its target by radio commands. The second type has sensors on board the vehicle that are capable of examining the approaching terrain and determining what corrections, if any, are necessary to hit the target.

Guidance Information From Other Systems. Many of the types of guidance used in tactical precision-guided munitions (PGMs) are not possible for strategic missiles. For example, many tactical missiles rely on laser designators; an infantryman will shine a laser on the target, and the missile will home in on the reflected light. Since it is not likely that troops or even aircraft will be available near most of the hardened targets that PGRVs might be used against, such third-party options cannot be used for PGRVs. As a result of this problem and of the extreme speed at which RVs reenter the atmosphere, the design of precision-guided RVs has proven to be enormously more difficult than the design of tactical PGMs.

However, there are some outside systems on which a PGRV might rely for information. One such possibility is the NAVSTAR global positioning system (GPS). When it is fully deployed, the NAVSTAR system will consist of 18 satellites orbiting the earth; at any given point on the earth, at least four satellites will be within the "line-of-sight." By using the signals broadcast from these satellites, users with appropriate receivers and access to military codes can calculate their position to within 5-10 meters and can obtain accurate velocity information as well.[48] Thus, an RV equipped with a NAVSTAR receiver would be able to direct itself to within a few meters of its target, more than adequate for most of the tasks a PGRV might be assigned. This is probably the simplest and most "technologically mature" method for precision guidance of strategic missiles.

Research and development efforts in the United States have not concentrated on the use of NAVSTAR, however, mainly because it is feared that the Soviet Union may develop an anti-satellite weapon (ASAT) capable of destroying the NAVSTAR satellites, or that the satellites might be destroyed by the detonation of nuclear weapons in space.[49] It has been considered unwise to increase the vulnerability of RVs by having their guidance systems rely on satellites that may not be available when needed.

Ground-based radio beacons are another possible source of outside information for PGRVs. Since they don't need to be lifted into orbit, such beacons could be quite cheap, and they could be deployed in such large numbers as to be relatively invulnerable. It is still conceivable, however, that communications with such beacons could be jammed. While a beacon system could be very useful during the boost phase, most PGRVs reentering over the Soviet Union would be over the horizon from beacons located outside the U.S.S.R. itself, making it extremely difficult to use them for precision guidance.

Terminal Sensing. As a result of the hesitation to rely on NAVSTAR and other such systems, considerably more effort has been devoted to the use of sensors mounted on the reentry vehicle itself, which determine their position by examining the ground beneath them and comparing the results with maps carried in the RV's guidance computer. In essence, the image from the system's sensor is moved over the map until the two match up, or *correlate*, in statistical terminology: the position on the map at which the two match best is the guidance system's estimate of the position of the vehicle. Most such systems have the word "correlation" in their title.

Just as there are a large number of different types of maps in any comprehensive atlas, there are a large number of different possibilities for this type of guidance. Rather than describing each such possible system in detail, this section will provide a short overview of some of the issues involved in terminal sensor development, followed by a more detailed description of the system used on the Pershing II, the only PGRV currently deployed.

Several important characteristics distinguish one terminal sensing system from another. The first two distinctions relate to how the sensor "sees." A sensor can use a variety of different *wavelengths* of light, ranging from the wavelengths visible to the human eye to those used in radios. In addition, it can rely on *passive* detection of natural light, such as reflected sunlight or light emitted from the terrain, or it can be *active*, emitting its own beams of light and sensing their reflections from the terrain. The third distinction has to do with how the PGRV's computer interprets the information picked up by the sensor.

Wavelengths: Optical, Infrared, Microwave. Terminal sensors detect electromagnetic radiation (that is, light) of various wavelengths. A central question in the design of such a sensor, therefore, is which wavelengths of light it will sense. The human eye, for example, sees wavelengths between roughly 0.4 and 0.7 microns (a micron is one-millionth of a meter); these are referred to as the *visible*, or *optical*, wavelengths. Sensors which use light in this range provide very high accuracy and high resolution images, so that it is relatively easy to pick out distinguishing features of the terrain. Optical sensors also have the advantage of being more difficult to jam than longer-wavelength sensors such as those that sense microwaves. (To simplify, jamming means beaming a large amount of light toward the sensor at the particular wavelengths it detects, to interfere with its reception of the signal it is looking for. This problem and measures to overcome it will be discussed subsequently.)

Optical sensors fail dismally, however, in smoke, rain, snow, fog, or nuclear dust clouds. Furthermore, the optical images of many terrain features vary drastically from season to season. These two considerations limit the utility of optical sensors for PGRV applications.

Night is another barrier for passive optical sensors, such as the original version of the Digital Scene Matching Area Correlator (DSMAC) developed for precision guidance of cruise missiles. Since they rely on reflected sunlight, these sensors can work only during the day. This problem can be overcome by switching to an active system, which illuminates the terrain with an intense beam of light such as a laser. Such systems are sometimes referred to as laser radar, or ladar.[50]

The next longer wavelength is the infrared band, covering wavelengths from 0.7–300 microns. Sensors using these wavelengths also provide high accuracy and high resolution, although somewhat less so than those which sense visible light. Like optical sensors, infrared sensors are blinded by rain or heavy snow, but infrared sensors fare considerably better in smoke and fog, and even passive infrared detectors can operate as well at night as during the day. An important drawback of infrared sensors for PGRV applications is that anything which is heated to high temperatures gives off large quantities of infrared light. As a result, infrared detectors cannot see through the plasma that originally covers the reentry vehicle. Even once the vehicle has slowed sufficiently to leave the plasma, the severe heating of the RV and the air around it during high-speed reentry could make successful operation of an infrared detector difficult, if not impossible. This problem could be avoided by slowing the vehicle down substantially, to the speed of a standard air-to-air missile, and using an active cooling system to cool the area of the RV containing the sensor. This slowing, however, would also make the PGRV more vulnerable to possible defenses.

