Chapter 6

An Overview of Emerging Missile State Countermeasures

As we discuss in the previous chapter, the five original nuclear weapon states have in the past invested substantial effort and money in developing countermeasures to ballistic missile defenses and continue to do so. However, the question is often raised whether emerging missile states will have both the capability and incentive to deploy effective countermeasures to the US NMD system.

Some argue that the deployment of a US national missile defense will deter the development and deployment of missiles by emerging missile states because it would cast doubt on the effectiveness of such weapons.[1] This is only plausible if the steps emerging missile states could take to counter the defense were technically difficult or prohibitively expensive relative to acquiring ballistic missiles in the first place. As we discuss in this and subsequent chapters, this is simply not the case. Thus, if the United States deploys a national missile defense, it must expect that any adversaries interested in acquiring long-range ballistic missiles will continue to do so, and that countries that have acquired (at considerable expense and effort) long-range ballistic missiles to threaten the United States would also take steps to counter the defense by deploying countermeasures.

Any country that has both the technical capability and the motivation to build and potentially use long-range ballistic missiles would also have the technical capability and motivation to build and deploy countermeasures that would make those missiles useful in the presence of the planned US NMD system. Moreover, it must be assumed that a country that is developing long-range missiles with the intent of using or threatening to use them would have a parallel program to develop countermeasures.[2] This is especially true in the current environment in which the US plan to build an NMD system is headline news.

The 1999 National Intelligence Estimate (NIE) of the ballistic missile threat to the United States, which was prepared by the US intelligence community, reached the same conclusions, stating that[3]

- "We assess that countries developing ballistic missiles would also develop various responses to US theater and national defenses. Russia and China each have developed numerous countermeasures and probably are willing to sell the requisite technologies.
- "Many countries, such as North Korea, Iran, and Iraq, probably would rely initially on readily available technology—including separating RVs [reentry vehicles], spin-stabilized RVs, RV reorientation, radar absorbing material (RAM), booster fragmentation, low-power jammers, chaff, and simple (balloon) decoys—to develop penetration aids and countermeasures."
- "These countries could develop countermeasures based on these technologies by the time they flight test their missiles."

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[1] BMDO Fact Sheet, "National Missile Defense Program," no. JN-99-05, March 1999, p. 2, available online at *www.acq.osd.mil/BMDO/bmdolink/pdf/jn9905.pdf.*

[2] If a country purchases a long-range ballistic missile rather than developing its own, the United States must assume that the country selling the missile would be willing to sell countermeasures as well.

[3] National Intelligence Council, "National Intelligence Estimate (NIE): Foreign Missile Development and the Ballistic Missile Threat to the United States Through 2015," unclassified summary, September 1999.

In this chapter, we provide an overview of countermeasures to the planned NMD system that would be available to an emerging missile state capable of deploying a long-range ballistic missile. Most of these countermeasures would be useful against any defense that used exoatmospheric hit-to-kill interceptors.

Some of the countermeasures discussed below would be effective for an attack using one missile, where others would be most effective if the attack involved more than one missile. As we discussed in Chapter 1, we will consider a limited attack of tens of missiles.

Some of the countermeasures we discuss in this chapter would be effective against one type of sensor but not against all of the planned NMD sensors. (The full defense will include ground-based radars that operate in the X-band and the UHF band, and satellite-based infrared and visible sensors. In addition, the kill vehicle will use visible and infrared sensors to home on its target. See Chapter 3 for more details.) We do not limit this discussion to countermeasures that are effective against the full suite of planned sensors for two reasons: different countermeasures can be combined together into packages that would be effective against all the sensors, and there are situations in which defeating only one type of sensor will defeat the defense.

We do not claim that the discussion here is comprehensive in that it includes all of the countermeasures that are both useful to an attacker seeking to penetrate the planned NMD and feasible for an emerging missile state to implement. Rather, this chapter is intended to give an idea of the range of techniques that might be employed by an emerging missile state seeking to defeat an exoatmospheric ballistic missile defense and to suggest those that might be most promising from the perspective of an attacker.

In the following chapters, we will focus on three of these countermeasures in much greater detail. These three countermeasures were chosen because they appear to combine high effectiveness against the planned NMD system with ease of deployment. For this reason, we will use the examples discussed in the next three chapters as a baseline threat for assessing the likely operational effectiveness of the NMD system. We believe the administration and Congress should also take these examples into account in their assessment of the system’s effectiveness.

To best structure the discussion in this chapter, we group the countermeasures according to the general strategy they employ to defeat the defense. We discuss each countermeasure in more detail in the rest of the chapter, but first describe them briefly here. An emerging missile state could

- Overwhelm the defense by deploying too many real targets for the defense to intercept. For an emerging missile state, this strategy is feasible for chemical or biological weapons delivered by submunitions.
- Overwhelm the defense by deploying too many false targets, or decoys, for the defense to intercept. The decoys are designed so the defense sensors are unable to discriminate them from the real warheads. There are several classes of decoys: (1) replica decoys, which replicate the warhead as closely as possible; (2) decoys using signature diversity, where the decoys are made to appear slightly different from each other and the warhead; and (3) decoys using anti-simulation, in which the warhead itself is disguised to mimic a decoy. Using anti-simulation, the attacker can disguise the warhead in several ways: for example, by enclosing it in a radar-reflecting balloon, by covering it with a shroud made of multilayer insulation, by hiding it in a cloud of chaff, by using electronic decoys, or by using infrared jammers (e.g., flares).
- Reduce the radar signature of the warhead. Doing so could reduce the range at which defense radars could detect the warhead and thus reduce the time available to the defense, and could make other countermeasures more effective.
- Prevent hit-to-kill homing by the kill vehicle, or make it more difficult, by reducing the infrared signature of the warhead. Doing so would reduce the range at which the infrared sensors on the kill vehicle could detect the warhead, leaving it less time to change course in order to hit the warhead. The attacker could reduce the infrared signature of the warhead by covering it with a low-emissivity coating or by using a shroud cooled to low temperatures by liquid nitrogen.
- Prevent hit-to-kill homing by hiding the exact location of the warhead. The attacker could hide the warhead by enclosing it in a very large metallized balloon or in one of a large number of smaller balloons tethered together. Doing so would prevent the defense sensors from

determining the location of the warhead, in which case the kill vehicle could only hit it by chance.

- Prevent hit-to-kill homing by making the warhead maneuver.
- Launch preemptive attacks on ground-based components of the defense system using cruise missiles or short-range ship-launched missiles, small airplanes, or special operations forces.

Overwhelming the Defense: Submunitions for Biological and Chemical Weapons

Here, the goal of the attacker is simply to present the defense with so many real targets that it is unable to intercept them all.

For missiles armed with biological or chemical warheads, an attacker can defeat a limited missile defense simply by packaging the biological or chemical agent in up to more than one hundred small warheads—called submunitions—rather than in one large unitary warhead. If we assume that an emerging missile state has only five long-range missiles, an attack could easily involve 500 submunitions. In this case, even if the defense expended all 250 of its interceptors, it could at best intercept half of the incoming submunitions, and thus reduce the amount of agent that reached the ground by a factor of two. However, doing so would not necessarily reduce the number of people killed or injured by a factor of two.

Using submunitions would not only overwhelm the defense, but would be a more effective way of dispersing the agent. Therefore an attacker would have a strong incentive to use submunitions to deliver these agents even in the absence of missile defenses. The use of submunitions to deliver chemical or biological agents is discussed in more detail in Chapter 7.

Since nuclear warheads cannot be subdivided into arbitrarily small parts, this strategy cannot be used for missiles carrying nuclear warheads. In this case, the most straightforward response to a limited defense deployment would be to deploy large numbers of warheads to overwhelm it. This could be done either by deploying a large number of missiles with single warheads or by deploying a smaller number of missiles with several warheads per missile. As discussed in Chapter 5, the United States, Russia, Britain, and France have all deployed multiple warhead missiles, largely motivated by concerns about the potential deployment of Soviet or US strategic missile defenses.

However, an emerging missile state is unlikely to be able to use this strategy to overwhelm the defense. Such states would have a limited capability to produce the fissile material needed for nuclear warheads, and their nuclear arsenals would thus likely consist of a small number of warheads. Moreover, deploying a large number of intercontinental missiles—whether they carry one or more nuclear warheads—would be a relatively expensive way of overwhelming a limited defense and may well be beyond the financial means of any of the emerging missile states.

Instead, an emerging missile state seeking to deliver a nuclear weapon via long-range missile would likely conclude that deploying a relatively small missile force with countermeasures is a more feasible and cost-effective approach to defeating a limited NMD system. Decoy warheads are one type of countermeasure that also relies on overwhelming the defense; we discuss these next.

Decoys: Overwhelming the Defense with False Targets

One important class of countermeasures uses a large number of decoys, or false targets, that the defense sensors cannot discriminate from the nuclear warhead. The defense then has to shoot at all the targets—real and simulated—to avoid letting the nuclear warhead penetrate unchallenged. But a limited defense would simply run out of interceptors if the attacker uses enough decoys.

As discussed in Chapter 3, the defense plans to fire multiple interceptors at each target to achieve a high probability of intercepting the warhead. If time permits, the defense plans to use a “shoot-look-shoot” strategy in which it will fire one or more interceptors, assess whether the target was intercepted, and then, if necessary, fire additional interceptors. The final system planned for deployment would have up to 250 interceptors deployed at two sites—one in Alaska and one in North Dakota.

To avoid wasting interceptors (and potentially running out of them), the planned NMD intends to discriminate decoys from warheads. However, even if its sensors are not able to discriminate the warheads from the decoys, the defense could still choose to fire all its interceptors to intercept as many of the incoming objects as possible. In this way, the defense would have some chance of intercepting the warhead and preventing any damage on the ground. However, the effectiveness of the defense system would be greatly reduced if the attacker deploys a large number of decoys. For example, if an emerging missile state with only ten missiles deploys a total of two nuclear warheads and 500 decoys, a defense with 250 interceptors will have less than a 50 percent chance of intercepting each warhead, and less than a 25 percent chance of intercepting both warheads. Thus, the attacker will have at least a 75 percent probability of getting a warhead through the defense.

Of course, the defense might not want to use all its interceptors at once, but would likely reserve some for later use. For example, the defense might be concerned that the ten missiles launched were only carrying decoys, and that the attacker would launch more missiles with nuclear warheads a short while later. If the defense had launched all its interceptors against the first ten missiles, there would be none left to intercept the nuclear warheads on the remaining missiles.

Decoys are a particularly attractive strategy against exoatmospheric defenses. Decoys designed to defeat an exoatmospheric defense take advantage of the fact that there is no atmospheric drag in the vacuum of space, so that lightweight objects travel on trajectories identical to that of a much heavier warhead. Because the decoys can be lightweight, the attacker can use a large number of them. (Because both the size and range of a missile depends on the weight of the payload it is carrying, there is in general an incentive to limit the payload weight to achieve a greater range and/or to limit the overall size of the missile.)

As such lightweight decoys and the warhead begin to reenter the atmosphere, the decoys would be slowed down more rapidly by atmospheric drag, allowing the warhead to be identified. However, depending on the altitude at which such slowing and warhead identification occurs, it might be too late for an above-the-atmosphere interceptor to intercept the warhead before it passed below the interceptor's minimum intercept altitude. Moreover, for attacks against targets far from the interceptor deployment site, the defense would need to launch its interceptors before the lightweight decoys could be discriminated. This in itself would cause problems for the defense, since it would need to commit its interceptors before it knows whether timely discrimination is even possible. The attacker could exploit this uncertainty by using a mix of lightweight and somewhat heavier decoys. In general, the heavier a decoy is, the lower in the atmosphere it would go before the defense could discriminate it.[4] Moreover, if the defense has to intercept high within the atmosphere rather than above the atmosphere, it would not have time to assess whether the first interceptors missed the target before launching additional interceptors and would be unable to use its planned "shoot-look-shoot" strategy.

Several different decoy strategies are possible. Below, we discuss three categories of decoys: replica decoys, decoys using signature diversity, and decoys using anti-simulation. Although these are presented as distinct approaches, in actual practice there are likely to be overlaps between them.

Replica Decoys. Perhaps the most obvious approach would be to deploy large numbers of decoys that are intended to be indistinguishable in appearance from the nuclear warhead (indistinguishable to the defense sensors, but not necessarily to the human eye), but are much lighter in weight. Such decoys are known as *replica decoys*. If successful, the use of replica decoys would leave the defense with the choice either of firing at every possible target, which, depending on the relative number of interceptors and decoys, may not be possible, or of letting the warhead penetrate unchallenged. While replica decoys are probably what most people imagine when they think about decoys, they are not necessarily the most effective decoy approach, as we discuss below. Figure 6-1 is a photograph of a US replica decoy that was deployed in the 1960s.

Given the high measurement resolution of the NMD X-band radars, a replica decoy would need to be very similar in shape to the warhead and have a similar radar cross section. It might also need to mimic any dynamical characteristics of the warhead, such as the rotation about its axis and any wobbling in this rotation. In order to be effective against SBIRS-low, a replica decoy would also need to have a similar temperature and emit a similar amount of infrared energy as the warhead in the wavelengths used by the defense sensors.[5] Doing so might require putting a heater in the decoys.

It should be possible for an emerging missile state to construct and deploy credible replica decoys that are much lighter than a nuclear warhead and that could be deployed in significant numbers by a long-range ballistic missile delivering such a warhead. The American Physical Society's Directed-Energy Weapons study

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[4] The altitude at which discrimination could occur would depend on the ballistic coefficient of the decoy, $\beta = W/(C_D A)$, where W is the weight, C_D is the drag coefficient, and A is the cross-sectional area.

[5] The requirement that the decoy emit a similar amount of infrared energy means that the product of the decoy's surface area and emissivity must be similar to that of the warhead.

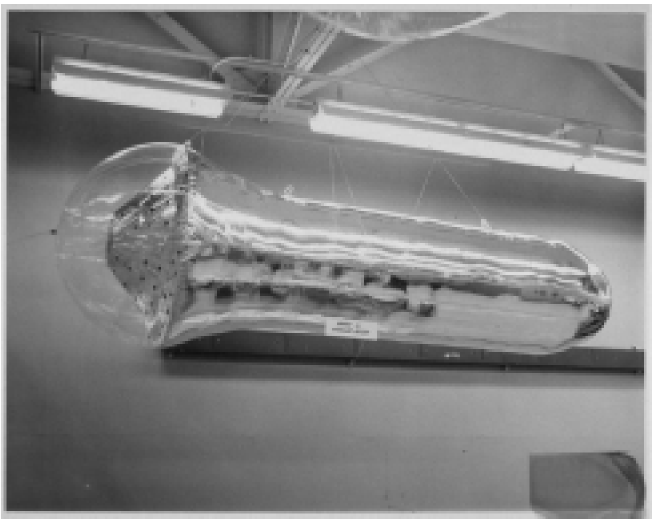

Figure 6-1. Photograph of a US replica decoy for the MARK IV reentry vehicle that was used on some Titan ICBMs. *US Air Force photo 113217 USAF, dated 19 October 1961, reprinted from Chuck Hansen,* "Swords of Armageddon," *CD-ROM (Sunnyvale, Calif.: Chukelea Publications, undated) Vol. 7, p. 560.*

concluded that such decoys might weigh as little as a "few kilograms including dispensing and erection hardware."[6] This figure presumably was an estimate for the Soviet Union, but given the relative simplicity of such decoys, this figure seems plausible even for an emerging missile state.

Decoys Using Signature Diversity. A potential attacker considering the use of replica decoys may be concerned that the defense will be able to identify and exploit some small observable difference between the warhead and the decoys. One way to address this issue would be to modify the decoy strategy to exploit the fact that while the defense might know the general characteristics of the warhead, it would not know the exact characteristics. Thus, rather than trying to exactly replicate the warhead, the decoys would be made to have slightly different signatures from the warhead and from each other. This would prevent the defense from picking out the warhead as the one object that was different from the rest.

For example, the attacker could use cone-shaped decoys with the same shape as the nuclear warhead, but of slightly varying lengths and nose radii of curvature. Such decoys would have slightly different radar cross sections from the warhead and each other. Because they would have the same shape, several of these decoys could be stacked over the warhead inside the nosecone of the missile. Small weights on the inner surface of the cones could be used to control their moments of inertia so that each one would wobble in a manner similar to (but slightly different from) the warhead. The attacker could also diversify the infrared signature of the decoys by using small heaters or, for daylight attacks, different surface coatings that would result in different decoy temperatures.

Decoys Using Anti-simulation. With anti-simulation, the attacker takes the deception one step farther by modifying the appearance of the warhead. Rather than making a decoy simulate the warhead, the attacker disguises the nuclear warhead. By introducing variability into the warhead appearance, a wide range of decoy characteristics can be made compatible with those of the warhead, thus greatly complicating the decoy discrimination problem for the defense. Indeed, when the possibility of altering the warhead appearance is taken into account, it is clear that there is no need for the decoy to resemble a bare warhead at all. The attacker can either use decoys that are similar in appearance to the disguised warhead, or exploit the advantages of signature diversity by using decoys that vary in appearance, differing from the warhead and each other.

Anti-simulation techniques can also be used to defeat a defense strategy commonly used to deal with large numbers of potential targets—"bulk filtering." In this technique, objects with characteristics that are a poor match to those the defense expects the warhead to have are either not observed because of sensor filters or observed very briefly and immediately rejected without the need for a detailed examination. This approach allows large numbers of false targets to be screened out rapidly, but is vulnerable to being deceived by anti-simulation techniques. If the attacker disguises the warhead, this could lead the defense to reject the warhead itself as a possible target. The attacker could also deploy at least one decoy that would have observed characteristics similar to what a bare warhead would have.

The attacker can modify the appearance of the nuclear warhead in many different ways. By changing its shape, the attacker can change the radar cross section of the warhead as measured by an X-band radar by several orders of magnitude. By changing its surface coating, the infrared signature of the warhead can change by more than an order of magnitude. Or, as we discuss in more detail below, the attacker can disguise the warhead by enclosing it in a radar-reflecting balloon, by covering it with a shroud made of multilayer insulation, by hiding it in a cloud of chaff, or by using electronic radar jammers.

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[6] American Physical Society Study Group, "Science and Technology of Directed Energy Weapons," *Reviews of Modern Physics,* Vol. 59, no. 3, Part II, July 1987, p. S153.

Metallized Balloons. One anti-simulation strategy would be to enclose the nuclear warhead in a metallized mylar balloon, similar to but larger than those sold at supermarket checkouts. This would be released along with a large number of empty balloons. Because radar waves could not pass through the thin metal coating, the radars could not determine what was inside each balloon. However, a nuclear warhead gives off heat and could thus heat the balloon enclosing it. To prevent discrimination by infrared sensors, the attacker could control the temperature of each balloon by equipping it with a small heater. Alternatively, for attacks during daylight, the thermal behavior of the balloons could be controlled by passive means: the attacker could set the temperature of each balloon by choosing a surface coating with a specific solar absorptivity and infrared emissivity. For attacks during nighttime, the temperature of the balloons will not depend on the surface coating, but can be varied by varying the shape of each balloon (see Appendix A).

Although each balloon could be made similar in appearance, it might be even more effective to make each balloon different in shape and to design them to achieve a range of different temperatures. In this case, each balloon—including the one with the warhead—would look different to the NMD sensors, and none of them would look like a bare warhead. We discuss this metallized balloon countermeasure in more detail in Chapter 8.

Shrouds of Multilayer Insulation. Alternatively, the attacker can conceal the nuclear warhead in a shroud made of thermal multilayer insulation and release it along with a large number of empty shrouds. Thus, the anti-simulation decoys are simply empty shrouds with a lightweight frame and of a size and shape that could cover a warhead. The frame could be collapsible (like an umbrella). Alternatively, several decoys could be packed over a conical warhead, Dixie-cup style, which would also avoid crushing the insulation.[7]

Multilayer insulation consists of many layers of metallized plastic (such as aluminized mylar) with very thin spaces between the layers.[8] It is a very effective insulator commonly used to maintain an object at a low temperature in a vacuum.[9] A shroud made of this material would effectively conceal the thermal effects of the warhead, so that there would be no need to cool (or heat) the warhead to match the temperature of an empty shroud. Moreover, because radar waves could not penetrate the metallic covering of the shrouds, the defense radars could not determine which shroud contained the warhead.

To prevent discrimination by the X-band radars, the attacker would also need to prevent the empty shrouds from behaving differently from the shrouded warhead. Because the empty shroud may not be rigid, it may begin to wobble or spin around a stable axis. However, the attacker can avoid this behavior by properly weighting the frame to which the insulation is attached.

Chaff. Rather than hiding the nuclear warhead within a balloon, the attacker could hide it within a cloud of radar-reflecting chaff strands, while also deploying chaff clouds without warheads. Since the radar would not be able to detect the presence of the warhead within the chaff cloud, each of the chaff clouds not containing a warhead would in effect act as a decoy.

A piece of chaff is simply a conducting wire cut to a length that maximizes its radar reflections, which is one-half the radar wavelength. For the planned NMD X-band radars, the appropriate length of a piece of chaff is about 1.5 centimeters (0.6 inches), whereas chaff effective against the early-warning radars would be 0.35 meters (1.1 feet) long.[10] Assuming that the warhead has been properly shaped to reduce its radar cross section (see Appendix C) and is oriented with respect to the radar so as to maintain this low radar cross section, each chaff wire would have a radar cross section comparable to that of the warhead.[11] Since one pound

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[7] This is presumably the approach used by a warhead shaped decoy named "Dixie Cup" that was investigated by Philco-Ford Corporation for the Air Forces in the mid-1960s. See "Filter Center," *Aviation Week and Space Technology*, 28 November 1966, p. 94.

[8] The layers are largely prevented from touching one another by small plastic spacers at intervals large compared to the spacer size.

[9] The vacuum between any two layers greatly reduces the heat transfer by conduction, and the highly reflective metallization reduces the heat transfer by radiation with an effectiveness that increases geometrically with the number of layers. Multilayer insulation is punctured with many small holes to permit the air to escape quickly in a vacuum.

[10] In practice, the chaff strands would be cut to a number of slightly varying lengths to account for the ability of the radar to operate over a span of frequencies.

[11] The attacker would chose the orientation of the warhead according to the location of the defense radars, which would be known to the attacker. While this orientation might not be the optimal one for reentry, since the attacker would not be trying (nor able) to achieve high accuracy, this is unlikely to be a serious concern. On some trajectories, it may be possible for several radars to simultaneously observe

of chaff could contain millions of chaff wires, the attacker could deploy numerous small chaff dispensers that would create many chaff clouds, only one of which would contain a warhead. The radar reflections from the chaff strands would prevent the X-band and early warning radars from determining which cloud contained the warhead. Because the chaff strands would be spreading radially outward from the dispenser, each dispenser would emit strands continuously over the roughly 20 minutes it is traveling through space to maintain a high density of chaff strands near the dispenser (where the warhead, if there was one, would also be located).

Because chaff clouds would only prevent discrimination by radar, the attacker would need to use other means to prevent the SBIRS-low satellite-based infrared sensors from discriminating the chaff cloud with the warhead from the empty chaff clouds. One possibility would be for the attacker to use flares in each chaff cloud to generate a large infrared signal that would overwhelm that of the warhead. Or the attacker could deploy a plastic balloon, possibly with a small heater inside each of the chaff clouds that did not contain the warhead.

Electronic Decoys. Another anti-simulation strategy is to drown out the reflected radar signals from the nuclear warhead by placing an electronic radar source on the warhead; this technique is known as "jamming." The decoys would then simply be electronic radar jammers without the warhead. Thus, jammers can be used both to produce false targets and to disguise the warhead.

Because modern missile defense radars, such as the planned X-band radars, can operate anywhere within a wide frequency range and can change frequency rapidly, a simple broad-band jammer (like those used in World War II) that would drown out the radar over all the possible frequencies it could be operating at would need to be very powerful.[12] For this reason, the attacker is likely to prefer electronic decoys that return a signal at the same frequency the radar uses and can therefore be very low power.

As the 1999 NIE noted, low-power jammers are readily available technology. Electronic radar jammers can be made using commercially available transponders to return identical signals from both warheads and decoys.[13] Small antennas on the nose of the warhead and decoys would receive the radar signals sent by the defense radars; the signals would then be amplified and stretched in time, by a variety of methods, to last somewhat longer than the radar signal reflected by the bare warhead, and returned to the radar. The defense radars would thus receive identical returns from the transponders on the warhead and the decoys, which would overwhelm the smaller signals that are reflected from the warhead and decoys themselves. The attacker could also use signature diversity: by designing each transponder to emit somewhat different signals so that every potential target had somewhat different characteristics, the attacker would prevent the defense from searching for the one target that is slightly different from all the others.

Because commercially available antennas and amplifiers have a very wide frequency response,[14] the attacker would not need to know the precise frequency of the defense radar, nor could changes of the radar frequency within its operating range reveal which target is the warhead and which is a decoy. Moreover, antennas of the type needed, particularly "spiral" type antennas, can be made very small, as small as a centimeter in diameter. Lightweight electronic decoys weighing no more than a few kilograms could be made using such antennas and lightweight amplifiers and power supplies, allowing large numbers of such decoys to be deployed along with the actual warhead. Because the electronic equipment is small, the decoys could also be packaged into small conical shapes with relatively high ballistic coefficients. This would permit the decoys to penetrate deeper into the atmosphere than some other types of lightweight decoys. (See Figure 6-2 for a schematic drawing of a US Navy electronic reentry decoy.)

Since antennas are available that are essentially isotropic in their response over a wide range of angles, the

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the warhead from widely different directions; in this case it might be difficult or impossible for the attacker to shape the warhead or its shroud so that it simultaneously has a low radar cross section as viewed by each of the radars.

[12] For example, consider a radar able to operate over a 1 GHz range of frequencies. The jammer would have to spread its energy over this entire band of frequencies. But a radar pulse with a length of 1 µsec (or chain of coherently integrated pulses) would have a bandwidth of only 1 MHz, and only 0.1% of the jammer's energy output would be within this bandwidth.

[13] Sherman Frankel, "Defeating Theater Missile Defense Radars with Active Decoys," *Science and Global Security*, Volume 6 (1997), pp. 333–355, and Sherman Frankel, "Countermeasures and Theater Missile Defense," *Surface Warfare*, July 1996, pp 38–40.

[14] See for example, antenna catalogues from Marconi Aerospace Electronic Systems, Inc., 305 Richardson Road, Lansdale, Pennsylvania.

attacker can prevent any nutation and other motions of the warhead and decoys about their spin axis from producing detectable changes in the transponder's signal. Moreover, by varying their amplification with time, the transponders could also simulate such nutations electronically. In addition, since modern radars can store and analyze sequences of signals, to hide any possible correlations between successive return signals, the transponders (including the one on the warhead) could send back signals that differ from radar pulse to radar pulse.

More generally, the use of modern microchip technology could permit even emerging missile states to deploy a whole new class of "intelligent decoys" that could improve on these simple transponder decoys.

These electronic decoys would prevent discrimination by the defense radars. The attacker would need to take additional steps to prevent discrimination by the SBIRS-low infrared sensors.

Late Deployment of Decoys. When attempting to defend a country as large as the United States with interceptors at a few sites, there is a great premium on being able to launch interceptors as early as possible after the launch of an attacking missile, both to allow the greatest time for the interceptor to reach its target and, ideally, to permit firing multiple interceptors at different times in a shoot-look-shoot strategy. Depending on the relative location of the missile launch point, the target against which the missile is launched, and the interceptor launch site, the attacker could attempt to exploit long interceptor fly-out times by withholding the deployment of decoys until after all the interceptors have been committed. In this case, the defense would have committed its interceptors before it knew how many decoys would be deployed and whether it could discriminate them from the warhead. A North Korean attack on Hawaii might be one scenario where this tactic could be effective. One disadvantage of this approach is that decoy deployment would likely occur in full view of the X-band radars, raising the possibility that the defense could discriminate the decoys by observing their deployment.

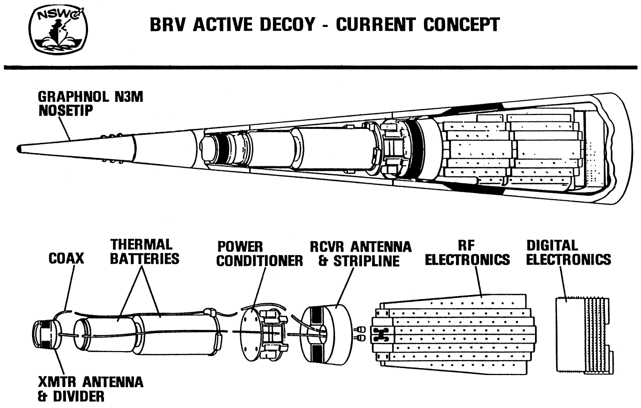

Figure 6-2. A schematic drawing of a US Navy electronic reentry decoy from a Naval Surface Weapons Center briefing (1984).

Reducing Radar Signatures

By reducing the radar signatures of the targets, the attacker could decrease the range at which the target would be detected by the defense radars, and hence the time available for the defense to act. This would make the job of the defense more difficult and could make other countermeasures possible or more effective. For example, an attacker would almost certainly need to reduce the radar cross section of a nuclear warhead if chaff is to be used to hide the warhead.

The attacker could reduce the radar cross section of the nuclear warhead by shaping the reentry vehicle (or a shroud around it) to minimize radar reflections back to a radar and/or by using radar-absorbing material on the surface of the reentry vehicle or shroud. The attacker might choose to use a shroud if the shape of the warhead itself did not make a low radar cross section easy to achieve. For example, as discussed in Appendix C, the attacker could give the warhead the shape of a sharply-pointed cone with a rounded back end (a cone-sphere), which would reduce its nose-on radar cross section for the X-band radars by a factor of about 10,000 relative to a cone with a flat back, to roughly 0.0001 square meters. While the radar cross section would be lowest if such a warhead was viewed nose-on by the radar, it would also be significantly reduced over a wide range of angles around nose-on, at least ±60 degrees. Thus, the attacker would need to use some degree of orientation control to keep the warhead pointed in the general direction of the radars, which is feasible. The 1999 National Intelligence Estimate stated that "RV reorientation" is a technology that is readily available to emerging missile states.[15]

Shaping the RV would not be as effective against the early warning radars, since their wavelength of roughly 0.66 meters is comparable to the dimensions of the warhead. Nevertheless, by using a cone-sphere the attacker could reduce the observed radar cross section by a factor of ten or more—to roughly 0.01 to 0.1 square meters.

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[15] National Intelligence Council, "NIE: Foreign Missile Development," p. 16.

By reducing the warhead's radar cross section in this way, the attacker may be able to significantly degrade the range at which a given radar could detect the warhead. However, depending on the trajectory of the warhead, the radar detection range might be limited more by the horizon. For some trajectories, the warhead would not rise over the horizon until it was close enough to the radar that it could be detected with a reduced radar cross section.

What is likely more significant is that by reducing the radar cross section of the warhead and decoys, the attacker would degrade the ability of the X-band radars to discriminate different objects from one another. Moreover, the attacker would need to reduce the radar cross section of the warhead to implement other possible countermeasures, such as the use of chaff clouds.

Prevent Hit-to-Kill by Infrared Stealth

By reducing the infrared signature of its nuclear warhead, the attacker could reduce the detection range of both the SBIRS-low infrared sensors and of the kill vehicle's infrared seeker. Even if the warhead's infrared signature could be reduced sufficiently to prevent detection by SBIRS-low infrared sensors, this would not necessarily defeat the defense since the warhead could still be tracked by the defense radars (and possibly by the SBIRS-low visible-light sensor). However, the smaller infrared sensors on the kill vehicle would not have as great a range as those on SBIRS-low, and the performance of the kill vehicle would depend critically on how much time it has to maneuver to hit its target and thus on how far away it can detect the target. By reducing the infrared signature of the warhead, the attacker might be able to reduce the detection range of the kill vehicle's infrared seeker enough so that the kill vehicle either could not detect the warhead or did not have enough time to home on the warhead after detecting it. In this case, the defense would fail catastrophically, even if the warhead could be tracked by the defense radars and SBIRS-low. We discuss two ways an attacker could reduce the infrared signature of a warhead.

Low-Emissivity Coatings. One way to reduce the signature of the warhead would be to cover it with a low emissivity coating, since the infrared signature of the warhead is determined by its temperature and the product of its emissivity and surface area. A warhead covered with a carbon-based or wood ablative covering would have an infrared emissivity of about 0.9 to 0.95, while a warhead with an outer surface of unpolished steel would have an emissivity in the range of 0.4 to 0.8. If the warhead was instead covered with a thin polished gold coating (with an emissivity of about 0.02), its emissivity would be reduced by a factor of about 20 to 40.

Since a gold-covered warhead would tend to warm up to well above room temperature in sunlight (see Appendix A on the thermal behavior of objects in space), this approach would be best suited to trajectories that were completely or largely in the earth's shadow. On such nighttime trajectories, a heavy warhead would slowly cool below its initial temperature, which we assume is room temperature (300 K). However, the attacker could reduce the infrared signature of the warhead even further by instead enclosing the warhead in a thin, gold-plated balloon that was thermally insulated from the warhead (see Chapter 8 for a discussion of how this could be done). Such a balloon would quickly cool to nearly its nighttime equilibrium temperature of about 180 K. If the balloon reached an equilibrium temperature of 200 K, its infrared signature would be further reduced by a factor of about 10 (for infrared sensors in the 8 to 12 μm band) to 200 (for sensors in the 3 to 5 μm band) relative to that of a balloon at 300 K. Thus, by using this entirely passive approach, an attacker could reduce the infrared signature of the warhead by a factor of 200–400 (8 to 12 μm band) to 4,000–8,000 (3 to 5 μm band). This would correspond to a decrease in the kill vehicle detection range by a factor of from 14–20 (8 to 12 μm band) to 60–90 (3 to 5 μm band), which would significantly reduce the time available for the kill vehicle to maneuver to hit the warhead.

As we discuss in Chapter 9, the attacker would need to orient the warhead to make sure that earth infrared radiation reflected from the warhead would not reach the infrared sensor.

Cooled Shroud. Using low emissivity coatings or passive cooling may not reduce the range at which the warhead could be detected enough to prevent the defense kill vehicle from detecting and homing on the warhead. The attacker could obtain a much greater reduction in detection range by enclosing the nuclear warhead in a cooled shroud. Such a shroud could be isolated from the warhead by commercially available superinsulation material and be cooled by a small quantity of liquid nitrogen. Cooling the shroud to liquid nitrogen temperature (77 K) would reduce the infrared signature of the warhead by a factor of at least one million relative to its signature at room temperature.[16] The warhead would then be effectively invisible to the kill vehicle. Again, the attacker would need to take care to prevent reflected radiation from reaching the infrared sensor on the kill vehicle. This countermeasure would work even if the warhead were detected and tracked by the defense radars; however, the shroud could also be shaped to reduce its radar cross section against the X-band radars. This cooled shroud countermeasure is discussed in more detail in the Chapter 9.

Prevent Hit-To-Kill Homing by Hiding the Warhead

Another set of countermeasure strategies would exploit the fact that a hit-to-kill interceptor must hit its target directly to destroy it.

For example, the attacker could enclose the warhead in a large metallized balloon, with a radius of, say, 5 meters or larger. If the kill radius of the hit-to-kill interceptor is much smaller than the balloon, it would be unlikely to hit the warhead inside the balloon even if it hits the balloon itself. In fact, the attacker can make the kill probability as small as desired by increasing the radius of the balloon. The attacker might be concerned that the balloon itself would be destroyed by the impact of the interceptor (which would depend in part on how the balloon was constructed), thus leaving the warhead exposed for a second interceptor to hit. In this case, the attacker could pack additional balloons around the warhead to be sequentially inflated as their predecessors were destroyed.

As another alternative, rather than using a single large balloon, the attacker might use a cluster of perhaps dozens of closely spaced tethered balloons, only one of which contains the warhead. These would be spaced closely enough so that SBIRS-low could not assist in discrimination, and if necessary (for example, at night) the balloons without the warhead might contain heaters to simulate the heat radiated from the warhead. In this case, each kill vehicle would at best be able to destroy a few of these many balloons, making small the odds of destroying the warhead.

Warhead Maneuvers

Another countermeasure strategy would be for the warhead to make unexpected maneuvers to confuse the interceptor or disrupt the kill vehicle's homing process. As discussed in Chapter 5, Russian countermeasures reportedly include warheads that make midcourse maneuvers,[17] and China's recent test of a spacecraft intended for manned flight demonstrated a low-thrust rocket propulsion system that reportedly could be used to make warheads maneuver to defeat an NMD system.[18] Emerging missile states could also use this strategy.

To maneuver outside the atmosphere (where the exoatmospheric NMD interceptors would intercept their targets), the warhead would need to use thrusters. Although maneuvering continuously using thrusters would require too much fuel to be practical, one maneuver or a series of several preplanned maneuvers could disrupt the defense.

For example, an attacker could also use a series of preprogrammed warhead maneuvers as a complement to lightweight decoys that the defense could discriminate below a given altitude. In this case, the warhead would make a series of maneuvers to bridge the gap between the altitude at which the decoys would be screened out and the minimum intercept altitude of the NMD interceptor.

Preemptive Attacks on Defense Components

Some of the defense components, particularly the ground-based radars and the in-flight interceptor communications systems (IFICS), could be quite vulnerable to attack. It is unlikely, for example, that the planned NMD system could even attempt to defend its radars in Britain against a missile attack from Iran or Iraq. Other forward-based radars, such as those in the Aleutians, on Greenland and on the US coasts, could be vulnerable to short-range ship-launched cruise missiles or radar-homing missiles, attacks delivered by civilian or military aircraft, or even by attacks by agents or special operations forces using shoulder-fired rockets. If such attacks succeeded in eliminating several or even one of the radars, it would leave gaps in the radar coverage so that the defense would be dependent only on SBIRS-low for interceptor guidance against incoming missiles on certain trajectories. Without X-band radar coverage, the defense's ability to discriminate decoys from warheads would be severely degraded, putting the defense at a great disadvantage. If an attack destroyed one of the IFICS, this could prevent the defense from communicating with its interceptors.

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[16] For an infrared sensor that operates at a wavelength of 10 µm, the infrared signature would be reduced by a factor of a million; for a sensor that operates at 5 µm, the reduction would be a factor of a trillion.

[17] David Hoffman, "New Life for 'Star Wars' Response," *Washington Post,* 22 November 1999, p. 1.

[18] Associated Press, "Space Technology Could Beat US Defences, Scientist Says," *South China Morning Post,* 22 November 1999, p. 1.

Chapter 7

Emerging Missile State Countermeasure 1: Submunitions with Biological or Chemical Agents

As we have seen in the previous chapter, there are many types of countermeasures that an emerging missile state could use.

We believe the planned NMD program has seriously underestimated the effectiveness of the simple countermeasures that would be available to an emerging missile state and has overstated the technical difficulties in developing and building such countermeasures.

In this chapter and the following two, we describe in detail three such countermeasures that could defeat the planned NMD system. These are: (1) biological or chemical weapons deployed in submunitions that would overwhelm any limited NMD system, (2) nuclear weapons deployed with numerous balloon decoys using anti-simulation techniques that would overwhelm the planned NMD system, and (3) nuclear weapons deployed with a cooled shroud that would prevent the planned hit-to-kill interceptor from homing on it.

It is essential that the United States accurately define the baseline ballistic missile threat from emerging missile states; otherwise, any assessment of the operational effectiveness of the planned NMD system will be meaningless. The question “Will it work?” can only be asked in the form “Will it work against what?” The threat that the NMD system appears to be designed against is simply not realistic. At a minimum, the baseline threat should include the three delivery options and countermeasures discussed in this and the next two chapters.

Should the Baseline Threat Include Chemical and Biological Weapons?