In part because of this heat problem, infrared sensors are more often considered for use on cruise missiles, with their comparatively slow speeds, than for ballistic missile reentry vehicles. The more recent version of the DSMAC cruise missile guidance system mentioned above was a passive infrared detector.[51]

Beyond infrared are the millimeter and K-band microwave wavelengths, stretching from 300 to 24,000 microns. Wavelengths longer than this have not been seriously considered for PGRV applications, because the longer the wavelength, the more bulky the antenna required to receive it; antennas for wavelengths in the X, C, or S microwave bands would be too large to be used effectively on a reentry vehicle. Millimeter and K-band are the wavelengths utilized by most PGRV concepts under consideration. While they do not provide the same level of accuracy and resolution available from optical or infrared light, they are adequate for PGRV applications. More important, if designed carefully such systems can see through all but the heaviest weather and can operate at night as well as during the day.

Passive detection of these longer wavelengths is more difficult, as millions of times less natural light is available in this range than in the optical range. While some passive microwave detectors have been developed, most microwave systems are active, sending out beams of radiation. Active microwave systems are what is meant by the term radar (which stands for radio detection and ranging). Emitting the necessary radar beams requires a large amount of power, and receiving the reflected beams requires large antennas, since the wavelengths are relatively long; the result is that active radar systems are substantially bulkier and more complex than most optical or infrared systems. In addition, they are more easily jammed, although jamming can often be overcome, as will be discussed later.

Current Terminal Sensing Concepts. In addition to the type of sensor, terminal sensing concepts can be distinguished by what features the sensor looks for, and how its information is interpreted by the PGRV's guidance computer. For example, a sensor might simply measure the height of the ground. The guidance computer would then convert the measurements into something like a topographic map, which it could compare with similar maps in its memory. Alternatively, the sensor might take something like a photograph of the ground, comparing the brightness of various terrain features rather than their height. Another important distinction is whether the system takes such measurements at a number of points along a line, in which case it is referred to as a *line correlator*, or whether it creates an image of an area on the ground, in which case it is referred to as an *area correlator*.

In general, line correlators are the simpler of the two. Such a system typically is guided by an inertial guidance system to the area covered by the first strip map in the computer's memory. The sensor then looks down at the terrain below as the RV flies over it, and the guidance computer searches through its onboard map of the area, looking for a match with the information coming in from the sensors. If an adequate match is found, the computer updates the inertial guidance system with this new estimate of the PGRV's position, and the vehicle flies to the area of the next map, where the process is repeated. The best known such system is the TERCOM (for terrain comparison) system developed for the cruise missile. Other line correlators under development include the Range Only Correlation System (ROCS), and Microwave Strip-Map Radiometry, sometimes referred to as just Microwave Radiometry, or MICRAD.

The TERCOM system is probably the most fully developed of the terminal sensing techniques that have been investigated, and is also among the least complex. It measures the height of the ground, with a radar that looks directly down from the missile. These altitude measurements are then compared with a map consisting of a series of boxes, each labeled with a number which represents the average height of the ground in the box. The accuracy of the system is limited by the detail of the map, which in turn is limited by the amount of memory that can be stored in the computer. While future advances in computer memory capacity could make it possible to have extremely small boxes, current systems reportedly have box sizes of 30–70 meters. In addition, the last TERCOM map is typically 30 kilometers from the target, partly in order to avoid having the system be confused by craters caused by weapons that might have arrived earlier than the slow-flying cruise missile. The missile must then fly the last 30 kilometers on its inertial guidance system; since most inertial guidance systems develop errors of the order of a mile for every hour they are in operation, this last inertially guided stretch will introduce additional inaccuracy. As a result, it is estimated that the overall accuracy of current TERCOM-equipped systems is approximately 100 meters. Since cruise missiles are continuously guided (and therefore continuously accumulating small errors) for several hours before they reach their targets, they need terminal sensing to achieve such accuracies. For ballistic missiles, however, an accuracy of 100 meters would be no more than that projected for the inertially guided MX.[52] Thus, considerable improvements in the TERCOM technique would be necessary before TERCOM would be very useful for PGRV applications.

TERCOM has several other difficulties as well. Since it relies on measuring variations in the height of the ground, it cannot operate effectively over flat terrain. Similarly, since it uses the *average* height in a rather large box, it cannot operate in areas where the height of the ground varies rapidly over distances less than the length of the box, such as mountains and cliffs. These problems can largely be avoided by programming the missile to avoid such terrain. Another difficulty is the possibility of the system being confused by seasonal variations such as deep snow on the ground, and leaves in forests, which during the summer can give the illusion that the ground is at the height of the treetops. Perhaps the most important hazard of TERCOM (although it is difficult to assess) is the possibility of human error in the compilation of the maps. Map-compilation (using satellite photographs of target areas) has in fact been one of the most difficult and expensive portions of the cruise missile program; approximately $1 billion has been spent on TERCOM maps so far.[53] The possibility of human error, however, is a difficulty that TERCOM shares with essentially all terminal sensing techniques.

Range-only correlation is a similar system, except that rather than looking straight down, the radar looks sideways, measuring the range between the missile and various terrain features. MICRAD is a passive system which relies on the fact that different ground features naturally emit different amounts of microwave radiation, especially if they are at different temperatures; it measures this radiation for comparison with its computer maps.

More complex systems rely on creating an image of an area on the ground, similar to an ordinary map or photograph, rather than measuring a series of points along a line; this is then compared with images stored in the computer, which are compiled from satellite information. Such systems are called *area correlators*. Area correlators are generally more accurate than line correlators, but they are more complex as well, with the greater problems complexity implies.[54] Area correlators under discussion include several active radar systems, such as the Radar Aimpoint Guidance (RADAG) system for the Pershing II, the Advanced Radar Mapping Concept, and the Boeing Shaped Scan Correlator. Some passive area correlators are also under consideration, such as the Radiometric Area Correlator (RAC, which relies on microwave emissions, like the MICRAD line correlator), and Aimpoint, an optical system.[55]

Limiting Factors on Terminal Guidance. Perhaps the most frequently mentioned difficulty with terminal guidance systems is their vulnerability to countermeasures. There are a variety of means of overcoming most possible types of countermeasures, but typically they incur some other penalty, such as additional weight and complexity or reduced accuracy.

One possible countermeasure already mentioned is to jam the sensor by beaming at it a large amount of energy at precisely the wavelength it picks up. (This is of course an oversimplified description of how jammers operate; the precise description of electronic countermeasures and counter-countermeasures is beyond the scope of this chapter.) It is easiest to jam sensors which use long wavelengths, but an optical or infrared sensor could also be blinded by a strong beam of light.

One way of overcoming this type of interference is the use of an "agile" sensor, that is, one which moves from one wavelength to another, so that the defender cannot tell what wavelength to use in jamming. An agile sensor generally requires a much more complex system, however, implying significant penalties in weight and increased complexity. Using inertial guidance rather than terminal sensors to fly the very last leg of the journey is another way to avoid jamming, as well as to avoid confusion by bomb craters as described above. Since jamming devices are expensive, they would usually be deployed only near valuable targets, so a system which took its last look at a distance from such a target would be largely impervious to jamming. This is the technique envisioned for most PGRVs. However, the use of inertial guidance for the last leg of the flight means a significant reduction in the accuracy of the system; indeed, this fact has been described as "one of the principal reasons why you can't achieve some of the extremely high accuracies that are quoted."[56]

Another possible countermeasure is to change the appearance of the territory around the target. For example large sheets of metal foil spread over the map area would confuse many radar correlation systems. Similarly, the use of smoke or fog screens could confuse optical systems. Again, however, this tactic can be overcome by having the system finish sensing at a significant distance from the target, since the defender cannot possibly cover his entire territory with such devices. Another technique to avoid confusion by such methods is to look at features which are so large and obvious that they are impossible to disguise, such as roads, large building complexes, shorelines, etc. Since such features also tend to keep their basic shape regardless of season and weather, having the PGRV look for them also eliminates much of the seasonal variability problem.

The question of how to test PGRVs is another significant issue. For safety reasons, the U.S. does not currently conduct any long-range ballistic missile tests over land. Current ICBM-test RVs reenter over Kwajalein Atoll in the Pacific, while SLBM RVs reenter over the open ocean. Some terminal guidance techniques could not be tested without large land areas over which to fly. This would probably mean that such vehicles would have to reenter over U.S. territory, raising safety questions if the test should go awry. Ideally, such tests should be conducted over a wide variety of different types of terrain, meaning that many different testing areas might be required, further complicating the problem.

Probably the most important single limitation on terminal guidance techniques for reentry vehicles is the size of the equipment required. To fit a high-precision maneuvering and inertial guidance system, a sensor, an advanced computer and possibly a transmitter into an object as small as an RV (typically 1–2 meters long, 0.3–0.7 meters base width, and 200–600 kilograms in weight) and still have room left for the bomb is an extremely difficult task of miniaturization. The technology to build anything other than an extremely large and heavy PGRV does not yet exist. The RV for the Pershing II, which will be described in the next section, is 4.2 meters long, and weighs 1,362 kilograms. This would be too heavy for the Minuteman rocket to fire to the Soviet Union, even if it only carried a single RV. As a result of these difficulties, it would probably require a decade or more of serious effort before a reasonably sized PGRV for ICBM and SLBM applications (as opposed to shorter ranges like that of the Pershing) could be developed and deployed.[57] Moreover, deployment in a decade would require that the basic sensing technology involved be completed within the next few years, making it unlikely that such a system would have an accuracy better than 20-30 meters; the achievement of inaccuracies close to zero remains in the distant future.

PGRVs and ABM Evasion. To design an RV which is equipped both for precision guidance and for the high-velocity maneuvers necessary for ABM evasions would further compound these design difficulties. Both the sensors and the computing capacity of the PGRV would have to be hardened to withstand high accelerations and intense nuclear radiation. The vehicle itself would have to have an extremely high-performance maneuvering system like that on the AMaRV vehicle.

In addition, there are difficulties with some of the guidance techniques involved. Few of the techniques under consideration are capable of seeing through the plasma which surrounds the RV at speeds of more than 2700–3000 meters per second. The heating caused by high-speed passage through the atmosphere might prevent infrared sensors from operating effectively unless the PGRV were travelling at still slower speeds. More important, most precision correlation systems require that the RV be travelling rather slowly in order to make the necessary correlations. TERCOM, for example, was designed for cruise missiles travelling at speeds of the order of 300 meters per second. In addition to speed limitations, some guidance techniques cannot be used if the RV is flying an erratic swerving course.

Since the crucial parameters of an RV intended to evade ABMs are its high speed and high maneuverability, many of the PGRV concepts which have been investigated so far would be difficult to adapt to an evasive MaRV. However, it is by no means impossible that a MaRV capable of combining the two roles could be developed in the future. For the present, the ABM treaty and the corresponding absence of large-scale Soviet deployments of ABMs make these potential vulnerabilities less serious than they would otherwise be.