Discussions of the potential threats from emerging missile states tend to focus on ballistic missiles armed with nuclear warheads. That focus may not be justified, however.

The three emerging missile states of greatest concern to the United States—North Korea, Iran, and Iraq—are all reported to have programs to weaponize chemical and biological agents. Once successful, these countries could presumably produce large amounts of these agents and have a far larger stockpile of these weapons than of nuclear weapons. North Korea, for example, is believed to have enough fissile material to produce possibly two nuclear weapons and is not believed to currently have the capability to produce significant additional quantities. It may, therefore, see its few nuclear weapons (assuming it is able to weaponize its fissile material) as too scarce and valuable to fire on a relatively untested ballistic missile of unknown reliability, preferring instead to deliver them by a more reliable method, such as by ship. Arming missiles with chemical or biological warheads, which would be more plentiful, would therefore make sense.

If the United States is concerned about ballistic missile attacks from emerging missile states, then it must include biological and chemical warheads in the baseline threat the NMD system would need to defend against.

Submunitions

The most effective method for delivering chemical or biological (CB) weapons by ballistic missile is to divide the missile’s payload into 100 or more bomblets, or submunitions, each carrying up to a few kilograms of CB materials.[1] Shortly after the missile booster burns out, these bomblets would be released from the

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[1] For chemical weapons, all of this material would be the active agent. For biological weapons, the active agent might only be only a fraction of this quantity, with the rest being inert materials such as anti-caking substances if the material is in powder form or a liquid if it is in slurry form.

warhead in a way that makes them spread out in a cloud as they travel through space toward the target. Each of these bomblets would then land at a slightly different location, thereby dispersing the agent more effectively than would be possible if delivered in one large "unitary" warhead. A warhead using bomblets could easily be designed to disperse several hundred kilograms of CB materials over a region 10–20 kilometers in diameter.[2]

For biological weapons, even the small quantity of agent carried in a bomblet can be extremely lethal. For example, the M143 bomblet developed by the United States carried only about 6 grams of anthrax spores in a slurry, but this corresponds to 300 million lethal doses (in the hypothetical situation in which it is administered as an aerosol with no loss to the atmosphere).[3]

The analysis presented in this section shows that, if a country has developed chemical or biological agents suitable for delivery by ballistic missile, there would be no technical barriers to that country delivering those agents in bomblets rather than a single, large warhead. We show below that the chemical or biological agents in the bomblets can be protected from reentry heating using standard heatshield materials that were developed thirty years ago, and that this heatshield would also protect the agent from heating or cooling of the bomblet during its 30-minute flight. We also show that the atmosphere would slow bomblets to aircraft speeds at low altitudes, and that this has a number of advantages for the attacker. For example, it makes dispersal of the agent easier than for a unitary warhead, and it allows more thorough testing of the bomblets since testing can be done from aircraft.

It is clear that if the attacker successfully deploys submunitions this measure would defeat the defense since there would simply be too many targets for the defense to intercept. Thus, there is no need to test the NMD system against submunitions. Instead, the Pentagon should make clear that the planned NMD system is neither designed to nor capable of defending against chemical or biological agents delivered by missiles using submunitions.

US missile defense programs provide a strong incentive for countries to develop and deploy submunitions since they would be highly effective countermeasures to the planned NMD system, as well as to many US theater missile defense systems. If the submunitions are released from the missile shortly after its boost phase ends, they would overwhelm any missile defense system designed to intercept its targets after the boost phase (such as the planned NMD system).[4]

However, regardless of US missile defense plans, a country planning to deliver chemical or biological weapons by ballistic missile would have a strong motivation to divide the agent into a large number of small bomblets rather than to use a single large warhead, since bomblets offer a number of important advantages to the attacker.

The most important advantage is that bombets can disperse CB agents more effectively than a unitary warhead, for several reasons. The first is the problem of oversaturating a small area with agent by using a unitary warhead. A unitary warhead delivers a large amount of agent to the impact point, and relies on air currents to spread it over a larger area. The concentration of agent will be highest near the impact point and will decrease as the agent spreads away from that point. Making the concentration large enough to deliver a lethal dose far from the impact point means that the concentration at the impact point is much larger than required to give a lethal dose, and any agent beyond what is required for a lethal dose is simply wasted. Delivering smaller concentrations to many points using submunitions reduces this overcontamination problem.

The importance of spreading out chemical and biological agents using submunitions to avoid simply overcontaminating a small region was recognized early and

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[2] The Pentagon has also voiced concern about the possibility of countries developing radiological submunitions, in which a small conventional explosive could be used to scatter radioactive materials such as cobalt 60 or strontium 90. (David Fulghum, "Small Clustered Munitions May Carry Nuclear Wastes," *Aviation Week and Space Technology*, 11 October 1993, p. 61.)

[3] A lethal dose of anthrax is reported to result from inhaling 10,000–20,000 spores (See, for example, SIPRI, *CB Weapons Today*, p. 67.

[4] We note that there have been reports that the ERINT interceptor of the PAC-3 theater missile defense system was successfully tested against submunitions carrying simulated chemical agent. This refers to an intercept test on 30 November 1993 in which ERINT intercepted a target missile carrying 38 canisters filled with water intended to simulate chemical weapons submunitions. (David Hughes, "Army Selects ERINT Pending Pentagon Review," *Aviation Week and Space Technology*, 21 February 1994, p. 93.) However, in this test the submunitions were not dispersed early in flight; instead the canisters were all clustered together in a single package, which makes no sense from the point of view of an attacker facing a missile defense. So this test did not demonstrate that submuntions could be defeated by a terminal defense system.

grew out of work on mustard gas during World War II. The first development was of cluster bombs for aircraft, but submunitions for missiles were soon designed as well.[5]

The second advantage of bomblets is that they can be distributed in a pattern that covers a greater portion of a city with the agent than is possible with a unitary warhead. When the agent is dispersed from the impact point of a unitary warhead, the wind carries it in a long, narrow plume, which cannot cover a city effectively.

In addition, by spreading out the bomblets over a large area, an emerging missile state can help compensate for the poor accuracy of its ballistic missiles. Missile inaccuracy could easily be several kilometers or more, especially under the assumption that the missile would undergo only a limited flight-test program.[6]

A final advantage of bomblets is that, at low altitude, atmospheric drag slows them to much lower speeds than unitary warheads. Since bomblet speeds at these altitudes are typical of aircraft speeds, some methods of dispersing the agent from the bomblets may be possible that are not possible with unitary warheads.[7]

The total mass of the casings, heatshields, and dispensing mechanism for a chemical or biological warhead using bomblets would be expected to be greater than the mass of the casing and heatshield for a unitary warhead. Thus a missile equipped with bomblets would be able to carry less agent than would a unitary warhead. Such a trade-off is sometimes referred to as a “payload penalty.” However, for bomblets this should not be considered a penalty, since the net result is more effective delivery of the agent. This is precisely what led the United States to develop bomblets for chemical and biological agents on aircraft and short-range ballistic missiles (see box for more details).

Would an emerging missile state encounter any technical barriers to using submunitions? Below we examine the key technical issues a country would face in building and deploying submunitions and find that an attacker would face no such technical barriers.

The development of submunitions of various types began in the 1940s and effective heatshield materials for ballistic missiles existed in the 1960s. Technical information about both of these is widely available in the open literature. Much of the technical information about heatshields resulted from nonmilitary research, particularly research related to spacecraft. Although the calculations we perform in this study are not highly detailed, information for considerably more detailed analyses than we do here is readily available.

The level of technology required to develop submunitions is simpler than that required to build long-range ballistic missiles. So if a country has developed long-range missiles, it could also develop submunitions.[8] If a country received foreign technology and/or expertise to assist its missile program, it is likely that foreign assistance would also be available to develop submunitions to deploy on the missiles. Even if a country simply purchased its ballistic missiles, it would also be able to purchase submunition technology, since a country willing and able to sell long-range missiles would presumably also be willing and able to sell submunition technology for those missiles.[9]

Indeed, the 1998 report of the Rumsfeld Commission stated

> All of the nations whose programs we examined that are developing long-range ballistic missiles have the option to arm these, as well as their shorter range systems, with biological or chemical weapons. These weapons can take the form of bomblets as well as a single, large warhead.[10]

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[5] Stockholm International Peace Research Center (SIPRI), *The Problem of Chemical and Biological Warfare, Volume I: The Rise of CB Weapons* (New York: Humanities Press, 1973). pp. 106–107.

[6] Executive Summary, *Report of the Commission to Assess the Ballistic Missile Threat to the United States (Rumsfeld Commission Report)*, 15 July 1998, and National Intelligence Council, “Foreign Missile Developments and the Ballistic Missile Threat to the United States Through 2015, September 1999. Both discuss the limited testing programs of emerging missile states.

[7] A less commonly discussed advantage of using bomblets is that a combination of different agents could be used in an attack—for example, fast-acting agents and persistent agents—by putting different agents in different bomblets. (“A New Generation of CB Munitions,” *Jane’s Defence Weekly*, 3 April 1988, p. 852.)

[8] In its January 1996 report about theater missile defense, the Defense Science Board concluded that the United States must expect emerging missile states to deploy “advanced” submunitions for chemical and biological weapons on their theater missiles, and noted that its own “red team” effort had designed, built, and flown versions of such submunitions (*Report of the Defense Science Board/Defense Policy Board Task Force on Theater Missile Defense*, January 1996, pp. 14, 16).

[9] The Soviet Union was reported in the late 1980s to be developing new types of chemical and biological submunitions for a variety of delivery systems, including short-range ballistic missiles. (“A New Generation of CB Munitions.”)

[10] *Rumsfeld Commission Report*, p. 7.

US Programs for Delivery of Chemical and Biological Weapons

Early in its development of chemical and biological weapons in the 1940s and 1950s, the United States recognized that using unitary warheads for delivery would oversaturate a small region with the agent and that winds would subsequently spread the agent in only a narrow plume. That led the United States to research ways to disperse the agent more effectively and, in turn, to develop submunitions.[a]

In fact, the United States developed chemical and biological submunitions for several of its short-range missiles and for B47 and B52 aircraft in the 1950s and 1960s.[b] These bomblets were small, carried small amounts of agent, and had simple dispersion mechanisms to spread the agent once the bomblet was at or near the ground. For example, the M139 bomblet was an 11.4-centimeter-diameter sphere that carried 0.6 kg of GB nerve agent or liquid biological agents. It entered the US inventory in the early 1960s and was used on several short-range missiles: Little John (16 km range), Honest John (38 km range), and Sergeant (140 km range). It disseminated the agent on impact with an explosive charge and was reported to have an 86 percent agent dissemination when used with the Honest John.

The M143 bomblet was a 8.6-centimeter-diameter spherical bomblet designed to carry liquid biological agents. It used 0.5 grams of explosive charge to disseminate the agent on impact. It was said to release 8 percent of the slurry as inhalable aerosol. This bomblet had a mass of only 0.34 kilograms when filled with 190 milliliters of slurry containing about 6×10^{12} anthrax spores. It entered the US inventory in the mid-1960s and 750 such bomblets were carried in the M210 warhead on the Sergeant missile.

The United States also developed other methods to release and disseminate agents. The E95 bomblet was a 7.6-centimeter-diameter sphere designed to carry dry biological agent for anti-crop use, delivered by plane or missile. It was designed to burst open in midair to disseminate the agent over a large area. The E120 bomblet, a 11.4-centimeter-diameter sphere being developed in the early 1960s, carried 0.1 kg of liquid biological agent. Vanes on the outside of the casing caused it to rotate as it fell, so that it would shatter and roll around on impact, spraying the agent from a nozzle.

Note that all of these bomblets are small enough to fit inside the heatshield in the 20-centimeter-diameter spherical configuration considered in this chapter.

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[a] See, for example, Dorothy L. Miller, "History of Air Force Participation in Biological Warfare Program 1944-1951," Historical Study 194, Wright-Patterson Air Force Base, September 1952, p. 81.

[b] These short-range missiles were designed to release the bomblets late in flight rather than soon after boost phase. For information on these bomblets see Stockholm International Peace Research Center (SIPRI), *The Problem of Chemical and Biological Warfare, Volume II: CB Weapons Today* (New York: Humanities Press, 1973). p. 84, and Sherman L. Davis, "GB Warheads for Army Ballistic Missiles: 1950-1966," Historical Monograph AMC 51M, Edgewood Arsenal, Maryland, July 1968.

Moreover, according to a 1995 news report in *Aviation Week and Space Technology*,

> US intelligence officials are predicting the capability to release submunitions from ascending ballistic missiles could be on the world market within five years. They believe that China and North Korea will have the capability to build fractionated warheads. Such weapons could dispense up to 100 5–10 lb submunitions at altitudes of 36 mi [60 km] or less. … US planners here are worried that China or North Korea will produce and sell the weapons to military powers such as Iran, Syria, Iraq or Libya.[11]

A number of countries have developed submunitions for short-range missiles. Iraq apparently developed and deployed submunitions to deliver chemical weapons on its Scud missiles prior to the 1991 Gulf War. According to a Pentagon official, following the war UN inspectors found that Iraq had "designed and prepared for firing" a chemical warhead for a Scud missile, "which basically consisted of a bunch of little containers." The official also stated that developing a mechanism for dispersing such bomblets early in a missile's flight would not be difficult for North Korea, China, and Iran, either.[12] The dispersal mechanism for long-range missiles could be quite similar to that for shorter range missiles.

In addition, North Korea is believed to have devel-

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[11] *Aviation Week and Space Technology*, 24 July 1995, p. 19.

[12] *Aviation Week and Space Technology*, 29 April 1996, p. 23.

oped submunitions for its 300- and 500-kilometer-range Scud missiles. And the Ballistic Missile Defense Organization said in 1997 that Syria was only months away from producing chemical bomblets for its 500-kilometer-range Scud-C missiles.[13]

The Design, Construction, and Use of Submunitions: Key Technical Issues. In this section we consider the key technical issues a country would face in building and deploying submunitions to determine how difficult it would be to use this means of delivery. These issues are (1) how to dispense the bomblets after burnout and (2) how to design a heatshield for the submunitions so they will withstand the heat of reentry. We also briefly discuss the issue of dispersing the agent from the bomblet. Consistent with the conclusion of the Rumsfeld Commission quoted above, we find that these issues would not be difficult for an emerging missile state to address.

For our analysis, we assume that the ballistic missile used to deliver the attack can carry a payload of 1,000 kilograms or more a distance of 10,000 kilometers. The payload would consist of a large number of bomblets and a dispensing mechanism.

A missile of this range would burn out at an altitude of 200–300 kilometers—well above the atmosphere. At launch, a shroud would cover the bomblets to protect them from atmospheric heating. The missile would drop this shroud before burnout, once it was at a high enough altitude. (North Korea has demonstrated its ability to perform this step, since it successfully released a shroud that covered the third stage of its Taepo-dong-1 missile during its launch in August 1998.)

Shortly after the booster burns out, the warhead section would release the bomblets, kicking each one out with a slightly different speed so that while travelling to the target they would spread out in a cloud of predetermined size. We discuss below two ways this could be done. Note, however, that developing a dispersing mechanism is not demanding on the scale of the technology required to build a long-range ballistic missile. Moreover, a dispersing mechanism could be extensively tested on the ground and would not require flight testing.

The bomblets would then fall through the vacuum of space for about 25 minutes. They would begin to reenter the atmosphere at a speed of roughly 7 kilometers per second, but atmospheric drag would slow them down so that they would hit the ground with speeds of 75–150 meters per second. As we show below, it is straightforward to develop a heatshield to protect the agent within the bomblet from the high temperatures that occur during reentry.

The final step in the flight of the bomblet is to disperse the agent in the bomblet when it is at or near the ground. As we discuss below, methods for dispersing the agent are well known.

For our analysis, we assume that each bomblet has a total mass of 10 kilograms and carries up to a few kilograms of CB materials. The dispensing mechanism will add perhaps 50–100 kilograms and the shroud roughly 50 kilograms to the payload,[14] allowing 85–90 submunitions of this size and mass to be deployed on a missile capable of carrying 1,000 kilograms. Our estimate below of heatshield requirements, along with the sizes of the US bomblets discussed in the above box, suggests that the bomblets could be made smaller and lighter than we assume here, which would allow the missile to carry more.

In this analysis, we consider submunitions of two shapes: a sphere with a diameter of 20 centimeters (roughly soccer-ball sized), and a cone with a length of 20 centimeters and a nose radius of 5 centimeters (see Figure 7-1).[15]

There would be sufficient room in the payload section of a long-range missile for at least 100 bomblets and the dispensing mechanism. Even if the last stage of the missile were as small as the North Korean Nodong missile, with a diameter of 1.3 meters,[16] a cylindrical payload section 1.5 meters long, capped by a conical section one meter long, would have a volume of two and a half cubic meters.[17] One hundred bomblets would

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[13] Paul Beaver, "Syria to Make Chemical Bomblets for 'Scud Cs'," *Jane's Defence Weekly*, 3 September 1997, p. 3.

[14] Assuming the shroud is a cylinder 1.3 m in diameter and 1.5 m long, capped by a conical nose section 1 m long, it would have a surface area of about 9 m^2. If the shroud is made of aluminum alloy (with a density of roughly 2,800 kg/m^3 and has an average thickness of 2 mm, then the mass would be roughly 50 kg. Note, however, the shroud can be dropped well before the end of boost phase, so that the upper stage of the missile does not have to accelerate this mass. As a result, the amount by which the mass of the shroud reduces the payload that could be devoted to bomblets would be considerably less than 50 kg.

[15] This shape was used for calculating the heating of the cone, but there is no special significance to these particular dimensions. The shape could be varied to improve the aerodynamic stability of the cone, for example.

[16] Some people assume that the Nodong missile will serve as the second stage of North Korea's long-range Taepo-dong 2 missile.

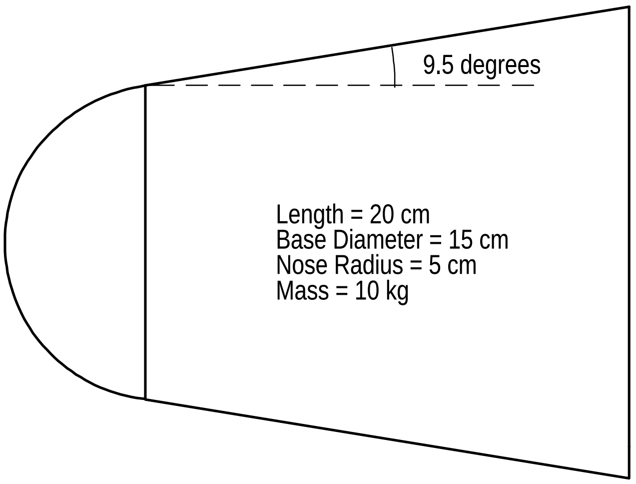

Figure 7-1. The configuration used for calculating the heating of a conical bomblet. *It has a nose radius of 5 cm, a base diameter of 15 cm, a length of 20 cm, a cone half-angle of 9.5 degrees, a mass of 10 kg, and a ballistic coefficient of 12,000 N/m^2 (250 lb/ft^2).*

occupy only a third of this volume, leaving plenty of room for the dispensing mechanism.[18]

Details of Dispensing Bomblets. It is useful to compare the trajectories of the bomblets with the trajectory that a unitary warhead would follow if launched by the same missile. The dispenser that releases the bomblets would follow roughly the same trajectory as a unitary warhead; this trajectory lies in a vertical plane containing the launch site and the point on the ground where the dispenser would impact (see Figure 7-2.)

The warhead section of the missile, including the dispenser and all the submunitions, will be travelling at a speed of roughly 7 kilometers per second when the bomblets are dispensed. Consider what happens if a bomblet is released with a push that gives it a small speed with respect to the dispenser in some direction. There are three directions to consider:

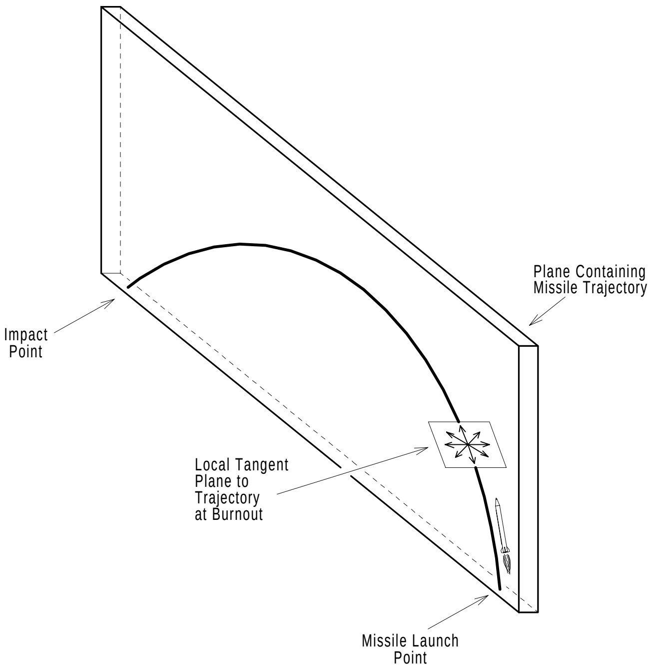

Figure 7-2. The trajectory a bomblet would have if it was given no additional δv after burnout of the missile. *The tangent plane to the trajectory at burnout is also shown. Giving the bomblets small velocity changes δv by adding velocity vectors lying in this plane will spread the impact points of the bomblets around the δv=0 impact point.*

(1) If the bomblet is given a speed perpendicular to the plane of the trajectory, it will drift in that direction until impact. The greater the speed the bomblet is given, the farther it will travel from its original impact point. Making the bomblet land 10 kilometers from the original impact point after a flight time of 25–30 minutes would require giving the bomblet a small speed of 5.5–6.5 meters per second (12–15 miles per hour) relative to the dispenser.[19]

(2) Giving the bomblet a push in the plane of the trajectory and in a direction tangent to the trajectory is equivalent to changing the burnout speed of the bomblet relative to the dispenser. Thus the trajectory of the bomblet will lie in the plane of the original trajectory but will have a slightly longer or shorter range. A speed of 2–5 meters per second (5–10 miles per hour) would change the range by 10–30 kilometers.[20]

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[17] On the Taepo-dong 1 missile that North Korea launched in August 1998, the shroud enclosed a cylindrical payload section that housed the third stage of the missile.

[18] If we estimate the volume that a spherical bomblet would occupy (including the space between bomblets) by a cube with sides of length 20 centimeters, then 100 such bomblets would occupy a volume of only 0.8 cubic meters.

[19] If δv is the additional speed imparted to the bomblet by the dispenser, the bomblet will land roughly a distance $\delta v \times t$ from the impact point it would have if δv were zero, in a direction perpendicular to the plane of the original trajectory, where t is the flight time after the bomblet is released. Spinning of the bomblets could affect their dispersion; this could be compensated by adjusting the speed of release.

[20] This is easily verified using the standard "hit equation" governing missile dynamics.

(3) Giving the bomblet a push in the plane of the trajectory but perpendicular to the trajectory changes the impact point of the bomblet very little, if the missile is on a standard maximum-range ("minimum-energy") trajectory.[21]

Thus, to spread out the impact points of the bomblets over a large area of roughly 10–20 kilometers diameter, the dispenser would give the bomblets different speeds (ranging from zero to a few meters per second) in directions lying in the local tangent plane of the trajectory. This can be done in several ways.

A particularly simple method of dispersing the bomblets would be to use springs to give the bomblets the required speeds. Consider a set of tubes having diameters just larger than that of the bomblets, lying in a plane, with each tube pointing in a slightly different direction in that plane (differing by perhaps 10 degrees). One could arrange a stack of such planar layers of tubes such that all the layers were parallel to the tangent plane of the trajectory; this orientation could be controlled by the guidance system of the missile during boost phase. The tubes in each layer would point in a different set of directions from those in other planes. Inside the tubes would be a line of bomblets with compressed springs between them. The number of layers and the number of bomblets in each tube would be determined by the size of the payload section of the missile.[22]

When the bomblets were released, they would shoot out of the tubes with a range of speeds determined by the stiffness of the springs, and in exactly the directions that would result in a dispersed set of impact points since the tubes would lie in the tangent plane to the trajectory. The shape of the impact pattern could be controlled by proper choice of the spring constants; springs of different stiffness (i.e., with different spring constants) could be used in the sets of tubes lying in different directions. (However, it would not be necessary for the attacker to carefully control the impact pattern.)

A second method of dispersing the bomblets would be to arrange the bomblets in a cylindrically symmetric pattern around the axis of the dispenser, which originally would be aligned with the axis of the missile and would thus lie along the direction of the velocity. After burnout, small thrusters would rotate the axis of the dispenser in the plane of the trajectory so that the axis was no longer aligned with the velocity. Another set of small thrusters would then be used to cause the dispenser to spin around its axis. Such thrusters are standard technology for missiles.

Each bomblet would be attached to the dispenser by a wire that would be released once the dispenser was spinning. In this way, the dispenser would release the bomblets in many different directions in the plane perpendicular to the rotation axis. Moreover, the speed of each bomblet would be different and would depend on how far the bomblet is sitting from the axis of dispenser.[23] To give the bomblets the range of speeds that are needed to disperse them over an area with a width and length of 20 kilometers, the dispenser would only have to spin at a rate comparable to the rate at which warheads are typically spun after burnout to stabilize them during reentry: a bomblet released at a distance of 1 meter from the rotation axis would require a spin rate of less than one revolution per second to give it a speed of 5 meters per second.

One could control the shape of the impact pattern of the bomblets by controlling the angle through which the dispenser was rotated before it was spun, but even without controlling this angle precisely, this method would result in a dispersed pattern at impact.

Details of Heat Shielding of Bomblets During Reentry. A key difference between the bomblets designed for short-range missiles and those designed for long-range missiles is that in the latter case, a substantial heatshield would be required to protect the agent from the much higher levels of heat generated during the high-speed reentry through the atmosphere.

It is important to keep in mind that calculations show that a nuclear weapon delivered by long-range missile would experience higher heat loadings than a bomblet (see Appendix F for calculations of the heating on various reentering bodies). Thus, if an emerging missile state poses a threat of nuclear attack by long-range missile, it has mastered a level of heatshield technology that is adequate for bomblets.

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[21] A push in this direction essentially results in a small rotation of the burnout velocity of the bomblet within the plane of the trajectory. But on a maximum-range trajectory, the range varies only to second order in a change in the angle of the burnout velocity.

[22] If the tubes point only in directions within 90 degrees of the missile's velocity, then the dispenser could remain attached to the upper stage of the missile, which would make it easier to maintain its orientation until the bomblets were released.

[23] The speed δv of a particular bomblet would be $r \times \omega$, where r is the distance the bomblet is sitting from the axis of rotation and ω is the angular speed of rotation of the dispenser.

One might think that bomblets require more demanding heatshield technology because (1) they are slowed in the atmosphere more than nuclear reentry vehicles and therefore take longer to reach the ground, so that the heat has longer to conduct to the interior of the bomblet, or because (2) chemical and biological agents are extremely sensitive to heat. We show below that neither of these is a problem.

How sensitive are CB agents to heat? As Table 7-1 shows, many of the common chemical and biological agents are not highly heat sensitive: they can survive much longer than the several minutes of reentry time at temperatures greater than room temperature (300 K).

Table 7-1. Stability of common CB agents to heat exposure.

Agent	Half-life at a GivenTemperature
Biological Agents	
Anthrax spores	4.5 hours @ 373 K (100° C)
Chemical Agents	
Sarin (GB)	2.5 hours @ 423 K (150° C)
Soman (GD)	4 hours @ 403 K (130° C)
VX	36 hours @ 423 K (150° C)

Source: Sidney Graybeal and Patricia McFate, GPALs and Foreign Space Launch Vehicle Capabilities*, Science Applications International Corporation (SAIC) Report, February 1992.*

The bomblets reenter the atmosphere at about 7 kilometers per second and are slowed by atmospheric drag. In the process, the original kinetic energy of the bomblet is converted to heat in the air around the bomblet, and some fraction of this heat is transferred to the bomblet itself. Two factors must be considered in designing a heatshield for the bomblet: the heating rate at the surface of the bomblet and the length of time the heat has to diffuse into the interior of the bomblet. For bomblets that slow down relatively quickly as they fall through the atmosphere, there will be a longer time for the heat that has been absorbed by the bomblet to diffuse into the interior (this process is known as “heat soak”).

As noted above, we consider two types of bomblets. The first is a sphere with a total mass of 10 kilograms and a diameter of 20 centimeters. This bomblet could be made to spin on reentry to spread the heating out over its surface. The second is a conical bomblet with a length of 20 centimeters and a nose radius of 5 centimeters, again with a mass of about 10 kilograms. This design has the advantage that it falls faster, so that the heat-soak time is shorter. It also lends itself to a simple fusing and dissemination method, since it can be oriented aerodynamically so that it hits the ground nose-first, which allows a disseminating charge to blow the agent out the back of the cone.

We find that it is straightforward to produce adequate heatshields for these designs that are consistent with the size and mass of these bomblets. Indeed, it appears that the bomblets could be made smaller and lighter than we consider here, which would allow more to be delivered on a given missile.

For this study, we have only considered relatively simple heatshield materials that were developed 30–40 years ago. Not only are these materials relatively simple, but considerable information about them is available to anyone, including an emerging missile state. However, considerably more advanced materials are in common use today and are commercially available.[24]

The primary heatshield material we consider is silica phenolic or “refrasil phenolic,” which is roughly 35 percent by weight phenolic resin impregnated into a fabric reinforced with high-purity glass fiber. Heatshield materials based on phenolic resins were considered state of the art in the 1960s because of their thermal, mechanical, and chemical properties. These materials reduce the heat transferred through them by ablating the outer surface away.

For the spherical bomblet with a heatshield made of silica phenolic, the thickness of material ablated from the surface is only about 3 millimeters. (See Appendix F for details of the heating and ablation calculations.) In addition, a shell of this material that is 2 centimeters thick will keep the temperature increase at the inside of the heatshield to less than 50° C by the time it hits the ground, and a 2.5-centimeters-thick shell will keep the temperature rise to less than 20° C. For a bomblet with a diameter of 20 centimeters, a shell of this material with a thickness of 2 or 2.5 centimeters would have a mass of 3.3 or 4.0 kilograms, respectively.

We also consider other standard heatshield materials of the same vintage as silica phenolic. For example, by using nylon phenolic, which has a low density

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[24] As one example, there is a material called Thermasorb, in which heat is absorbed with no rise in temperature by a phase transition in a material that could be used to fill a thin shell at the inner edge of heatshield (see *www.thermasorb.com*).

relative to silica phenolic, a greater volume of material will be ablated but a lighter heatshield can be used. Using nylon phenolic for the spherical bomblet would result in a surface ablation of about 9 millimeters, but restricting the temperature rise at the inner surface of the heatshield to 20° C would require the original thickness of the heatshield to be only 2 centimeters. A 2-centimeter-thick shell of this material would only have a mass of 1.2 kilograms, compared with the 4 kilograms needed for a silica phenolic heatshield that restricts the temperature rise to 20° C.

In practice, other simple things would improve the design and reduce mass. For example, it would make sense to use a thinner shell of ablating material and back it with a lightweight layer of highly insulating material. In addition, if the bomblet had a metallic shell for structure inside the heatshield, the metal would act as a heat sink and could reduce the amount of heatshield required.

For the conical bomblet using the same silica heatshield material considered above, about 1 centimeter of material would be ablated at the nose, where the heating is most severe, and about 3 millimeters of material would be ablated at a point on the wall a distance of 10 centimeters behind the nose. The calculations show that at the nose a thickness of less than 3 centimeters of material is required to keep the temperature rise at the back of the heatshield to roughly 20° C. On the side walls of the bomblet, 2 centimeters of material would keep the temperature rise at the inside surface of the heatshield to less than roughly 20° C, and 1.5 centimeters of material would result in a temperature rise of 70° C. A conical heatshield that had 5 centimeters of material at the nose and 1.5 to 2 centimeters of shielding on the walls would have a mass of about 1.7 to 2 kilograms. And, as above, in practice a country could do things to make the heatshield thinner and lighter than this.

These calculations demonstrate that effective, lightweight heatshields can easily be made for bomblets using even simple materials developed decades ago. Thus, even if a spherical or a conical bomblet of this shape were not used, it is clear that an adequate heatshield could be developed for a different design.

Heating or Cooling of the Bomblets During Midcourse. There seems to be a common misperception that the temperature of bomblets would drop dramatically during their roughly 25-minute flight between release from the missile and the beginning of atmospheric reentry and that this could harm the CB agent contained in the bomblet. As shown in Appendix A, if the bomblet is in the sunlight its temperature can either increase or decrease from an initial temperature of 300 K (room temperature), depending on the surface coating of the bomblet. Thus the attacker can easily design the bomblet so that its equilibrium temperature will be close to 300 K.

If the bomblet is in the dark, its temperature will drop, but will do so only slowly as it radiates away heat. Appendix F considers the case of the 10 centimeter-radius spherical bomblet with a 2-centimeter-thick heatshield made of silica phenolic. The appendix shows that if the bomblet were in the dark along its entire trajectory, after 30 minutes the temperature of the bomblet would drop by less than 20 K from its initial temperature of 300 K. So in neither case would the temperature change of the bomblet during the midcourse phase present a problem for the chemical or biological agent.

Releasing the Agent. The final step in delivery is to release the chemical or biological agent from the bomblet and disperse it. Of course, this would also need to be done for CB agents deployed in a unitary warhead, so if a country has weaponized these agents, it could apply these techniques to bomblets.

Several methods of fusing have been discussed in the open literature, including contact fuses that would detonate upon hitting the ground and barometric fuses that would release the agent at a preset altitude.[25] Note that at low altitudes, the speed of the bomblets would be very low: the spherical bomblet would impact the ground at 75 meters per second and the conical bomblet at 150 meters per second, corresponding to 170–340 miles per hour. These speeds, which are typical of aircraft, make dispersal easier than do very high speeds. Given these speeds, it would even seem possible to use a small sprayer to release the agent. This could be very efficient because sprayers can release the agent in the droplet sizes that are optimal for infecting people.

For the conical bomblet, an easy fusing method would be to have a contact fuse in the nose of the bomblet, which would ignite a dispersing charge when the nose hit the ground that would blow the agent upwards into a cloud. Designs for this type of dispersion mechanism have been around for 40 years.

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[25] SIPRI, *CB Weapons Today*, for example, references a number of US patents granted in the 1950s and 1960s for fusing and dispersal mechanisms, which give detailed descriptions and technical diagrams.

Because bomblets on a long-range missile undergo severe deceleration in the atmosphere, bomblets released from a 500-kilometer range missile like the Syrian or North Korean Scud-C, would have the same range of speeds at low altitudes as would these bomblets on long-range missiles.[26] As a result, the dispersal mechanisms developed for bomblets on short-range missiles could also be used for bomblets on long-range missiles.

Finally, it is important to note that because of the low speeds and altitudes the bomblets would have at release, dissemination of chemical or biological agents could be tested by dropping small bomblets containing simulated agents from aircraft. In this way, clandestine tests can be done to achieve the optimal particle size.

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[26] The braking force on a body in the atmosphere is proportional to the square of its speed. Thus the faster bomblets on a long-range missile will experience much stronger braking forces than slower bomblets. Bomblets having the same ballistic coefficients as those considered above released from a 500-km-range missile would have speeds of 90 to 150 m/s at impact.

Chapter 8

Emerging Missile State Countermeasure 2: Anti-Simulation Balloon Decoys for Nuclear Warheads

According to the September 1999 National Intelligence Estimate on the Ballistic Missile Threat to the United States, balloon decoys are a “readily available technology” that emerging missile states could use to develop countermeasures to the US NMD system.

In fact, the first two intercept tests of the NMD system included one balloon decoy along with the mock warhead. This test configuration, together with statements that it is representative of the threat, indicates that even the Ballistic Missile Defense Organization believes that such balloons are within the technical capability of an emerging missile state. In this chapter, we consider a countermeasure that would be only slightly more difficult to implement because it uses numerous such balloons, but would be much more effective against the planned NMD system because it also puts the warhead in a balloon. Of course, making and deploying such balloons would be technically much simpler than building and deploying a long-range missile and a nuclear warhead, which is the level of technology the United States assumes an attacker would have.

We conclude that an attacker seeking to deliver a nuclear warhead by a long-range ballistic missile could defeat the planned NMD system by enclosing the warhead in a metal-coated balloon that is inflated in space when the warhead is deployed, while at the same time releasing large numbers of similar, but empty, balloons. The attacker could prevent the planned NMD system from being able to discriminate the balloon containing the warhead and thus prevent the defense from reliably hitting the warhead.

The balloons could be either free-flying or tethered together. Above the atmosphere, where the attacker would use anti-simulation to make the warhead look like a balloon decoy, objects of different weights would follow the same trajectory. The thin metal coating of the balloon would prevent radar waves from penetrating the balloons to determine which contained a warhead.

The balloons could be identical in size and shape, or they could be designed so that each one was different from the others. They could be spherical or irregular in shape. In addition, the temperature of the balloons could be easily manipulated so that each one was at a different temperature (over a range of temperatures plausible for the balloon containing the warhead) to prevent the NMD system’s heat-detecting infrared sensors from being able to determine if a balloon contained a warhead.

As we describe below, for attacks on daytime trajectories (i.e., those in sunlight), an attacker could set the temperature of each balloon anywhere in a span of several hundred degrees centigrade simply by choosing the appropriate surface coating. By choosing surface coatings that would produce balloon temperatures near the initial temperature of the nuclear warhead, the attacker would essentially eliminate any thermal effect that a nuclear warhead would have on its balloon. Thus, if the warhead were initially near room temperature (300 K), the attacker could paint the balloons so that their temperatures would vary slightly around 300 K. In this way, the attacker would prevent all of the NMD infrared sensors—those on the SBIRS-low satellites and those on the kill vehicle—from discriminating the balloon with the nuclear warhead from the empty ones.

For attacks on nighttime trajectories (i.e., those in the earth’s shadow), the balloons would all cool to a low temperature. The temperature of the balloons would not depend on their surface coating, but only on their shape. If all the balloons had the same shape, the empty balloons would cool to a somewhat lower temperature (of about 180 K, or -93 degrees Celsius, for spherical balloons) than would the balloon containing the warhead. To prevent the infrared sensors from discriminating the warhead, the attacker could use small battery-powered heaters to bring the temperature of the empty balloons up to that of the balloon with the warhead. Alternatively, the attacker could use entirely passive means to mask the presence of the warhead. First, to reduce the heat transfer from the warhead to the balloon, the attacker could cover the nuclear warhead with superinsulation or a low-emissivity coating such as shiny aluminum foil or polished silver. Then the attacker could use balloons of different shapes, so that all the balloons would have different equilibrium temperatures that varied over a range of a few degrees. One of these balloons would contain a nuclear warhead but again, none of the NMD infrared sensors—those on the SBIRS-low satellites and those on the kill vehicle—would be able to discriminate the balloon with the nuclear warhead from the empty ones.

The attacker could also design balloons that would be effective regardless of whether the trajectory was in sunlight, or earth's shadow, or some of each. For example, the balloons could be of different shapes and have a surface coating that would give an equilibrium temperature near room temperature in the sunlight. If the attacker then covered the warhead with superinsulation or a low-emissivity coating, each balloon would have slightly different equilibrium temperature. Thus, the NMD infrared sensors could not discriminate the balloon containing the warhead from the empty ones on any trajectory, regardless of how much of it was in sunlight or the earth's shadow.

The NMD system would also attempt to discriminate the empty balloons from the balloon containing the warhead by using its X-band radars to observe any mechanical interaction between the nuclear warhead and its balloon. However, the attacker could also readily prevent such discrimination. If the attacker attached the warhead to its balloon using strings or spacers of the appropriate length, the balloon would move along with the warhead, whether or not the warhead was tumbling or spinning. The attacker could also make the empty balloons tumble and spin. And the attacker could use a similar string structure inside the empty balloons, so that all the balloons would have similar surface features where the strings were attached.