The Pershing II. The Pershing II is a modification of the Pershing I missile, originally deployed in 1964. The most significant changes are the new type of rocket fuel, which increases the range of the system, and the precision-guided reentry vehicle, which greatly increases its accuracy.[58]

The PGRV for the Pershing II is the only such vehicle which has actually been fully developed and deployed.

In order to maneuver during reentry, the Pershing II RV has four control vanes around its base, which can be moved in order to change the direction of the vehicle's flight. The first maneuver that the Pershing RV performs during reentry is simply a velocity-control maneuver, tilting upward to a horizontal course after passing through the upper atmosphere, to allow atmospheric drag to slow it to a speed at which the radar aimpoint guidance (RADAG) system can operate. After the vehicle has slowed, it tilts back down toward its target, the protective shroud over the radar system is jettisoned, and the radar begins to scan at an altitude below 20,000 meters.

The K-band radar on the Pershing II RV points not directly forward, but several degrees off to one side; it then scans in a circle at 2 revolutions per second, creating a circular image with a gap directly forward, much like a doughnut. Although the target is located in this gap, it is not necessary to close the hole since the surrounding images provide enough correlation for the maps in the computer's memory. Since the amount of detail the sensor can provide increases as the RV goes down toward the target, there are four different maps of the target area with increasing levels of detail, corresponding to different altitude bands. The RV is then guided directly in to the target. The accuracy of the system is estimated at 30 meters,[59] better than is currently achievable with any inertially guided long-range missile.

However, the Pershing II has failed a distressing number of its tests, and many of the failures have involved difficulties with the reentry vehicle. Two of the three most recent accuracy tests were failures, whereupon the Army decided that no further tests were required.[60] In addition, since the Pershing II does not use an agile radar and "looks" at the area immediately around the target, it may conceivably be vulnerable to countermeasures. It should be noted, however, that the system is designed so that if the RADAG system fails or is confused by countermeasures, the RV will continue on inertial guidance, although obviously with a reduction in accuracy.

As mentioned earlier, the Pershing II RV is extremely large, heavier than the heaviest vehicle that could be delivered by the U.S. Minuteman ICBMs. The yield of the warhead it carries is quite small, generally estimated at less than 50 kilotons. Thus, to convert the Pershing II PGRV for a practical longrange ICBM or SLBM would require very substantial miniaturization.

Summary of PGRVs. Precision-guided reentry vehicles generally rely on terminal sensing of terrain to improve their accuracy; terminal sensors can utilize optical, infrared, or microwave wavelengths. The primary use of PGRVs is to reduce collateral damage in limited nuclear war-fighting. While the concept of such an RV is rather simple, they remain a long-range program, and it is extremely unlikely that the U.S. will deploy a PGRV on an ICBM or SLBM system in the next decade. Indeed, cutbacks in reentry research funding have eliminated all current research on terminal sensing systems for reentry vehicles.[61] Some of the most significant limitations on such systems are their large size and complexity, their possible vulnerability to countermeasures, and the difficulty of testing them. Many types of PGRVs would be more vulnerable to possible future ABM systems than evading MaRVs.

POLICY AND ARMS CONTROL IMPLICATIONS OF REENTRY RESEARCH AND DEVELOPMENT

Like many other areas of strategic weapon R&D, reentry research could lead either toward stabilizing the strategic balance or toward increasing the risk of nuclear war. The stability of deterrence requires that the bulk of each side's nuclear forces be invulnerable to preemptive attack, so that there will not appear to be any possible gain from a first strike, and no "use them or lose them" pressures will prevail in times of crisis.

The most stabilizing aspects of current reentry research are those that concentrate on overcoming anti-ballistic missile systems, including development of penetration aids and evading MaRVs. These programs provide a hedge against any possible erosion in the U.S. deterrent force that might be caused by Soviet abrogation of the ABM treaty. In so doing, they also reduce the probability that such abrogation will occur by removing any possible gain the Soviets could achieve. Indeed, the 1981 U.S. Arms Control Impact Statement stated that U.S. penetration aids and evading MaRVs were adequte to "assure the penetration of sufficient numbers of U.S. RVs *regardless* of Soviet actions with respect to ABM improvements." (emphasis added)

Areas of reentry research that are specifically intended to increase the vulnerability of Soviet strategic forces, by contrast, destabilize the strategic balance, thereby possibly provoking undesirable Soviet responses. The most important research effort in this category is precision guidance. By creating a situation in which a preemptive strike could be carried out on land-based ICBMs with a minimum of civilian casualties, PGRVs would increase the probability that such a nuclear first-strike would be considered as a serious option in a crisis. Improving the accuracy of ballistic RVs is also a potentially destabilizing area of research, as is developing RVs capable of withstanding the fratricide which would be encountered in an attack on an ICBM field.

Development of these technologies by either superpower would decrease the stability of the nuclear balance. From the U.S. perspective, development of these technologies by the Soviet Union would be especially unfortunate, intensifying the threat to the land-based portion of the U.S. strategic nuclear forces, and eroding their deterrent value. Thus, it is useful to investigate whether it might be possible to negotiate and verify an arms control agreement limiting further progress in these areas. To do so, it is necessary to consider current Soviet reentry development, and U.S. methods of monitoring them.