Thus, by placing a nuclear warhead in a balloon and releasing it with other empty balloons, an emerging missile state would prevent the planned NMD system from being able to discriminate the balloon containing the warhead in midcourse.

The NMD system would then be confronted with a large number of potential targets, no two of which were identical in appearance, and any one of which could contain a warhead. Thus, to permit a midcourse intercept, the NMD system would either have to fire interceptors at all of the balloons or risk letting the balloon containing the warhead go unchallenged. Because the number of balloons deployed per missile could be large—up to 50 or more—the use of this countermeasure would quickly exhaust the NMD's supply of interceptors. The NMD system is intended to defend against an emerging missile state with tens of missiles; yet a state using only, say, five missiles could deploy one or more nuclear warheads in balloons and hundreds of empty balloons in an attack on a US city.

Although the NMD system is designed to intercept in midcourse, the defense could—as a last-ditch effort—attempt an intercept after the warhead and decoys begin to reenter the atmosphere, where air resistance would slow the lightweight balloon decoys relative to the heavier balloon containing the warhead. Unless the attacker took steps to prevent it, the X-band radars would be able to make very accurate velocity measurements using the Doppler shifts of the radar waves reflected from an object. At altitudes low enough that the velocity difference between light decoys and the heavy warhead could be measured, the radars would then be able to discriminate the balloon with the warhead from the other balloons. To implement this strategy, the defense would need to launch several interceptors at a predicted intercept point just above the minimum intercept altitude of the kill vehicle. However, to have enough time to reach the intercept point, the defense would need to launch these interceptors well before the balloons begin to reenter the atmosphere and then divert them in mid-flight if the X-band radars were able to discriminate the balloon with the warhead from the other ones.

This would present the defense with a significant problem because it would have to decide how many interceptors to launch before it knew how many of the balloons it could discriminate. If the defense was planning to discriminate during reentry and saw dozens of balloons deployed from each missile, it would need to assume that some of these balloons would be heavy enough to prevent discrimination above the kill vehicle's minimum intercept altitude. To achieve the high effectiveness and confidence levels planned for it, the defense would need to fire a large number of interceptors at the balloons deployed by each attacking missile. Thus, for an attack of tens of missiles, the defense would still be in the position of choosing between letting the warhead penetrate unchallenged or running out of interceptors.

Moreover, as we discuss in detail below, the attacker could take various steps to further complicate the job of the defense by lowering the altitude at which the X-band radars could discriminate a balloon containing a warhead from the other balloons. And, even if the X-band radars could determine in time which balloon in a cluster of numerous closely-spaced balloons contained a warhead, it may not be able to convey this information to the kill vehicle in a useful fashion. The ability of the radars to determine the angular position of the balloons (as distinct from their range) is somewhat limited. Thus, if the balloons are spaced closely together, the NMD system may be unable to pass an accurate enough map to the kill vehicle to allow it to home on the target using its own sensors.

We thus conclude that an attacker could prevent the planned NMD system from intercepting its nuclear warhead with high confidence by using anti-simulation balloon decoys.

As we discuss in more detail below, such balloon decoys would be easy to fabricate and deploy relative to building an intercontinental ballistic missile or a nuclear weapon. In fact, in the late 1950s the United States designed and built small metal-coated balloons to measure the density of the atmosphere, and placed several of these balloons into orbit in the 1960s. These balloons, which were 3.7 meters in diameter, are quite similar to ones that could be used as a missile defense countermeasure. (See Figure 8-1.) Detailed information on the design, construction, and deployment of these balloons has been publicly available for over thirty years; some of this information is provided in Appendix G on the NASA Air Density Explorer series of inflatable balloon satellites.

In the rest of this chapter we first discuss how such balloon decoys could be built. We then consider in detail how the attacker could prevent the NMD system from using any of its sensors to discriminate a balloon containing a warhead from empty balloons in midcourse, where the system is designed to intercept its targets. Finally, we discuss several measures the attacker could take to prevent the defense from using atmospheric drag to discriminate the target and then to make a last-minute intercept during reentry.

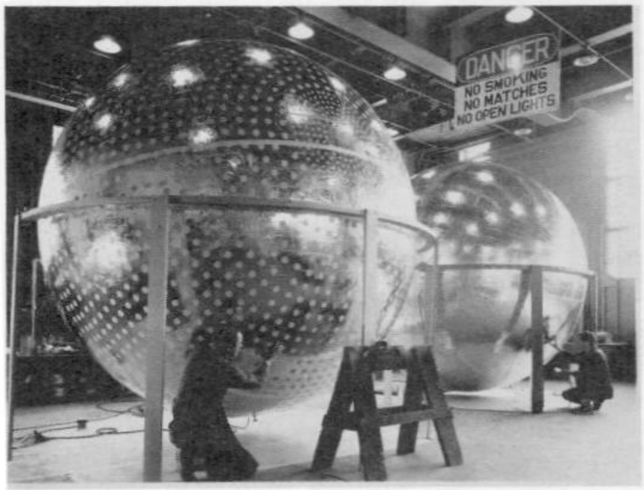

Figure 8-1. A photograph of one of the NASA Air Density Explorer inflatable balloon satellites.

Design, Construction and Deployment of Balloons

The balloon decoys could be built in a way similar to the way in which NASA built its Air Density Explorer balloon satellites. These satellites were made of a laminate[1] of two layers of aluminum foil and two layers of mylar, with the outer layer being aluminum. Each layer was 0.0005 inches thick, for a total thickness of 0.002 inches. The balloon satellites weighed roughly 4.5 kilograms (10 pounds).

An attacker could construct balloon decoys using a two-ply laminate of aluminum foil and mylar (or a mylar-polyethylene composite), with each ply having a thickness of 0.0001 to 0.001 inches. Both of these materials are widely available commercially. In fact, it may not even be necessary to make the laminate: aluminized mylar is commercially available for use in packaging.

To make a spherical balloon, the laminate would be cut into strips and glued together over a hemispherical mold, with the aluminum on the outside. However, there is no need for the balloons to be spherical. Other shapes may be easier to fabricate and fold and, as discussed below, may have other advantages as well.

The air would then be pumped out of the balloon, and the balloon folded into a small volume. (The 3.7-meter-diameter NASA balloons were folded into a cylinder 18 centimeters (7 inches) in diameter and 28 centimeters (11 inches) long.) The balloon that was to contain the warhead could be cut open and resealed once

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[1] A laminate is a material made by gluing or otherwise bonding together two or more thin layers.

the warhead was placed inside. The air could then be pumped out of the balloon, causing it to collapse down on the warhead. To keep the warhead positioned within the balloon once it was inflated, the balloon could be attached to the warhead either by several rigid spacers made of a material with low thermal conductivity or by strings. Alternately, the warhead could be left to float within the balloon.

When deployed, the balloons could be inflated in one of several ways. Here we will assume that the balloon is inflated with nitrogen (or another gas) to a pressure of 0.1 pounds per square inch (PSI).[2] This pressure would be more than adequate to inflate the balloons; it was the pressure used to inflate the NASA balloons. This gas pressure would stress the aluminum foil to its yield strength to give the balloon its maximum structural strength.[3] Once the balloon has been stressed to its yield strength, it will be stronger and will also have its wrinkles and folds removed, even if the gas is then vented out. Until the balloon was released and inflated, the nitrogen could be contained in a small steel bottle. After the balloon was inflated, the gas bottle could be made to detach and fall off outside the balloon, as was done for the NASA balloons.

We will consider two balloons that differ from each other in weight. The heavy balloon is spherical in shape, has a diameter of three meters, and is made of a laminate of a 0.001-inch-thick layer of aluminum foil and a 0.001-inch-thick layer of mylar (which gives it the same thickness as the NASA balloons). Balloons of roughly this size and thickness, and the gas used to inflate them, would weigh about 3 kilograms (6.5 pounds).[4] The dispensing mechanism for each balloon and the bottle the gas is stored in would add to this weight; if we assume the dispenser and bottle are comparable in weight to the balloon and gas, we get a total weight of 6 kilograms for each balloon deployed.

The NASA balloons were designed so that the gas used to inflate them would leak out over a period of several days after their deployment; ground tests of these balloons indicated that without their pressurizing gas they would remain spherical down to an altitude of about 120 kilometers. Because these heavy balloon decoys would be made of a material with the same thickness as the NASA balloons, they would also retain their shape down to about 120 kilometers if the gas was vented out after inflation.[5]

Considerably lighter balloons could be made by using thinner balloon materials. In this way the weight of the balloon, the gas, and the gas bottle could be reduced considerably. For our lightweight balloon model, we assume the material used to construct the balloon consists of a 0.00025-inch-thick mylar layer and a 0.0001-inch-thick aluminum layer. The thinner layer of aluminum will reduce the pressure required to take the aluminum foil to its yield strength, so less gas will be needed to inflate the balloon and a smaller and lighter bottle can be used to hold the gas. The total weight of the balloon, gas, and gas bottle would be about 500 grams (roughly 1 pound).[6,7] If we again assume the

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[2] Another means of inflating the balloons once they are deployed would be using chemical gas generators, like those that are used to inflate automobile airbags.

[3] The yield stress is defined to be the applied load at which the stress-strain relationship is no longer linear. In ground tests, the NASA researchers found that by subjecting the balloon to this level of stress, not only was its structural strength increased, but the folds in its surface were smoothed out.

[4] The volume of this balloon would be 14.1 cubic meters and its surface area 28.3 square meters. Filling a balloon of this size with nitrogen at a pressure of 700 Pa (0.1 PSI) would require roughly 96 liters of nitrogen at standard temperature and pressure (STP), or about 120 grams of nitrogen.

[5] The Ballistic Missile Defense Organization has a goal of 130 kilometers for the minimum intercept altitude of the NMD kill vehicle, so the heavy balloon decoys would retain their shape below this altitude.

[6] For material of this thickness, a balloon with a diameter of three meters would weigh about 440 grams.

The thinner layer of aluminum would reduce the pressure required to take the aluminum foil to its yield strength by a factor of ten. The inflation pressure could thus be reduced to roughly 70 Pa (0.01 PSI), so that only 12 rather than 120 grams of nitrogen gas were needed to inflate the balloon. (The dynamic pressure on the balloon due to reentry would not exceed the inflating pressure of 70 Pa until the balloon reaches an altitude of about 90 km.)

The gas bottle, made of steel, would weigh about 70 grams. If we assume a moderate bottle pressure of 1.4×10^7 Pa (2,000 PSI), the volume of the bottle would have to be about 0.07 liters (or 70 cubic centimeters) to hold the nitrogen. If we assume the bottle is a cylinder of length 8 centimeters, then its inner radius must be about 1.7 centimeters. Assuming a fairly low value of yield strength of 3.0×10^8 Pa (44,000 PSI), a steel bottle (with a density of 7.8 grams per cubic centimeter) would have a wall thickness of 0.085 centimeters and a mass of about 70 grams.

Note that we neglect the weight of the glue used to bond the balloon together.

[7] Even lighter balloons could be made. The aluminum layer could be made approximately a factor of ten thinner (only 0.00001 inches thick) and still be a good reflector of radar (this thin aluminum layer could be vapor-deposited onto the mylar). A mylar thickness of 0.00025 inches may be near

weight of the dispensing mechanism is roughly that of the balloon, this would give a total weight penalty for each balloon of very roughly 1 kilogram (2 pounds).

If the inflating gas was vented from them, these lightweight balloons would not retain their shape as low into the atmosphere as would the heavier ones. Their deformation would likely begin at an altitude of perhaps 150 to 160 kilometers.[8] However, they would retain their shape lower into the atmosphere if the gas was not vented.

A simple nuclear weapon would weigh perhaps 1000 kilograms, and it is reasonable to assume that the attacker could use about 10 percent of the payload, or roughly 100 kilograms, for countermeasures. Thus, if the attacker is satisfied with a relatively small number of decoys (15 or less) per missile, then a weight of 6 kilograms per decoy is acceptable, and the heavy balloon decoys could be used. However, if the attacker prefers to use a larger number per missile, then lighter decoys would be needed. It is reasonable to expect that an attacker could deploy as many as 100 of the lightweight (0.5 kilogram) balloon decoys we describe above on a missile along with a nuclear warhead. An emerging missile state with tens of missiles might not have enough nuclear warheads to arm each missile, in which case it could have several missiles whose entire payloads were devoted to balloons of various weights. (The attacker would probably not want to use the entire payload to deploy light balloons because the defense might well conclude that the missile could not carry hundreds of decoys and a warhead. Instead, the attacker would likely choose to deploy perhaps 25 to 50 heavy balloon decoys.)

We also note that the attacker could test the construction and deployment mechanism using clandestine ground tests. The attacker would likely not want to test these balloon decoys by flight testing them since the United States could observe such tests.

How Anti-Simulation Balloon Decoys Would Prevent Midcourse Discrimination

To understand how the balloons would prevent the NMD system from discriminating the balloon containing the warhead from the other balloons during midcourse, it is useful to first consider the "ideal" case: a metal-coated balloon travelling through the vacuum of space where the warhead suspended inside the balloon does not interact with the balloon in any physical way. Compared with an empty but otherwise identical balloon, the appearance of the balloon with the warhead would be exactly the same to radar, infrared, and visible sensors. No sensor planned for use by the NMD system could determine which balloon had the warhead and which did not; discrimination would be impossible.

However, the real world would differ from this ideal case in two ways, either of which could potentially be used by the NMD system to discriminate a balloon containing a warhead from an empty balloon:

(1) The warhead would interact thermally with the balloon, possibly causing changes in the balloon temperature (either over the whole balloon, or in hot or cold spots), including changing the rate at which the balloon changed temperature after it was released.

(2) The warhead would interact mechanically with the balloon, possibly causing changes in the shape or motion of the balloon.

Below we consider each of these issues in turn, showing how the attacker could mask these effects to prevent the defense from determining which balloon contains a warhead.

We also note that it would not be possible for the NMD sensors to discriminate a balloon with a warhead from the empty ones during their deployment because at this distance the sensors would be unable to resolve closely-spaced objects, and would therefore not be able to observe the deployment of countermeasures in any detail. As discussed in Appendix B, the resolution of the SBIRS-low infrared sensors would be too poor to allow any imaging of a balloon or warhead-sized object; instead these sensors would see all midcourse objects as point emitters. The early warning radars have even poorer resolution (see Appendix D). Even if an X-band radar was in a position to observe the

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the practical lower limit for the mylar thickness. Neglecting the weight of glue, this would give a balloon mass of about 280 grams, including the inflating gas, but not the gas bottle. (The designers of NASA's 100-foot-diameter Echo I satellite planned to use 0.00025-inch-thick mylar with a 0.000009-inch-thick layer of vapor-deposited aluminum, but found that to get the required inflation reliability 0.0005-inch-thick mylar was required. However, for the much smaller balloons considered here the 0.000025 mylar thickness would likely be sufficient.) See G.T. Schjedahl Company, "Design and Fabrication of Inflatable and Rigidizable Passive Communications Satellites (Echo I and Echo II)," Conference on Aerospace Expandable Structures, Dayton, Ohio, October 23–25, 1963, pp. 576–604.

[8] The reentry forces on the balloon would be a factor of ten lower at an altitude of 160 km than they would be at 120 km.

deployment, its resolution would also be inadequate to distinguish between the different objects, which would be densely spaced when they are deployed.[9]

Discrimination by Infrared Sensors: The Thermal Effects of the Warhead on the Balloon. As we show in this section, the attacker could completely eliminate any ability the defense might have to discriminate based on infrared data from either SBIRS-low or the kill vehicle's seeker. We consider daytime and nighttime attacks separately since the thermal behavior of objects in space is different in these two cases. The attacker can choose to fly its missiles on trajectories that are either (entirely or mostly) sunlit or in the earth's shadow. The attacker can thus choose to design its balloons to be effective against infrared sensors in either regime. Alternatively, it could choose to build balloons that would be effective against IR sensors on both daytime and nighttime attacks, as we discuss below.

Daytime Attacks

The thermal behavior of empty balloons. As discussed in detail in Appendix A, the equilibrium temperature of an object in sunlit space is largely determined by its surface coating. Thus, the attacker can easily vary the equilibrium temperatures of its empty balloons by applying various surface finishes, such as paint. Table 8-1 lists the equilibrium temperature for a sunlit spherical object with different surface coatings: seven paints, two metal finishes, and mylar. The equilibrium temperature varies by more than 300 K, from 227 K for white titanium dioxide paint to 540 K for polished gold plate.

The examples we use in this section are all spherical balloons, because it is more straightforward to calculate the thermal properties of a spherical object than for a nonspherical object. However, we emphasize that the general results are applicable to a balloon of any shape. (We discuss later in this chapter and in more detail in Appendix A the effect of balloon shape on thermal behavior.) This discussion initially assumes that the entire surface of any given balloon will be at a uniform temperature; we will consider temperature variations over the surface of the balloons subsequently.

Table 8-1. Equilibrium temperature, for various coatings, of a sphere in sunlight.

If an object in orbit is in sunlight, its surface coating will determine the equilibrium temperature. This equilibrium temperature is listed for a sphere (or spherical shell) coated with each material; it is independent of the size of the sphere. Unless otherwise stated, all objects are assumed to be in low earth orbit, at an altitude of several hundred kilometers. It is also assumed that the spheres are spinning and tumbling in such a way that all parts of their surface are equally exposed to sunlight, although clearly this can only be approximately true. (See Appendix A for details of calculation.)

Surface Coating	Equilibrium Temperature of Sphere in Sunlight (K)
White titanium dioxide paint	227
White epoxy paint	237
White enamel paint	241
Mylar	265
Aluminum silicone paint	299
Grey titanium dioxide paint	307
Black paint	314
Aluminum paint	320
Aluminum foil (shiny side out)	454
Polished gold plate	540

Table 8-1 shows that by painting all or part of the surface of a balloon whose outer layer is aluminum foil with one or several different paints, any equilibrium temperature between 227 K and 454 K can be obtained. (For example, if the aluminum is entirely covered with white titanium dioxide paint, it will have an equilibrium temperature of 227 K. If instead part of its surface is covered with black paint, it will have an equilibrium temperature between 314 K and 454 K, depending on how much of its surface is painted.) Thus, the attacker can choose the equilibrium temperature of each balloon. In fact, NASA used just this approach to control the temperature of its Air Density Explorer Balloons in order to keep the radio beacons inside the balloons within their operating temperature range. The aluminum outer surface of these Air Density Explorer Balloons was partly covered with small circles of white paint to reduce the balloon's equilibrium temperature.[10] (See Appendix G).

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[9] Although the X-band radars would have high range resolution, they would have poor angular resolution. Because the objects will be densely spaced when they are deployed, each radar range slice would contain multiple objects, and the radar's poor angular resolution would make it unable to distinguish between different objects that were at the same range. In addition, there would be screening effects because balloons between the radar and the deployment mechanism would block the radar's view.

If the initial temperature of a lightweight balloon when it is released is significantly different from its equilibrium temperature (which need not be the case), its temperature would change rapidly, since the heat capacity of such a balloon would be very low. How quickly a balloon comes to its equilibrium temperature depends on how different its initial and equilibrium temperatures are from one another and how great its heat capacity is. As we show in Appendix A, using the lightweight balloon model described above (with a mass of 0.5 kilograms), an empty balloon initially at room temperature (300 K) will reach its equilibrium temperature within about a minute, while the 3-kilogram balloons could require several minutes, depending on their surface coatings.

The thermal behavior of a balloon containing a warhead. How would the presence of a warhead inside a balloon affect its thermal behavior?