Soviet Reentry Efforts

Although the U.S. and U.S.S.R. have deployed a similar number of total missile reentry vehicles, the U.S.S.R. has a wider variety of different types, corresponding to their larger variety of ballistic missiles. It is not surprising, therefore, that the Soviets conduct more RV flight tests than the United States.[62]

Nonetheless, Soviet reentry technology typically lags approximately five years behind its U.S. counterpart. The Soviets have trailed in the development of RVs with high betas, and RVs with high spin rates. Other areas which the U.S. has pursued have been largely ignored by the Soviet Union; it is reported, for example that no current Soviet ICBM employs any penetration aids, and the Soviets have yet to test a MaRV for any long-range ballistic missile.[63]

The U.S. keeps track of Soviet reentry efforts primarily by observation of their flight tests, as it is difficult to obtain detailed information about their technology in the R&D stage. RVs in these tests generally reenter either over the Kamchatka Peninsula northeast of Japan or over open ocean in the Pacific. Since the monitoring of flight testing is the main source of information about Soviet ballistic missiles, the United States devotes considerable effort to it. Systems for monitoring the reentry phase of a missile's flight include radars, and infrared and optical telescopes based on land, ships, and aircraft.[64]

Land-based radars used by the U.S. include the enormous Cobra Dane phased-array radar on Shemya Island in Alaska, and the Altar and Tradex radars on Kwajalein Atoll. The Cobra Dane radar was specifically designed to monitor Soviet missile tests. It can reportedly detect an object the size of a basketball at ranges of 3,000 kilometers and track up to 100 such objects simultaneously. As mentioned earlier, the Altar and Tradex radars and the optical telescopes on Kwajalein were built to track incoming U.S. test RVs. The radars can track incoming RVs to within 3 meters and determine their velocity to within 0.01 meters/second, and the telescopes can provide detailed information about the size and shape of the RV and the flow of heated air around and behind it.

The range of these systems is limited by the curvature of the earth, however. Since Soviet RVs typically reenter tens or hundreds of miles away from them, the critical last stages of reentry will be below their horizon. For this reason, the U.S. also employs a number of ship-based radars (a new such system under development is called Cobra Judy). The Soviet Union is required by treaty to issue an international warning when test RVs are going to reenter over the Pacific, so the U.S. can position ships in the area to monitor the reentry. Additional information is provided by airborne monitoring, which gives infrared and optical data similar to that given by the Kwajalein optical telescopes. While warning is not currently required for Soviet tests into the Kamchatka Peninsula, it is sometimes possible for the U.S. to detect the preparations for a test launch and to have ships and airplanes ready to monitor the test.

The combination of these techniques allows the U.S. to have some confidence in its assessments of the shape, weight, and ballistic coefficient of Soviet RVs. In addition, the chemical composition of the RV's nosetip and heatshield can usually be determined, by the use of Fourier spectroscopy, from the information received by optical and infrared telescopes. Any significant maneuvers by the RV could be detected, as could the flaps or vanes necessary for executing such maneuvers.

Since the Soviet Union does not possess any land bases in the areas where U.S. test RVs reenter, they rely on trawlers equipped with radars and other equipment to monitor U.S. tests. Because all its ICBM and SLBM tests are over international waters, the U.S. must issue warnings before every test, which allows the Soviet boats to take position before the test. Thus, the Soviets also have an extensive ability to monitor U.S. reentry tests.

Arms Control Possibilities

The fact that reentry tests can be closely monitored raises several possibilities for arms control. Reentry research is crucially dependent on flight testing. Therefore the most promising approach to verifiable arms control limitations on reentry development would be limitations on reentry vehicle flight testing.

As early as the mid-1970's, some Congressmen and outside scientists recognized that development of PGRVs would destabilize the strategic balance.[65] Few, however, were willing to sacrifice the evading MaRV program, so it was suggested that further testing of PGRVs be banned but that tests of evading MaRVs be allowed to continue. Even a cursory look at the monitoring capabilities of each side, however, suggests that it would be essentially impossible to verify whether a given evading MaRV was also equipped with a terminal sensor, especially if the sensor was passive.[66] Defense Department spokesmen argued against a total ban on MaRV flight tests, saying that the advantages of continuing research on evading MaRVs outweighed the disadvantages of possible future PGRV developments. In the absence of any real method for limiting one without the other, the idea of a MaRV ban slowly faded away.

The current situation, however, presents an opportunity. As we have seen, both the Navy Mk 500 and the ASMS AMaRV evading vehicles have completed their initial flight tests and are "on the shelf." Precision guidance work, by contrast, has ground to a halt, probably a decade short of U.S. deployment of a PGRV for an ICBM or SLBM, and the Soviet Union is even further from deployment of such a vehicle. If a ban on further testing of all MaRVs were negotiated within the next several years, the development of PGRVs could be forestalled, with evading MaRVs available to the U.S. as a hedge against Soviet deployment of ABMs. A ban on the testing of MaRVs would drastically slow, if not stop, further progress toward the development of PGRVs, and without PGRVs it will remain impossible for any leader to believe that a strategically significant counterforce strike could be launched without causing millions of civilian casualties. The "threshold" of strategic nuclear war would remain high. Such a ban would be verifiable with higher confidence than many of the provisions of current treaties, and since it would give the Soviets the desirable opportunity to foreclose a technology in which they are behind, it should be negotiable as well.

Such a ban would require several subsidiary agreements. First, it should be tied to the ABM treaty, so that abrogation of the ABM treaty by either side would give the other side freedom to move forward with testing of evading MaRVs. This "enforcement" provision would provide a minor further deterrent to abrogation of the treaty. In addition, it would be necessary for each side to agree to test its reentry vehicles only within specified areas, and only after giving sufficient warning to the other side. This would prevent RV testing in areas (such as the center of the Soviet Union) in which the other side would be unable to monitor the test. Such provisions could be monitored with satellites.