The temperature of the massive warhead would change only slightly in the short time between when it is launched and when it reenters the atmosphere, but the much lighter balloon enclosing the warhead would rapidly reach its equilibrium temperature. Because a warhead inside a balloon could be at a different temperature than the balloon, and because the warhead has a much greater heat capacity than the balloon, its presence inside a balloon could affect the thermal behavior of the balloon. If the attacker did not take steps to prevent or mask these effects, there are several ways in which the defense might be able to determine which balloon contained the warhead. These include: the direction of the temperature change of the balloon after its release (i.e., whether the balloon heats or cools); the rate of the temperature change of the balloon (i.e., how quickly it reaches its equilibrium temperature); and its final equilibrium temperature. We show below that the attacker could prevent the NMD system from using any of these thermal effects to discriminate an empty balloon from one containing a warhead.

Direction of temperature change. Assuming that both the warhead and the balloon are at the same temperature when deployed, the presence of a warhead inside a balloon would not cause that balloon to warm up when, if empty, it would have cooled down (or vice versa). The warhead can only pull the temperature of the balloon back towards the initial warhead temperature. (For example, if the warhead and balloons are initially at room temperature (300 K) when they are released, the warhead will pull the balloon temperature back towards room temperature.) Thus, a balloon with a warhead inside may cool down or heat up more slowly than a similar empty balloon. However, whether a balloon warms or cools after its release does not, by itself, indicate whether the balloon contains a warhead.

Rate of temperature change and equilibrium temperature of balloons. If the warhead and balloon are at different temperatures, the warhead will transfer heat to (or from) the balloon in several ways: by radiation, by conduction through any spacers used to position the warhead within the balloon, by conduction through the gas in the balloon, and by motion-driven convection of the gas. As discussed in more detail in Appendix H, radiation is likely to result in the largest heat transfer. Thermal conduction through any spacers could be made negligible. Conduction through the gas will give rise to a smaller effect than radiation and could be avoided by venting the gas. The effect of convection of the gas could also be avoided by venting the gas.

What is most important is that the rate of heat transfer between the warhead and the balloon will be small compared with the solar power incident on the balloon (which would be about 10,000 watts for a balloon with a diameter of three meters). This would permit the attacker to use balloons that have small differences in how efficiently they absorb solar energy (and radiate infrared energy) to completely obscure the thermal effect of the warhead (see Appendix H).

Although it is possible to hide a warhead in a balloon with any equilibrium temperature, the attacker could essentially eliminate the effect of the warhead on the thermal behavior of the balloon by simply choosing a surface coating that produces a balloon equilibrium temperature close to the initial temperature of the warhead. In this way, there would be only a small temperature difference to drive the heat transfer, and the warhead would produce only a negligible thermal effect for the defense to detect. Thus, if the warhead is initially near room temperature (300 K), the attacker could enclose it in a balloon with a surface coating that produced an equilibrium temperature near 300 K. The attacker would construct the other balloons so that they would have equilibrium temperatures within a narrow range around this temperature. The defense would then see numerous balloons at slightly different temperatures and would have no way of knowing which one contained the warhead.

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[10] The first of these 3.7-meter-diameter balloon satellites, Explorer IX, had 17 percent of its surface covered with white paint, and the second, Explorer 19, had 25 percent of its surface covered with white paint.

This approach is illustrated in Figure 8-2. The heavy lines show the temperature variation of several lightweight aluminum balloons (our lightweight balloon model described above with a mass of 0.5 kilograms), covered with varying amounts of white enamel paint. We assume the paint is distributed over the surface of the balloon, perhaps using small circles as was done for the NASA balloons. We also assume the balloons are at room temperature (300 K) when released. As the figure shows, varying the fraction of the balloon surface that is covered by the white paint from 21 to 26 percent would produce a temperature spread slightly greater than 10 K around the initial temperature of 300 K, with the balloons reaching their equilibrium temperatures in less than one minute.

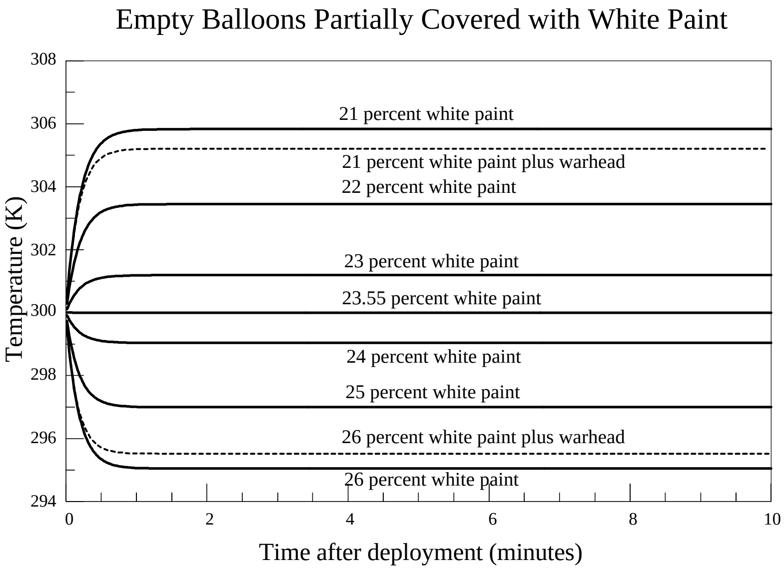

Figure 8-2. Temperature as a function of time after deployment of lightweight (0.5 kg) aluminum balloons coated with varying amounts of white paint to give equilibrium temperatures near 300 K (thick curves).

Changing the fraction of the balloon covered by white paint from 21 percent to 26 percent produces a temperature span of just over 10 K around 300 K. In addition, two balloons containing warheads with emissivities of 0.036 are also shown. These calculations assume that heat transfer occurs only through radiation to or from the warhead, but for one balloon the magnitude of the heat transfer is taken to be five times larger than it would actually be. The calculations also assume that both the balloon and the warhead are spherical; balloons and warheads of other shapes will give qualitatively similar results.

Figure 8-2 also shows the effect of adding a warhead to a balloon (specifically, to the balloons with 21 and 26 percent of their surface covered with white paint).[11] We assume the warhead has a low emissivity finish or surface coating, such as aluminum foil (with an emissivity, ε, of 0.036), and treat the inside of the balloon as a blackbody. For both balloons, the heat transfer is taken to be five times larger than would actually be produced by a warhead with a surface emissivity of 0.036.[12]

As this figure shows, the effect of the warhead would be to pull the equilibrium temperature of its balloon back towards room temperature, but the shape of the curve is essentially unchanged. The thermal behavior of the balloons containing the warheads would be indistinguishable from that of empty balloons covered with slightly different amounts of white paint. Thus, by using balloons with surfaces designed to produce a small span of temperatures around the warhead temperature, the attacker could easily hide any thermal effect of the warhead.

Alternatively, a spread of temperatures could be obtained by painting the same fraction of each balloon's surface, but using slightly different paints on each balloon. For example, consider using three different types of white paint. A balloon with 25 percent of its surface covered with white enamel paint will have an equilibrium temperature of 297 K. However, the same coverage with white titanium dioxide paint gives an equilibrium temperature of 287 K and painting it with white epoxy paint gives an equilibrium temperature of 292 K. (All of these assume a warhead initially at 300 K with an emissivity of 0.036 inside, and heat transfer by radiation only.)

The attacker can instead introduce a variation in the balloons' equilibrium temperature by varying the shapes of the balloons (see Appendix A). For example, if a sphere with a diameter of 3 meters had an equilibrium temperature of 300 K, then a cylinder with the same surface composition that was 3 meters long and had a base diameter of 3 meters would have an equilibrium temperature of roughly 284 K.[13] Thus, by using a variety of balloon shapes the attacker could also get a spread of equilibrium temperatures.

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[11] Although our calculations allow the temperature of the warhead to vary, because the thermal mass of the warhead is large, its temperature would remain essentially unchanged during the trajectory.

[12] This is done to allow for the possibility that motion-driven gas convection could increase the heat transfer.

[13] As discussed in Appendix A, for a balloon of a given surface coating, its equilibrium temperature will be proportional to the fourth root of the ratio of its average cross-sectional area to its surface area. For a sphere, this ratio is 0.25, and its fourth root is 0.707. For a cylinder that is 3 meters long and has a base diameter of 3 meters, the

For balloons designed to equilibrate around room temperature, the attacker could also introduce additional uncertainty by slightly heating or cooling the warhead prior to launch, and placing it in a balloon with the same equilibrium temperature. Then even if the defense could *exactly* determine the balloons' surface composition, it could not tell which balloon had the warhead inside. However, such heating or cooling of the warhead would not be necessary, since the defense would not be able to exactly determine the balloons' surface compositions (particularly when, as discussed below, the variation of temperature over the balloons' surfaces is taken into account).

Thus, we have shown above that neither the equilibrium temperature of a balloon nor the rate at which it obtains this temperature is sufficient for discrimination. In fact, it is clear that the attacker has many different options for designing balloons to prevent discrimination based on the thermal behavior of the balloons. The only possible thermal effect that might allow discrimination would be the very small drift in balloon temperature that could take place if the temperature of the warhead inside changed. However, this would only be a factor for balloons designed to have an equilibrium temperature considerably different from the warhead's initial temperature, and even so would be very small.[14] Moreover, as we discuss next, the temperature of the balloons would not be uniform over their surfaces, and this variation would mask any small temperature drifts due to the warhead.

Nonuniform balloon temperatures. The above discussion assumes that the entire surface of each balloon would be at a uniform, albeit changing, temperature. However, in actuality this would not be the case because different parts of the balloon would be exposed to and absorb different amounts of incident radiation. For example, for a balloon directly between the sun and the earth, the hottest area of the balloon surface would be facing directly towards the sun, while the coldest area would be located about 90 degrees away.

The temperature variations due to this effect can be significant. NASA calculations for their Air Density Explorer balloon satellites indicated there would be about a 50 K temperature difference between the hottest and coldest points on the satellite (for the case in which 17 percent of the balloon surface was covered with white paint).[15] If the inside of the balloon satellite were aluminum rather than mylar, this temperature difference would have more than doubled. These calculations assumed a balloon with a stable orientation relative to the sun. For a balloon without such a stable orientation, these temperature differences would get averaged out to some degree. However, unless the balloon was spinning in such a way that all parts of its surface received equal exposure to the sun, some temperature variation would remain.

There could also be temperature variations due to the distribution of paint on the surface of a balloon. In fact, the attacker could deliberately create hot and cold spots on the surfaces of the balloons by using different types of paints. (NASA used an area of white paint on the surface of its balloons to create a cold spot over the location of the radio tracking beacon inside the balloon.) From the point of view of the attacker, such temperature variations over the surface of the balloons would in fact be desirable, because if there were any possibility that the presence of the warhead inside the balloon would create hot or cold spots (for example via conduction along spacers), such deliberately created temperature variations would mask any such warhead effects.

Thus, in general, it must be expected that the balloons would not be at uniform temperatures, but would have significant and spatially complex temperature variations over the surface of each balloon. This would further complicate the already nearly impossible task of thermal discrimination.[16]

Nighttime Attacks. At night the situation is considerably different because the only significant external source of heating is infrared radiation from the earth.

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ratio of its cross-sectional area to its surface area can vary between 0.167 and 0.212, depending on its orientation. If we assume an average of 0.2, we get a balloon temperature of 283.7 K for a balloon surface composition that would give a temperature of 300 K for a sphere. (See Appendix H.)

[14] For example, consider an aluminum balloon containing a warhead with an emissivity of 0.036 and an initial temperature of 300 K. The temperature of the balloon would change at a rate of 0.0007 K per minute due to the changing temperature of the warhead.

[15] Coffee, et al., figure 17.

[16] In fact, even if the attacker designed the balloon enclosing the warhead to have an equilibrium temperature very different from the initial temperature of the warhead, and there was a very small drift in the balloon temperature due to the changing temperature of the warhead inside, such temperature variations over a balloon's surface would make precise measurements of the average temperature of the balloon very difficult and would prevent any potential warhead-related hot or cold spot from being used for discrimination.

At night all spheres at low earth-orbit altitudes would equilibrate at about 180 K, regardless of their surface composition. Objects of different shapes would equilibrate at slightly different, but still low, temperatures (see Appendix A).

Given this low equilibrium temperature, the effects of a room-temperature warhead inside a balloon could be quite significant. For example, the balloon discussed above (with 25 percent of its surface covered with white enamel paint), which would equilibrate at 297 K in sunlight, would at night equilibrate to about 180 K if empty but to about 187 K if it contained a warhead with a surface emissivity of 0.036 and the heat transfer was due only to radiation (and to 204 K if the heat transfer from the warhead is five times that due to radiation). However, the attacker can take straightforward measures to prevent discrimination based on the thermal effects of the warhead inside the balloon.

One straightforward way for the attacker to prevent discrimination would be to put heaters in the empty balloons and heat them to temperatures similar to that of the balloon containing a warhead. Such a heater would not need to provide a large amount of power. For a balloon with a shiny aluminum outer surface, a heater that delivered 25 watts to the interior surface of the balloon (the actual power output of the heater might have to be somewhat higher) would raise the balloon's equilibrium temperature from 180 K to 197 K. A heater that delivered 50 watts would increase the equilibrium temperature to 210 K. Such heaters could be made by depositing a resistive layer on the inner surface of balloon (or by using a resistive tape), similar to the way many rear car windows are defrosted. A small battery could be used to provide power.[17] But there would be no reason to use even this big a heater if the attacker first reduced the heat transfer from the warhead to the balloon (in the ways we discuss below) so that the difference in equilibrium temperatures between an empty balloon and one containing a warhead would be only a few degrees K. In fact, keeping all the balloons at as low a temperature as possible would be to the attacker's advantage since the colder the balloons were, the more difficult it would be for an infrared sensor to detect them.

To reduce the heat transfer from the warhead, the attacker could vent out the inflating gas and give the surface of the warhead the lowest possible emissivity.[18] By covering the warhead with shiny aluminum foil, the attacker could reduce the emissivity of this surface to 0.036. However, the attacker could devote special attention to reducing the emissivity of the warhead and thus ought to be able to obtain an even lower emissivity than that of aluminum foil. For example, the attacker could give the warhead a surface finish of polished silver, with an emissivity of 0.01.

The attacker would also want to use a balloon whose outside surface had an emissivity as high as possible, so it would radiate heat away rapidly. For example, the attacker could cover the entire surface of the balloon with white paint. In this case, and for a warhead with a surface of polished silver, the equilibrium temperature of the balloon would be 0.5 degrees K higher with the warhead than without it. Another option, which might give an even smaller temperature difference, would be to cover the warhead with a multilayer superinsulation, with the outer layer having a low emissivity.

Thus, the attacker could readily reduce the temperature difference to a few Kelvin or less. In this case, a heater of only a few watts power could be used to heat the empty balloons to the temperature of the balloon with the warhead. Of course, the attacker could give each balloon a slightly different temperature from all the others to further complicate the task of the defense.

Moreover, once the attacker reduced the heat transfer from the warhead to such low levels, the attacker could use entirely passive means instead of heaters to mask the presence of the warhead in one of the balloons.

One straightforward passive way for the attacker to mask the presence of the warhead would be to vary the shape of the balloons. As discussed in Appendix A, the equilibrium temperature of a balloon varies with its shape. By using balloons of different shapes, the attacker could introduce a range of equilibrium temperatures that vary by at least 10 K, more than sufficient to mask the presence of a low-emissivity warhead.[19]

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[17] For example, a Duracell DL245 lithium manganese dioxide battery is capable of putting out 4.5 watts for at least 30 minutes. Each battery weighs 40 grams and they can be operated in series for higher power levels. It would be necessary to enclose them in superinsulation to keep them warm, as their performance falls off rapidly as their temperature falls below room temperature. For data sheets, see *www.duracell.com/oem/lithium/DL245pc.html.*

[18] Since the surface area of the balloon would be much greater than that of the warhead, reducing the emissivity of its inner surface would have a relatively small effect, and so here we will take the inside of balloon to be a blackbody with an emissivity of 1.

[19] If, as discussed previously, we assume a cylinder with a ratio of cross-sectional area to surface area of 0.2, we get a temperature of 170 K instead of 180 K for a sphere.

Decoys Effective for Both Daytime and Nighttime Attacks. The attacker could also choose to use balloon decoys that would be effective for both daytime and nighttime attacks. As described above for nighttime attacks, the attacker could insulate the nuclear warhead and give it a surface coating with a low emissivity to reduce the transfer of heat from the warhead to the balloon during nighttime attacks. Again as described above, the attacker could either use balloons with slightly different shapes so they would have slightly different nighttime equilibrium temperatures or use a small heater in the empty balloons. Then to ensure that the decoys would also work for daytime attacks, the attacker could give the balloons a surface coating so they would have daylight equilibrium temperatures that were near room temperature but slightly different from each other. The surface coating would not significantly affect the nighttime equilibrium temperatures. If the attacker chose to use balloons of slightly different shapes, then they could be given identical surface coatings because the variation in shape would result in different daytime equilibrium temperatures. If the attacker chose to use balloons of the same shape with a small heater, then they could be given slightly different surface coatings to give them slightly different daytime equilibrium temperatures.

Discrimination by Radars: Mechanical Interactions Between the Warhead and Balloon

We have shown above that the attacker could take straightforward steps—simply choosing the surface coating and shape of the balloons—to prevent the NMD infrared sensors from being able to discriminate the balloon with the warhead inside it from the empty balloons by observing the thermal behavior of the balloons. We have also shown that these steps would work for both daytime and nighttime attacks.

However, there remains the possibility that a mechanical interaction between the warhead and balloon could change the balloon's behavior in a way that the defense could observe and then use to determine which balloon contained the warhead. For example, a spinning warhead nutating about its spin axis might cause its enclosing balloon to nutate as well.

The X-band radars can make very detailed measurements of the time variation of the balloons' radar cross-section and radial velocity, and may even be able to produce an rough image of the target. (See Appendix D for details.) In order for this capability to be useful, however, there needs to be a way for the defense to relate the observed signal to phenomena occurring inside the balloon. As we discuss below, the attacker could take steps to prevent the defense from doing so.

The mechanical interaction between the warhead and balloon differs for a warhead that is not physically coupled to the balloon and one that is. In the case in which the warhead is not attached to the balloon, we can think of the warhead as "rattling around" inside the balloon. The warhead would collide with the inside surface of the balloon. Such collisions could have several effects on the balloon: they could change the velocity of the balloon, cause the balloon to spin or tumble, or change its shape.[20] Whether the NMD radars would be able to discriminate the balloon containing the warhead by observing such changes is difficult to assess. However, to avoid this possibility, the attacker could simply choose to physically attach the balloon to the warhead. This could be done using strings; the length could be such that the balloon is either tightly or loosely constrained when it is inflated. Alternatively, several spacer rods made of a low conductivity material could be used. The Explorer 9 satellite used a set of glass epoxy rods to stand off the transmitter unit from the

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[20] First, collisions between the warhead and the balloon could slightly change the velocity of the balloon. For example, if there was on average 1 meter of "rattle room" and a collision took place every 10 seconds, then on average the balloon would change its velocity by about 10 cm/second with each collision, the radial component of which might be detectable by the radar. Thus the radar might be able to detect a pattern of discontinuous radial speed changes superimposed over a smooth variation of radial velocity as the warhead travels through space. However, if the inflating gas is vented out of a balloon, there will be considerable "give" in the balloon wall, and the relative motion of the warhead will be quickly damped out.

Second, each collision between the warhead and the balloon might also change the spin characteristics of the balloon. Thus the defense might, by observing the balloon over a period of time, be able to observe that the way in which it is spinning is changing in a way inconsistent with the balloon being empty.

Third, any tumbling motion of a non-spinning warhead may get transferred to the enclosing balloon over a period of time, resulting in changes in the tumbling motion of the balloon that may be detectable. The attacker can attempt to minimize such differential tumbling by inflating the balloon after the warhead is deployed, so that the inflated balloon tumbles in the same way as the warhead.

Fourth, collisions could "dent" the balloon, slightly changing its shape. This could result in changes in the balloon's radar cross section that the radar might be able to detect superimposed on top of the changes taking place as the balloon spins or tumbles through space.

balloon's inner surface. In either case, the balloon would move with the warhead, eliminating the detection possibilities discussed above for an unattached warhead.

The remaining concern of the attacker would be that some characteristic of the balloon and warhead motion would be measurably different from that of an empty balloon.

If the warhead is not spinning, but is tumbling, then the balloon will tumble in the same way as the warhead. However, empty balloons could also easily be made to tumble when they are ejected from the missile (in fact, it may be difficult to make them *not* tumble). The defense would not know precisely what the underlying tumbling behavior of the warhead is.

If the warhead is spinning, then the balloon will take on the spin characteristics of the warhead (assuming the balloon skin is sufficiently rigid). However, empty balloons could also be made to spin—as indeed the Air Density Explorer Satellites were. More complex motions of the warhead could occur, such as nutating about its spin axis. However, such motions could also be simulated by empty balloons using properly distributed weights on the inner surface of the balloon. Indeed, even if the warhead is not spinning, the attacker could deploy several balloons specifically designed to have spin and nutation characteristics similar to what a spinning warhead might have.

The attacker might also be concerned that the attachment points would distort the balloon, making the one containing the warhead look different from the others. In general, this would argue against making the balloons perfectly spherical, so that any such distortion would not stand out. Clearly the attacker could also introduce deliberate distortion into empty balloons in order to mask any such effect. For example, if the attacker used strings to attach the warhead to the balloon, it could also use a simple structure of strings in the empty balloons so that the surface of the balloons would be exactly the same whether there was an internal string structure or a warhead to which the balloon was tethered.

More generally, the attacker could use a variety of techniques to obscure any motion that would signal the presence of a warhead, or as noted above, could even design one or more of the empty balloons to produce observable effects of the type that the defense would be trying to exploit in order to identify the balloon with the warhead. For example, some or all of the balloons could be equipped with a small vibrational device. If balloons that retain the inflating gas are used, one could be equipped with a small valve that would be opened periodically for a short period, giving the balloon a small "kick." The attacker could also tether a number of the balloons together, using either flexible or rigid tethers, to obscure any motions of the balloon containing the warhead. The possibilities of this type are numerous. Thus, even if the defense saw signatures of the type that it would associate with a warhead inside a balloon, until it actually saw an interceptor kill vehicle impacting a warhead, it could not be sure the balloon contained a warhead.

Discrimination and Intercept During Early Reentry

As discussed above, by enclosing the warhead in a balloon and simultaneously releasing numerous empty balloons, the attacker could prevent discrimination by both infrared sensors and radars as the balloons travel through the vacuum of space in the midcourse part of their trajectory.

However, if the attacker took no other measures to prevent it, the X-band radars might be able to discriminate the balloon with the warhead from the other balloons early in the reentry phase of their trajectories by measuring the velocities and positions of the balloons.[21] Although for many purposes the atmosphere can be treated as negligible above altitudes of 100 kilometers, here we consider the possibility of discrimination at significantly higher altitudes. As the balloons descend through the atmosphere, the lighter-weight empty balloons would be slowed more by atmospheric drag than would the heavier balloon with the nuclear warhead. This effect is sometimes called "atmospheric filtering." If the effects of atmospheric drag on the decoys relative to the much heavier warhead became apparent at a high enough altitude, the defense might have enough time to attempt to intercept the warhead before it passed below the kill vehicle's minimum intercept altitude.

In general, the heavier the balloons, the lower the altitude at which they could first be discriminated.[22]

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[21] The ability of the upgraded early warning radars to accurately measure small velocity or position changes due to atmospheric drag will be far inferior to that of the X-band radars (see Appendix D).

[22] The discrimination altitude would also be lower the smaller the balloon was, but since the balloons must be able to contain a warhead, they could not be made too small. The behavior of an object during reentry is largely determined by its ballistic coefficient, $\beta = W/(C_D A)$, where W is the object's weight, A is its cross-sectional area perpendicular to its velocity, and C_D is the drag coefficient. At altitudes above where the mean free path of air molecules is large compared with the size of the balloons, the drag coefficient

For example, Figure 8-3 shows the change in velocity due to atmospheric drag of three balloons with masses 0.5, 5, and 20 kilograms relative to that of a balloon containing a 1,000 kilogram warhead, for altitudes less than 500 kilometers. In this case, the balloons are spheres with a diameter of three meters. For a lightweight 0.5-kilogram balloon, the velocity change due to atmospheric drag would be roughly one meter per second at an altitude of 250 kilometers. For a 5 kilogram balloon, the velocity change due to atmospheric drag would be roughly 0.1 meters per second at an altitude of 250 kilometers.

Figure 8-4 shows the change in position (along the trajectory) due to atmospheric drag of balloons of various weights (again relative to that of a balloon containing a 1,000-kilogram warhead), for altitudes less than 500 kilometers. For example, for the 5-kilogram balloon, the displacement due to atmospheric drag would be roughly 1 meter at an altitude of 275 kilometers.

Nevertheless, statements by BMDO officials make it clear that they are counting on being able to discriminate the warhead in midcourse and are not planning to use atmospheric filtering to discriminate it during reentry. For example, NMD Program Manager Maj. Gen. William Nance stated recently that the greatest technical challenge in getting to the objective system and being able to deal with "more complex countermeasures" was the step from the C1 to the C2 system.[23] Yet the transition from the C1 to the C2 system does not place any X-band radars in the lower-48 states or Hawaii. Thus, the C2 system would have no X-band radars that could observe the reentry phase of a trajectory aimed at the lower 48 states or Hawaii, and therefore could not even attempt to use atmospheric filtering to discriminate the warhead for such attacks.

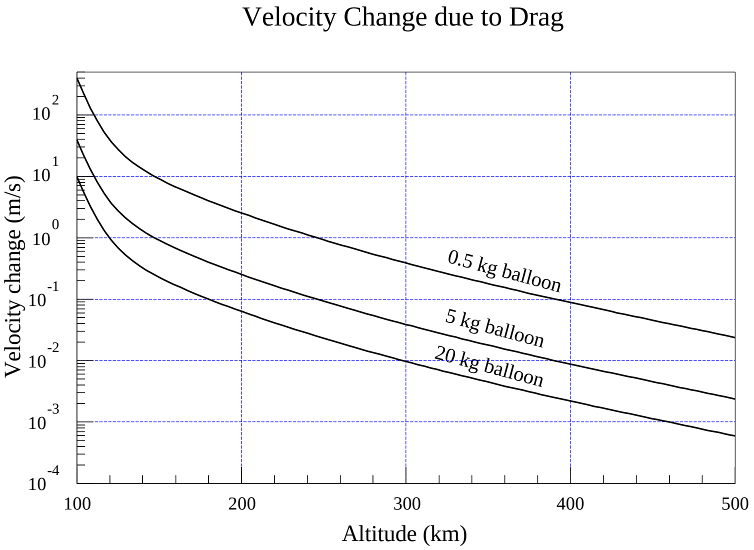

Figure 8-3. Velocity change due to drag.
This figure shows the change in speed due to atmospheric drag at various altitudes for three balloons with diameters of 3 meters and different masses, relative to the case of no drag. Since at these altitudes, the drag would have negligible effect on a heavy object like a nuclear warhead, these are effectively speed changes of the balloons relative to a warhead. The calculations assume the balloons are on a standard, 10,000-km range trajectory.

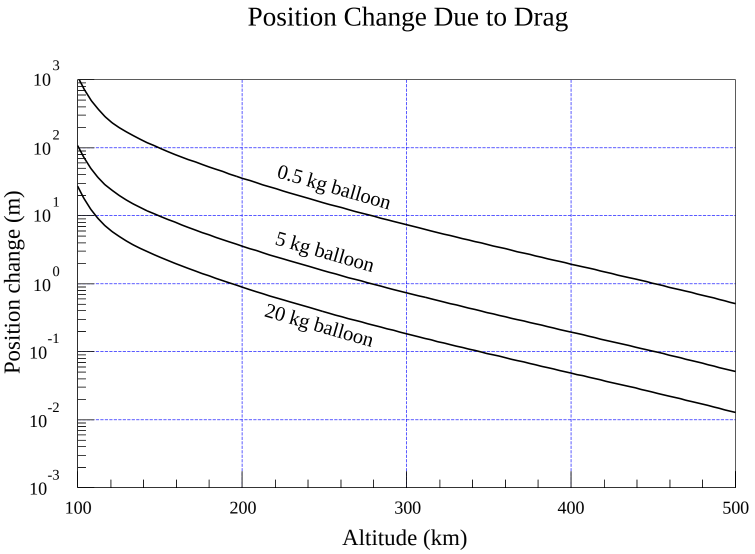

Figure 8-4. Position change due to drag.
This figure shows the change in position along the trajectory due to atmospheric drag for three balloons of different mass, relative to the case of no drag. Since at these altitudes, the drag would have negligible effect on a heavy object like a nuclear warhead, these are effectively changes in the positions of the balloons relative to a warhead. The calculations assume the balloons are on a standard, 10,000-km range trajectory.

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of the balloons would have a value of $C_D = 2$, independent of their shape. The mean free path of molecules in the atmosphere is several meters at 120 kilometers altitude.

[23] Michael Sirak, "A C1 to C2 Move Is NMD System's Most Stressing Upgrade, Says NMD Head," *Inside Missile Defense*, 3 November 1999, p. 10.

Another indication that the NMD system is not intended to discriminate using atmospheric filtering is that the X-band radars that are being built for the NMD system would have only a single face with a limited field of view (see below). A radar would therefore need to physically rotate to view balloons on widely separated trajectories as they neared the radar during reentry, which is when the radar would need to track them for atmospheric filtering. As a result, the radar would likely be unable to track balloons deployed by missiles on widely separated trajectories (such as those aimed at different cities). Thus, NMD X-band radars are not appropriate for a defense system designed to do atmospheric filtering.

It is not surprising that the United States is not planning to discriminate the warhead during reentry. For attacks against cities that are not located near one of the interceptor launch sites (which would include most US cities and the vast majority of the US population), the defense would have to launch its interceptors well before it could use atmospheric filtering to discriminate the balloon with the warhead, in order for the interceptor to have enough time to reach the intercept point. If the defense were able to discriminate the target from the decoys at a high enough altitude, it would then need to divert the interceptors in mid-flight once discrimination took place.

For example, for a North Korean attack on San Francisco, the interceptors closest to the reentry part of the trajectory would be those at Grand Forks, North Dakota.[24] It would take an interceptor at least 6.5 minutes to reach a potential intercept point near San Francisco. The defense could wait as long as possible to launch its interceptors by aiming at an intercept point just above the kill vehicle's minimum intercept altitude, say 150 kilometers. For a standard trajectory from North Korea to San Francisco, the balloons would be at an altitude of roughly 1,050 kilometers when the interceptors were launched (and at higher altitudes if North Korea used a lofted trajectory). If the defense wanted to attempt intercepts before the last possible second, the balloons would be at even higher altitudes when the interceptors would need to be launched. It would not be possible for the X-band radars to use atmospheric filtering to discriminate lightweight decoys from a balloon containing a warhead at such a high altitude, so the defense would have to launch its interceptors before it could distinguish the target from the light decoys.

The fact that the defense would have to launch its interceptors well before atmospheric discrimination could begin would present the defense with a significant problem. The defense would have to decide how many interceptors to launch and at what intercept point to launch them before it could know how many of the balloons the radars could filter out and at what altitude this discrimination would take place. Although the defense could determine the size of the various balloons in midcourse, it could not determine the weight of each balloon decoy, and hence the altitude at which it could potentially be discriminated, until reentry. The defense would also not know how much total weight the attacker could devote to decoys, since that would depend on what the payload capacity of the missile was and how heavy the warhead was. Moreover, if North Korea had a missile that could deliver a warhead to 11,000–12,000 kilometers, which would be required to reach targets throughout the United States, it could carry considerably more weight to the shorter ranges needed to attack targets in Hawaii or the western United States.

The attacker could use a mix of balloon weights, either by making some balloons from thicker material or by putting small weights inside lighter balloons. (Like the nuclear warhead, these weights could be attached to the balloon by several strings or spacers of the appropriate length.) The heavier balloons would reach lower altitudes before they could be discriminated than would the lighter balloons. The attacker would probably want to have a relatively large total number of decoys to prevent the defense from trying to intercept all the balloons in midcourse. At the same time, the attacker would probably want to have a number of heavy decoys that would be difficult for the defense to discriminate in reentry.

If we assume that a missile carrying a nuclear warhead could devote 100 kilograms of payload to the balloons, then the attacker could easily deploy dozens of balloons of various weights. For example, the attacker could deploy 3 dozen lightweight balloons each weighing 0.5 kilograms and each using a deployment mechanism weighing another 0.5 kilograms. It could put the nuclear warhead in one balloon, and then use the remaining payload to distribute roughly 60 kilograms of weights throughout other balloons. For example, it could use six 10-kilogram decoys or twelve 5-kilogram decoys, or a mix of both.

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[24] Although the trajectory might carry the balloons relatively close to the interceptor site in Alaska, they would then be at very high altitudes. Since the defense must rely on atmospheric filtering, the engagement must occur when the warhead is near San Francisco and thus closer to the North Dakota site.

Of course, the defense would not know how much of the payload the attacker devoted to decoys or what mix of balloon weights the attacker chose to use. But if the defense was planning to use atmospheric filtering for discrimination and saw dozens of balloons deployed from each missile, it would need to assume that some of these balloons would be heavy enough to deny discrimination above the kill vehicle's minimum intercept altitude.

To achieve the high effectiveness and confidence levels planned for it, the defense would need to err on the side of launching too many interceptors. Since the defense reportedly plans to fire up to four interceptors per target, if it made the reasonable assumption that a dozen or more balloons would remain viable decoys, the defense would have to launch several dozen interceptors per missile to have high confidence that it could prevent the warhead from getting through.

Thus, because the defense would need to launch its interceptors before it knew how many of the decoys would remain viable down to its minimum intercept altitude, it would need to fire a large number of interceptors at the balloons deployed by each attacking missile. Recall that the planned NMD system is intended to defend against an attack of tens of missiles from North Korea and other emerging missile states. Thus, the defense would still be in the position of choosing between letting the warhead penetrate unchallenged or running out of interceptors.[25]

For this reason, forcing the defense to abandon its preferred midcourse intercept strategy to operate in this "last chance" mode would use up a large number of interceptors and would significantly degrade the confidence in the defense effectiveness. Moreover, as we discuss below, the attacker has several ways in which it can exploit some of the limitations of the X-band radars to further complicate this defense tactic.

First, we consider what steps the attacker could take to prevent discrimination at altitudes that would be high enough to permit an intercept. Second, assuming the X-band radar viewing the reentry part of the trajectory was able to discriminate the balloon containing the warhead from the others, we consider what steps the attacker could take to prevent the radar from determining the *position* of the discriminated balloon accurately enough that this information would be useful to the kill vehicle, which must still home on the target using its own sensors.

Measures the Attacker Could Take to Prevent Discrimination. There are several measures an attacker could take to lower the altitude at which an X-band radar could discriminate the balloon containing the warhead from a balloon decoy. We discuss some of these below. The attacker could use some of these measures in combination with the others.

Denying High Precision Velocity and Position Measurements. As discussed in Appendix D, the X-band radars that would be part of the NMD system should be capable of making very precise measurements of the radial velocities of the balloons. Specifically, these radars would be able to measure the Doppler shift in the frequency of the radar return due to the radial component of an object's velocity. However, an X-band radar could not use Doppler shifts to measure the component of velocity in the direction perpendicular to the radar line of sight (i.e., the cross-range direction). The radar could measure the cross-range velocity of a balloon by plotting its angular position versus time, but because radars are limited in their ability to measure the angular position of an object, this method is generally less accurate.[26] Thus, an X-band radar would not be able to measure the cross-range velocity of a balloon as accurately as the radial velocity.

The X-band radars should also be capable of measuring the range to each balloon with high accuracy (see Appendix D). However, an X-band radar would

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[25] If the attacker had more missiles than nuclear warheads and was trying to force the defense to run out of interceptors, it might choose to use a missile to deploy only decoy balloons. A missile not carrying a nuclear warhead (and with a total payload of 1,000 kilograms) could deploy three dozen balloons with an average weight of 25 to 30 kilograms. Since the defense could not know that none of these balloons contained a warhead, it would have to assume that one did.

[26] While the radar would not be able to measure the cross-range position of a given balloon with high accuracy, it could possibly use ISAR (Inverse Synthetic Aperture Radar) techniques to image the collection of balloons and determine the position of the one containing the warhead relative to that of the other balloons (see Appendix D). However, since the collection of balloons—whether or not they were tethered together—would not be rigid, ISAR would be of very limited utility. Using the orbital motion to generate an ISAR image would take time, perhaps tens of seconds. A single image is only accurate in two dimensions, not three, although full three-dimensional imaging is (again in principle) possible if the radar makes two separate images with the right separation in angular aspects of the two images. If the attacker considers ISAR techniques to be a threat, it could take measures to thwart ISAR, including random motion of surfaces or appendages on the warheads and decoys, or random motion of the entire object (via

not be able to determine a balloon's angular (or cross-range) position with as great an accuracy as its range, even after tracking it for most of its trajectory.

Although the C3 NMD system would deploy up to nine X-band radars around the world, only some of these would be in a position where they could view the reentry phase of a missile trajectory that was targeted on the United States. Moreover, for attacks on most US cities, only one X-band radar would be in a position to view the reentry phase of the trajectory below an altitude of 400 kilometers. (See Table 8-2). Thus, the defense would have to rely on the measurements of one X-band radar to determine the velocity and position of the balloons during reentry.

The atmospheric drag would affect the total velocity and displacement along the trajectory of an incoming balloon, not just the components of velocity and displacement in the direction towards the radar. Therefore, unless the balloon was on a trajectory directly towards the X-band radar, the defense would need to estimate the total velocity of the balloon based on the radar's very accurate measurements of the balloon's radial velocity and its less accurate measurements of the balloon's cross-range velocity. Similarly, the defense would need to estimate the displacement along the trajectory based on its very accurate range measurements and its less accurate measurements of the balloon's cross-range position. The defense could attempt to use these velocity and position estimates for discrimination by comparing them with the values that would be expected for a balloon containing a heavy warhead and with those estimated for each of the other balloons. By making repeated measurements of the balloons and attempting to fit them to trajectories, the defense can reduce but not eliminate these uncertainties.

As discussed in more detail in Appendix D, the precision with which a radar could measure the radial velocity of an object depends in part on the characteristics of the X-band radar and how it was operated. For example, it would depend on the integration time chosen by the operator. Because some of these detailed characteristics about the X-band radars and how they would be operated are not publicly available, we cannot determine precisely the accuracy with which an X-band radar could measure the radial velocity of an incoming balloon. However, even if the X-band radar could measure the radial velocity *perfectly*, the limitations in how accurately it could measure the cross-range velocity would limit how accurately it would know the total velocity of a balloon. Similarly, even if the X-band radar could measure the range of a balloon perfectly, the limitations in how accurately it could measure the cross-range position would limit how accurately it could know the position of a balloon along its trajectory.

Table 8-2. The radar horizon for targets at different altitudes.

Because the earth's surface is curved, a radar would not be able to see a target at a given altitude if the target was further away than the corresponding radar horizon for that altitude. This table gives the radar horizon (the ground distance at which a radar could observe a target) for targets at different altitudes, assuming the radar can view an object 3 degrees above the horizon. For example, a radar would not be able to see an object at an altitude of 500 kilometers if that object was more than 2,250 kilometers from the radar (as measured on the ground.) Alternatively, the radar could only see an object at a distance of 2,250 kilometers from the radar if that object was at an altitude of 500 kilometers or greater.

Altitude of target (km)	Radar horizon (km)
500	2,250
400	2,000
330	1,800
250	1,500
200	1,300
150	1,100
130	1,000

From the defense perspective, these inherent measurement limitations would be least problematic for missiles on trajectories that approached the radar directly during reentry and worst for missiles on trajectories with a reentry that was perpendicular to the radar line of sight. Thus, the attacker could exploit these radar limitations by targeting cities not located directly in front of an X-band radar (of which there would be many). Doing so might be enough to prevent the defense from discriminating even relatively lightweight balloons at a high enough altitude to allow an intercept attempt. (See box.)