While a ban on further flight testing of MaRVs is the single most desirable agreement relating to reentry, other possibilities exist. Since the accuracy of ballistic RVs is limited by their ballistic coefficient, a limitation on testing of RVs with increased ballistic coefficients would provide some limit on the accuracy which could be achieved. Such an agreement would also provide a useful addition to the accuracy limitations inherent in a ban on MaRV testing. The same monitoring capabilities and subsidiary agreements could be used for each.

Another area to consider for arms-control limitation is RV size and weight. For some years, there has been a fierce dispute in this country over the importance of the fact that Soviet ballistic missiles carry much more throw-weight than their American counterparts. Those who argue that this factor is important point out that the existence of greater throw-weight capacity allows the Soviet Union, without further launcher development, either to increase the number of RVs on its ICBMs or to increase the yield of its warheads. Those who do not consider throw-weight important argue that the number of RVs can be limited directly through arms-control agreements, that throw-weight (especially the aggregate throw-weight of a large number of different missiles) is an inaccurate measure of destructive power, and that the destructive power of RVs is relatively unimportant. For attacks on cities, the yield of each of the thousands of RVs in the arsenals of either side is already many times that of the bomb which obliterated Hiroshima; for attacks on hardened targets, yield is much less important than accuracy. In any case, since Soviet missile throw-weight is roughly three times that of U.S. missiles, an arms control proposal which demands reductions to equal levels of throw-weight would require much larger reductions on the Soviet side, to which they are unlikely to agree.

One approach to limiting the increases in yield feared by some would be to place limits on both the *weight* and the *size* of reentry vehicles which could be tested. Such limits would have the additional benefit of providing increased confidence that the vehicles undergoing tests were not sophisticated MaRVs. However, it should be noted that if the technology of fuzing and arming mechanisms can be miniaturized, it is possible that large increases in yield could be accomplished without increasing the weight of the vehicle. For example, the Mk 12A vehicle now deployed on the U.S. Minuteman III ICBMs has roughly twice the yield of its predecessor, the Mk 12, while the increase in weight is closer to 10%. Since the Soviet Union is believed to be somewhat behind the U.S. in the development of such miniaturization, weight limits would leave them with more room for improvement than the U.S. would have. On the other hand, there is clearly a limit to such increases, so limits on the weight of RVs would have some utility in the long run. Another possible problem with a weight and size limit is the danger of "breakout." Developing a heavier RV with the same technologies as previous RVs would be a relatively simple matter requiring only a few tests, which could be accomplished rapidly after an abrogation of such an agreement. However, it seems likely that the Soviet Union would be less likely to increase the weight of its RVs in the presence of such an agreement than in its absence.

In short, it is clear that some aspects of reentry development would decrease the stability of the strategic balance. In particular, Soviet development of PGRVs would increase U.S. fears of a first strike against U.S. ICBMs. As a result, limitations on the testing of reentry vehicles could provide an important complement to other arms control efforts, in the search for a safer and more stable nuclear balance.

NOTES

1. 10,000 kilometers is one-quarter of the way around the earth, typical of the distance between many points in the U.S. and U.S.S.R. The reentry speed and angle given are those for the "minimum-energy" trajectory, the path which requires the least energy to reach a given distance, or equivalently, the path which can reach the farthest distance with a given energy. The minimum energy reentry angle for any ballistic missile is given approximately by:

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

where phi is the range angle through which the missile must fly. When phi is close to zero, as in the case of artillery, or rock throwing, the well-known result is that the optimum firing angle (ignoring atmospheric effects) is 45 degrees.

For a derivation of both the reentry angle and the reentry speed, see M. Bunn and K. Tsipis: *Ballistic Missile Guidance and Technical Uncertainties in Countersilo Attacks*, Report Number 9 of the Program in Science and Technology for International Security, Massachusetts Institute of Technology, August 1983.

2. See "Data for ICBM Reentry Trajectories," RAND Memorandum RM-3475-ARPA, April 1963.
3. Figure from Bunn and Tsipis, *op. cit.*
4. An approximate equation for the deceleration caused by atmospheric drag is:

$$D = \frac{\rho V^2}{2\beta}$$

where beta is the weight-to-drag ratio of the RV, rho is the density of the air, and V is the velocity of the RV with respect to the air. The beta is a function of the RV's speed, but at hypersonic speeds it is nearly constant, as long as the shape of the RV remains constant. However, the RV becomes more pointed during flight, and the beta therefore increases.

5. Graph from Bunn and Tsipis, *op. cit.*, based partly on information in F. M. Shinnick: "On the Linearized Atmospheric Contributions to Reentry Vehicle CEP," Master's thesis in Aeronautics and Astronautics, MIT, 1964. Again, individual points on the graph are valid only within very large ranges of uncertainty; the graph is intended to show an overall trend, not specific data points. In addition, the graph includes only those errors attributable to atmospheric factors, such as wind and density variations.
6. The beta of the Mk 4 is given in T. Greenwood: "Notes on Conversations with Avco Personnel," unpublished, 1975. Greenwood notes that at that time, Avco engineers felt the technology was available for an RV with a beta of 2000. In 1979 testimony before the House Armed Services Committee, Jim Miller, then head of the Ballistic Missiles Systems Branch of the Defense Intelligence Agency cited the beta of the Mk 12A as being "up around 2000" while Soviet RVs were then much less capable. In the past, Soviet reentry developments have generally lagged of the order of five years behind their U.S. counterparts.

7. The most cogent available exposition of this view is in R. B. Dirling, Jr.: "Asymmetric Nose-Tip Shape Change During Atmospheric Entry," presented at the 12th American Institute for Aeronautics and Astronautics (AIAA) Thermophysics Conference, June 1977.
8. Telephone interview with Col. Richard Rene, of the Advanced Strategic Missile Systems (ASMS) division of the Air Force Ballistic Missile Office (BMO), September 1983. ASMS is responsible for advanced reentry research for all three branches of the U.S. armed forces.
9. See H. King: "Ballistic Missile Reentry Dispersion," *Journal of Spacecraft and Rockets*, May-June 1980.
10. A more detailed discussion of RV testing is given in a subsequent section. For a particularly detailed example of laboratory testing of the onset of flow transition, see A. Martelluci and S. Weinberg, "Biconic Body With Slice/Flap," January 1982. National Technical Information Service, Report Number AD-A118242.
11. Diagram redrawn from H. Hurwicz, K. Kratsch, and J. Rogan: *Ablation*, NATO Advisory Group for Aerospace Research and Development, March 1972.
12. Dirling, *op. cit.*
13. Photo from G. Otey and E. English: "High-Beta Re-entry Vehicle Recovery," *Journal of Spacecraft*, May 1977.
14. In 1976 testimony, Gen. Alton Slay, then head of Air Force Research and Engineering, stated that "asymmetric nosetip ablation is the largest potential dispersion contributor" in current RVs. *DoD Authorization Hearings for FY1977*, Senate Armed Services Committee, p. 6450.
15. See testimony of Gen. Alton Slay, ibid, p. 6529.
16. See information supplied by the Department of the Navy in *DoD Authorization Hearings for FY76 and 7T* pt. 10, p. 5355–5356.
17. For a more detailed description of the fratricide problem, see Bunn and Tsipis, *op. cit.*
18. Ibid.
19. Author's calculations based on formulas in R. Turco, O. Toon, T. Ackerman, J. Pollack, and C. Sagan: *Long-Term Atmospheric and Climatic Consequences of a Nuclear Exchange*, 1983.
20. Telephone interview with Col. Rene, September 1983.
21. This description of the types of ablative nosetips which have been investigated is largely based on the testimony of Gen. Alton Slay, *op. cit.* p. 6449–6452.
22. Interview with Col. Rene, September 1983.
23. Drawings from Slay, *op. cit.*
24. Interview with Col. Rene, September 1983. See also Slay, ibid.
25. An extremely detailed and informative discussion of ABMs is given in A.

Carter and D. Schwartz, ed., *Ballistic Missile Defense*, Brookings Institution, 1984. For a briefer discussion, see Sartori, this volume.

26. Interview with Col. Rene, September 1983.
27. Author's estimate. The ionized-wake and radar simulator penetration aids are described in R.J. Smith: "The Search for a Nuclear Sanctuary (II)," *Science*, July 8, 1983.
28. Carter and Schwartz, *op. cit.*, and Sartori, this volume.
29. F. Hussain: "The Impact of Weapons Test Restrictions," Adelphi Paper number 165, International Institute for Strategic Studies.
30. Otey and English, *op. cit.* at 13.
31. Carter and Schwartz, *op. cit.*, and Sartori, this volume.
32. Testimony of J. B. Walsh, Deputy Director for Strategic and Space Systems, Defense Research and Engineering, in *DoD Authorization Hearings for FY1978*, Senate Armed Services Committee, p. 6587–6591.
33. R. Aldridge: *First Strike*, South End Press, 1983. Aldridge was responsible for the original concept designs of the Mk 500 MaRV.
34. Walsh testimony, *op. cit.*, p. 6589–6590.
35. For a discussion of MaRV guidance laws, see IEEE Conference on Decision and Control, Dec 7–9, including R. Rogers and J. Page: "Guidance and Control of Maneuvering Reentry Vehicles," D. Humphrey and R. Spooring: "A Steering Method for Bank-to-Turn Maneuvering," J. Cameron: "Explicit Guidance Equations for Maneuvering Reentry Vehicles," and S. Archer and D. Sworder, "A Class of Robust Guidance Laws for Reentry Guidance."
36. Testimony in *DoD Authorization Hearings for FY1975*, Senate Armed Services Committee, p. 6464.
37. Interview with Col. Rene, September 1983.
38. Walsh, *op. cit.* p. 6590.
39. Ibid, p. 6587–6592.
40. Figure from Fiscal Year 1980 *Hearings on Military Posture*, House Armed Services Committee.
41. Testimony of William Perry, Undersecretary of Defense for Research and Engineering, in *DoD Authorization Hearings for FY1981*, Senated Armed Services Committee, p. 2898 and 4099.
42. Testimony in *DoD Authorization Hearings for FY1978*, Senate Armed Services Committee, p. 6598.
43. Walsh testimony, *op. cit.*, p. 6600.
44. P. Klass: "Tests Find New Uses for Laser Gyros," *Aviation Week and Space Technology*, September 6, 1982.
45. Ibid. Another possibility for evading MaRV inertial measurement is the hemispherical resonator gyro; see W. Scott: "Delco Makes Low-Cost Gyro Prototype," *Aviation Week and Space Technology*, October 25, 1982. The Delco gyro is reported to be able to measure accurately at accelerations of up to 100 gravities, and to be more resistant to nuclear effects than the laser gyros.
46. Conversation with Dr. Peter Zimmerman, professor of physics at Louisiana State University, and one of the authors of the OTA report *MX Missile Basing*.

47. It is possible to conceive of other, more "blue-sky" missions for PGRVs, primarily against *mobile* strategic systems. For example, to attack bombers as they leave their bases, a reentry vehicle could be conceived that would use radar to sense the bombers and to direct its course to destroy them. Similarly, one could imagine a PGRV which would examine desert deployment areas for signs of the vehicles carrying Midgetman-type mobile missiles. A more remote possibility is the use of such vehicles against submarines. It is frequently possible for sonar systems such as SOSUS to locate submarines within a circle of radius 50 km or so at distances of hundreds of miles; a very large reentry vehicle could then be used which would act as a long-range homing torpedo, attempting to search out the submarine and destroy it. However, the reader should be aware that these ideas are for the moment no more than science fiction; indeed, they are so remote that they have never yet been mentioned by military officials as justifications for pursuing a PGRV program.
48. For a detailed description of the system, see *Global Positioning System*, a collection of papers published by the Institute of Navigation, Washington DC, 1980. The discussion in this handbook is somewhat dated by now, however, as some changes and further testing of the system have occurred since it was published.
49. For a discussion of the ASAT problem, see Raiten, this volume.
50. For discussion of laser radar, see P. Klass: "Laser Radar Missile Guidance Studied," *Aviation Week and Space Technology*, March 16, 1981. For a brief description of the earlier, optical version of the DSMAC, see J. Toomay: "Technical Characteristics," in R. Betts, ed: *Cruise Missiles: Technology, Strategy, Politics*, Brookings Institution, 1981.
51. Ibid. For a description of recent cruise-missile tests of DSMAC, see "New Cruise Missile Guidance System Tested," *Aviation Week and Space Technology*, April 6, 1981.
52. For discussion of TERCOM, see K. Tsipis, "Cruise Missiles," *Scientific American*, February 1977. Estimate of CEP of 100 meters is from *The Military Balance, 1983–1984*, International Institute for Strategic Studies, Autumn 1983.
53. Toomay, *op. cit.*
54. Testimony in *DoD Authorization Hearings for 1976 and 7T*, Senate Armed Services Committee, p. 5282–5287.
55. Many of these are enumerated in *DoD Authorization Hearings for 1975*, Senate Armed Services Committee, p. 3371.
56. Walsh testimony, *op. cit.*, p. 6607–6608. He continues: "The high accuracies are based on the accuracy of a single fix. Now, it is hard enough to take a fix to [deleted] which hold the most promise for high accuracy. However, to extrapolate this while the reentry vehicle is coasting for another [deleted] in a rather severe environment which stresses inertial systems through bending loads and the like means that even an accurate fix will turn into a relatively inaccurate strike."
57. Testimony in *DoD Authorization hearings for 1977* Senate Armed Services Committee, p. 6514. There is some dispute among the witnesses as to whether the time required would be fifteen years or even longer, but some

research has been done in the interim.

58. This description of the Pershing II is largely taken from that given by F. Berry: "Pershing II: First Step in NATO Theatre Nuclear force Modernization?" *International Defense Review, 1979.*
59. Accuracy estimate is from *The Military Balance*, 1983–84.
60. Information on recent tests is from *Aviation Week and Space Technology*, July 25, 1983.
61. Interview with Col. Rene, September 1983.
62. Greenwood notes, *op. cit.*
63. For five-year lag, see testimony of Col. L. Koerkenmeier, Program Element Monitor, Advanced Ballistic Reentry Systems, in *DoD Authorization Hearings for 1976 and 7T* Senate Armed Services Committee. Koerkenmeier estimates that in beta and spinning, the Soviets were "more than 5 years" behind, possibly "5–10." For lack of penetration aids on Soviet missiles, and absence of Soviet MaRVs, see Aldridge, *op. cit.*, and R. J. Smith, *op. cit.* A decade ago, the Soviets reportedly attempted to develop one MaRV, a terminally-guided system for the submarine launched SS-NX-13 missile, but this was a tactical system probably intended for use against ships, with a range of only 650 kilometers; it was a technical failure, and was never deployed. See R. Berman and J. Baker: *Soviet Strategic Forces*, Brookings Institution, 1982, p. 57–58.
64. More detailed descriptions of this monitoring are given in F. Hussain, *op. cit.*, and in Bunn and Tsipis, *op. cit.*, Appendix C.
65. One of the major proponents of this idea was Congressman Tom Downey. See "How to Avoid Monad—And Disaster," *Congressional Record*, September 20 1976, beginning at S16210.
66. See R. Garwin: "Test Restrictions on Maneuvering Reentry Vehicles," 1977, unpublished, for an argument against separate limitations, on grounds of verifiability.

7.
DEFENSE AGAINST BALLISTIC MISSILES

Development and Theories

Leo Sartori

INTRODUCTION

Interest in an antiballistic missile defense (ABM) did not disappear in the wake of the ABM Treaty of 1972. Research continued quietly, at a modest level of funding, in line with the generally accepted view that an effective ABM was, for many reasons, not feasible. The situation changed markedly after President Reagan's speech in March, 1983, when he again held out the idea that the solution to our vulnerability to the threat of long-range nuclear weapons was defense. In what was quickly dubbed by the press his "Star Wars" speech, Reagan stressed the potential of exotic technologies such as space-based directed energy weapons and the so-called "third generation" of nuclear weapons, the nuclear-bomb-powered X-ray laser. His hope was to remove the threat of hostile nuclear explosions from our shores, with a shield of defensive weapons in space making our borders once again inviolable. The inevitable effect of his speech was to prompt discussion of all kinds of ballistic missile defenses, reopening a question that had been dormant in American public life: Might it not be possible to conceive of a defense against nuclear weapons?

It was recognized that to be effective, an antiballistic missile defense had to do two things: (1) It had to be perfect, or very nearly perfect. The power of the weapons is so great that if even 10% of the attacking warheads get through, the result will be catastrophic; and (2) It had to cost