Nevertheless, the attacker might still choose to take other steps to lower the defense's discrimination altitude, as we discuss below.

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cold-gas thrusters). Either technique would deny the fine Doppler discrimination necessary for ISAR images. The motions of surfaces and appendages would not need to be large; amplitudes of a radar wavelength (about 3 cm) would be sufficient.

Exploit the Defense Geometry. The attacker could make atmospheric filtering more difficult by exploiting other defense weaknesses. As noted above, the planned NMD system may have a serious vulnerability since each X-band radar would have only a single face with a limited electronically scanned field of view of about 50 degrees in both azimuth and elevation. The radar would therefore need to rotate to view balloons on widely separated trajectories (with azimuths that varied by more than 50 degrees). One offensive tactic would be to launch two (or more) missiles, timed to arrive simultaneously, with one aimed at a target to one

The Velocity and Position Measurement Accuracy of an X-Band Radar

To what accuracy, in actual practice, an X-band radar could measure the location and velocity of an object is not publicly known. In this box we estimate limits on this accuracy based on general principles.

The discussion here assumes that the accuracy with which a radar can measure an object's angular position after tracking it for a period of time is roughly given by the radar beamwidth divided by 100 (see Appendix D, particularly equation (D-3), which for the NMD X-band radars would be roughly 2.4×10^{-5} radians, or 0.0014 degrees. Thus, for the discussion in this box, we assume the cross-range measurement accuracy would be approximately given by (2.4×10^{-5} radians) R, where R is the range from the radar to the object (not the ground range). The cross-range position uncertainty would increase with the object's range from the radar; for an object during reentry at a range of 500 kilometers from the radar, it would be roughly 12 meters. If the actual angular position measurement accuracy is less than or greater than the beamwidth divided by 100, these figures should be scaled accordingly.

Consider an object travelling on a trajectory at an angle γ with respect to the line of sight of the radar. At any given time, the radar could accurately measure the range to the object, but would measure its cross-range position with an uncertainty $R\,\Delta\theta$. Thus, the uncertainty in the object's position along its trajectory, ΔP, would be approximately $\Delta P = R \sin\gamma\,\Delta\theta$, where R is the range from the radar to the object. (This is easily seen when the object is travelling perpendicular to the line of sight of the radar, so that $\gamma = 90$ degrees, since ΔP is then just the full cross-range uncertainty in the position.) For a balloon reentering at an angle γ of 30 degrees or greater, the position uncertainty along the trajectory ΔP would be roughly 6 to 12 meters at a range R of 500 kilometers (when the balloon was at an altitude of 200 kilometers), and roughly 12 to 24 meters at a range R of 1,000 kilometers.[a]

Next consider the same object travelling at a velocity V and an angle γ with respect to the line of sight of the radar. At any given time, the radar can accurately measure the radial component of velocity V_r. We assume it can measure V_r perfectly. The defense then estimates the full velocity from this measurement by using $V = V_r / \cos\gamma$. But the value γ is uncertain since the defense does not know the object's trajectory precisely. The uncertainty in V due to the uncertainty in γ is thus $\Delta V = V \tan\gamma\ \Delta\gamma$. Since V is large, even a small $\Delta\gamma$ can lead to a significant uncertainty ΔV.

The uncertainty in determining the object's trajectory arises from the uncertainty in measuring its angular position. On the other hand, tracking the object over time and attempting to fit the measurements to a trajectory allows the defense with repeated measurements to reduce the angular uncertainty $\Delta\theta$ of the object's position to the value given above. Thus, the uncertainties $\Delta\gamma$ and $\Delta\theta$ are related, and we expect that they must be roughly the same size, or about 2.4×10^{-5} radians. Using this value of $\Delta\gamma$, a balloon reentering at a speed V of 7 kilometers per second would have a velocity uncertainty ΔV of roughly 0.1–0.2 meters per second for trajectories having γ equal to 30 degrees or greater.

Thus, the defense would have the most difficulty if the attacker targeted cities that were on trajectories that did not travel directly toward an X-band radar during reentry.

Moreover, these estimates suggest that the inaccuracy ΔP with which the defense could determine the position of a balloon along its trajectory may be great enough that the defense could not use position along the trajectory for discrimination. For example, the position uncertainty would be roughly the same size as the position change due to drag on a 5-kilogram balloon at 150 kilometers altitude (see Figure 8-4).

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[a] This assumes the trajectory is a standard one with a reentry angle of 23.5 degrees with respect to the earth.

side of the radar and the other at a target on the other side of the radar. For example, North Korea could launch missiles that were simultaneously targeted on San Francisco and San Diego, and Iran or Iraq could launch missiles that were simultaneously targeted on Boston and Washington. Depending on the speed with which the X-band radar (in California and Massachusetts, respectively) was able to rotate, it would lose time and might even be unable to observe the reentry portion of one of the two missile trajectories. For example, if the radar could rotate at a rate of 10 degrees per second, 15–20 seconds might be required to switch between the two targets.[27] In practical terms, this would likely force the radar to choose to observe only one of the targets during the critical reentry phase.

Cold-Gas Thrusters. Another option for the attacker would be to use small thrusters to speed up the empty balloons or slow down the balloon containing the warhead.[28] To avoid having to equip each decoy with its own thruster (and orientation system), the attacker could equip the warhead with such a thruster and then orient the warhead so that the thrust is along its velocity axis. Such a drag-simulating thruster could use cold gas to avoid being detected by infrared sensors. While this measure may sound difficult, small thrusters of the type that would be needed for this purpose would not be difficult to make or acquire and are certainly simpler technology than that required to make a long-range missile, which the attacker is assumed to have.

As noted in Appendix E, two decades ago Britain reportedly developed decoys with small liquid-fueled thrusters attached to compensate for the difference in atmospheric drag on light decoys and heavy warheads during reentry.[29]

Spinning or Oscillating Balloons. To create variations in the velocity and position of the surface of the balloons and thus mask the effects due to atmospheric drag, the attacker could spin the balloons as they were released. By using a balloon with an irregular shape, and/or attaching lightweight corner reflectors (which could be made out of aluminum foil) at random positions to the surface of a spherical balloon, the attacker would ensure that strong radar reflections would be generated by various parts of the balloon as it spun. The attacker could spin the balloons so that the surface velocities due to spinning would be large compared with the velocity changes due to atmospheric drag.[30] The X-band radar would then see a set of irregular time-varying Doppler shifts from each balloon that would mask the velocity change due to atmospheric drag. The irregularity and spinning would also mask the displacement of the balloons due to atmospheric drag. To enhance this effect, the attacker could even make irregular star-shaped balloons that had long points sticking out with corner reflectors attached to them. Constructing such balloons would not require high quality control since variations between the balloons would only add to the variation of the signals seen by the radar. Moreover, if the balloon was nutating or more generally spinning in a complicated way, which one would expect, this would tend to randomize the Doppler shifts seen by the radar.

Rather than spinning the balloons, the attacker could use lightweight springs to cause variations in the velocity and position of the surface of the balloons. For the balloons containing small weights or a warhead, the attacker could attach one or more springs between the weight (or warhead) and the balloon. The springs would remain compressed during most the balloon's flight, so that these balloons could not be distinguished from those without springs. A simple timer could then release the springs early in reentry. The springs would cause the balloon to oscillate irregularly around the center of mass. Using two springs with different spring constants attached to different parts of the balloon could produce a very complicated motion. The attacker could even add a small battery-powered motor to drive the springs if it was concerned about the oscillations damping during reentry.

As a result of simple measures like these, the radar would measure a time-varying spread of velocities and positions for each balloon. The irregularity in the

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[27] Ten degrees per second appears to be a typical rotation rate for such large radar structures.

[28] Richard L. Garwin. "The Future of Nuclear Weapons" presentation for the Second ISODARCO School, Beijing, China, April 1990.

[29] Robert S. Norris, Andrew S. Burrows, and Richard W. Fieldhouse, *Nuclear Weapons Databook, Volume 5: British, French, and Chinese Nuclear Weapons* (Boulder, Colo.: Westview Press, 1994), p. 113.

[30] A balloon with a diameter of 3 meters spinning at one revolution per second would have a maximum surface velocity due to the spinning of about 10 meters per second, whereas one spinning at 5 revolutions per second would have a maximum surface velocity of about 50 meters per second. In these cases, the difference in surface velocity between one edge of the balloon and the edge on the opposite side would be 20 and 100 meters per second, respectively.

Doppler shifts and the position measurements would keep the radar from being able to time average to find the small signal it was looking for. Thus, although the defense would be able to average out these effects to some degree, the attacker could deny the radar the extremely precise measurements that would be required for discrimination at high altitudes.

Tethered Clusters of Balloons. The attacker could tether together the balloons deployed by a missile in one or more clusters so that during the early part of reentry, the balloon containing the warhead would help compensate for the drag on the others in the cluster. Thus, tethering would reduce the change in velocity and position that the lighter weight balloons would experience due to atmospheric drag relative to the balloon containing the warhead. Even at an altitude of 200 km, the atmospheric force on a balloon with a diameter of 3 meters is less than 0.14 newtons (half an ounce) so the tethers would not need to have much structural strength. Moreover, if the decoys were spaced close enough together, then even if the radar could discriminate the balloon containing the warhead, it would not be able to spatially resolve the individual balloons in order to provide information to the kill vehicle as to which balloon was the target.

Exploit Defense Limitations in Determining the Target Position

Even if the X-band radars could discriminate the balloon with the warhead from the other balloons, the radar would need to convey this information to the kill vehicle in a form that would allow the kill vehicle to identify and home on the correct balloon. Ideally, the radar would create a three-dimensional "map" of the balloons, and the defense would then use this information to create a two-dimensional map of the balloons as seen by the kill vehicle.

However, the inability of radars to measure the cross-range position of an object with high accuracy means that a map an X-band radar constructs could have intrinsic ambiguities regarding the position of the objects it sees. Depending on the situation, these ambiguities could prevent the radar from being able to construct a map that the kill vehicle could use to identify the proper target.

More specifically, as we discuss above, an X-band radar viewing the reentry of a cluster of balloons would be able to determine that a given balloon was located at a certain range, but in the cross-range directions could only tell that it was located within a circular area perpendicular to that range. We will refer to that circular area within which the X-band radar can locate the object as the "uncertainty disk." The size of the uncertainty disk grows as the distance from the radar. If the balloons were close enough together and far enough away from the radar, their uncertainty disks would overlap so that the radar would not be able to physically distinguish the balloons in the cross-range directions. In this case, the radar could only distinguish different balloons by their range, but could not create a three-dimensional map of where the balloons were relative to one another.

The infrared sensor on the kill vehicle would not be able to measure the range to an object, but only its angular position. The ambiguity in the radar map would mean that in general, if the balloons were close enough together, the kill vehicle could not determine the position of the target using the radar map. This would only be possible for some cases, depending on the intercept geometry.

The optimal situation for the defense would be if the kill vehicle were approaching the object at roughly 90 degrees to the radar line of sight, in which case there would be no uncertainty in the cross-range positions of the two balloons as seen by the kill vehicle. The worst situation for the defense would be if the kill vehicle line of sight were the same as that of the radar, then the radar would simply pass on the uncertainty in the cross-range positions of the two balloons to the kill vehicle.

Thus, the attacker could make the map confusion problem worse for the defense by attacking cities for which the radar and kill vehicle lines of sight to the reentry part of the trajectory would not be close to 90 degrees during the reentry phase. The attacker could also choose to attack cities far from the radar so that the distance from the radar to the object would be large and the uncertainty in cross-range position would be large.[31]

We illustrate this problem in Figure 8-5 for a case in which there are only three balloons. However, the map confusion for the kill vehicle would increase as the number of balloons increased.

By considering a simple case with two balloons having their uncertainty disks centered on the radar line of sight we derive an estimate of when the radar map could be inadequate to determine the position of two balloons as seen by the kill vehicle. The condition is:

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[31] The attacker could even use cold-gas thrusters on some of the balloons, as described above, but oriented in random directions to create greater confusion during reentry.

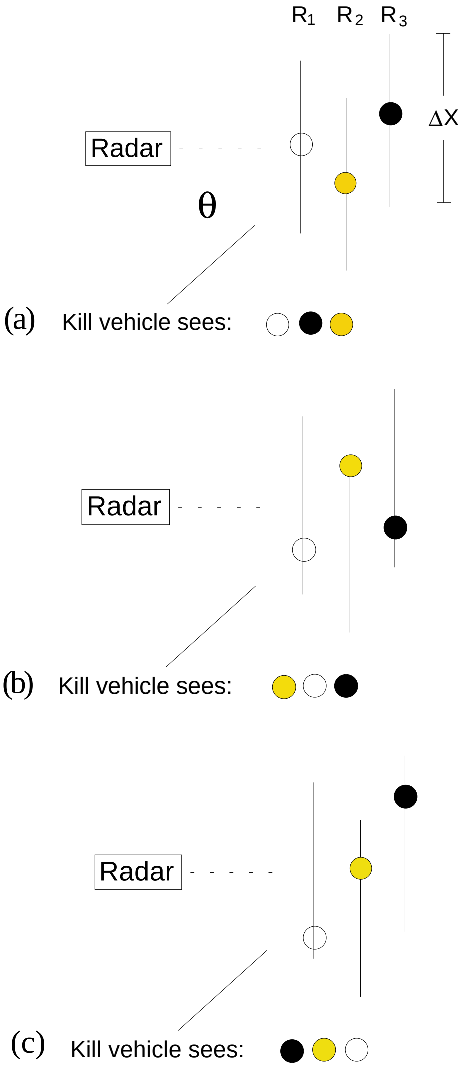

Figure 8-5. Radar map confusion for three balloons. *This figure shows a simple situation in which the radar observes three balloons, at ranges* R_1*,* R_2*, and* R_3 *from the radar. The balloons are distinguished by shading in the figure, but would be indistinguishable to the kill vehicle. The plane of the page is the plane containing both the radar line of sight and the kill vehicle line of sight to the target cluster. In this plane, the kill vehicle line of sight is at an angle* θ *with respect to the radar line of sight.*

The radar's best guess at the cross-range positions of the balloons is shown in (a), along with the uncertainty disk for each balloon. The uncertainty disks are shown here edge-on as lines with a length equal to the cross-range uncertainty ΔX*.*

But the balloons may actually lie anywhere on their uncertainty disks (and need not lie in the plane of the paper, since the disks are two dimensional). Figures (b) and (c) show other possible positions of the three balloons. As shown, the kill vehicle would see very different relative locations of the balloons in the three cases. Thus, even if the X-band radar could identify the balloon containing the warhead, it could not in this case construct a map that would allow the kill vehicle to identify that balloon.

$$\Delta R = (R_2 - R_1) \le \Delta X / \tan\theta = (2.4 \times 10^{-5}) \times R / \tan\theta \qquad (8\text{-}1)$$

where R_2 and R_1 are the ranges from the radar to the two balloons, θ is the angle between the kill vehicle and radar lines of sight, ΔX, is the uncertainty in the radar measurement of the cross-range position of the balloons, and R is the approximate range from the radar to the balloons.

Equation (8-1) shows that the position confusion could occur for any angle θ as long as $\Delta R/R$ was sufficiently small. The attacker could ensure that this ratio was small by tethering the balloons together. Note that ΔR is the component of the separation between balloons along the line of sight of the radar, and in general will be smaller than the physical spacing of the balloons. Assuming the cluster of balloons was slowly rotating, the ranges from the radar to the various balloons would change, and the range differences ΔR between pairs of balloons could get arbitrarily small as balloons rotated past each other. The potential for confusion would increase significantly as the number of balloons in the cluster increased.

To understand the effect of this position confusion on the defense, we consider several specific attack scenarios. We assume that all of the X-band radars planned for the full C3 system would be in place, and that interceptors could be launched from either of the sites in Alaska and North Dakota. We further assume that the radar would attempt to identify the warhead by atmospheric filtering, so that the intercept attempt would occur late in the trajectory. We look at the geometry of the intercept engagements, and determine what value of ΔR would lead to the confusion described above, and could thus prevent the kill vehicle from attempting to intercept the right balloon.

We find that for attacks from North Korea against Seattle or Los Angeles, such position confusion could occur if the range differences ΔR seen by the radar were less than about 10 meters.[32] The attacker could easily ensure this would be the case by tethering the balloons

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[32] For a North Korean attack on Seattle, the closest radar would be the one at Beale Air Force Base in Northern California (to be deployed as part of the C-3 system) and the interceptors could be launched from either Alaska or North Dakota. At an altitude of 150 kilometers, the slant range from the balloons to the radar is roughly 1,200 kilometers. For interceptors launched from North Dakota, θ would be approximately 70 degrees; for interceptors launched from Alaska, θ would be closer to 180 degrees. Thus, it would be to the advantage of the defense to use the interceptors launched from North Dakota. In this case, position confusion could occur if ΔR were roughly 10 meters or less.

together. We find a similar result for attacks from Iran or Iraq against Los Angeles.[33] For an attack from Iran or Iraq against Chicago, position confusion could occur if the range difference were less than about 40 meters.[34]

If the reentry of the balloons could be seen by more than one X-band radar, it might be possible for the defense to combine the position information provided by the multiple radars to construct a better map for the kill vehicle and to eliminate or reduce the position confusion discussed above. However, as discussed above, since we are considering engagements below about 400 kilometers altitude, for most target cities the balloons would only be in the field of view of one X-band radar (see Table 8-2).[35]

For a North Korean attack on Los Angeles, the closest radar would be the one at Beale Air Force Base in Northern California (also to be deployed as part of the C-3 system) and the interceptors could be launched from either Alaska or North Dakota. For interceptors launched from North Dakota, θ would be approximately 25 degrees, whereas θ would be approximately 45 degrees for interceptors launched from Alaska. Thus, it would be to the advantage of the defense to use the interceptors launched from Alaska. At the closest intercept point to the radar at Beale, the altitude of the balloon would be 250 kilometers and the range to the radar would be 390 kilometers. In this case, the kill vehicle would again be unable to distinguish between balloons if ΔR were roughly 10 meters or less.

[33] For attacks from Iran or Iraq against Los Angeles, the closest X-band radar would be the one at Beale, California. For interceptors from Alaska or North Dakota, θ would be roughly 50 degrees. At the closest intercept point to the radar, the balloons would be at an altitude of 250 kilometers, and the range to the radar would be roughly 470 kilometers. In this case, position confusion could occur if ΔR were roughly 10 meters or less.

[34] For attacks from Iran or Iraq against Chicago, the closest X-band radar would be the one at Grand Forks, North Dakota (to be deployed as part of the C-3 system). For interceptors from Alaska, θ would be roughly 30 degrees; and for interceptors from North Dakota, θ would be zero degrees, so interceptors from Alaska would have a better viewing angle. For an intercept at an altitude of 150 kilometers, the range to the radar would be roughly 1,000 kilometers. In this case, position confusion could occur if ΔR were roughly 40 meters or less.

[35] Adding a laser range-finder to the kill vehicle could address the problem somewhat. (While there are currently no plans to do this, the possibility has been discussed. See Sirak, "A C1 to C2 Move.") Doing so would allow the kill vehicle to make better use of the range information from the radar to reduce position ambiguities. For example, this would be the case if the kill vehicle and radar line-of-sights were parallel or antiparallel (θ = 0 or 180 degrees). However, we find that potential ambiguities would still exist for a range of angles θ, and that even with the additional information provided to the kill vehicle by a laser range-finder, it would be very difficult if not impossible for the defense to pass an adequate map for a large cluster of closely spaced objects.

Chapter 9

Emerging Missile State Countermeasure 3: A Nuclear Warhead with a Cooled Shroud

If a nuclear warhead were covered with a metal shroud cooled to a low temperature, then the range at which the infrared sensors on the kill vehicle could detect the warhead would be reduced. If the warhead is cooled to a low enough temperature, then the detection range can be reduced enough so that even if the kill vehicle is able to detect the warhead, it would not have enough time to maneuver to hit it.

As we discuss below, a thin metal shroud that is cooled by liquid nitrogen to a temperature of 77 K would be straightforward to implement above the atmosphere. The level of technology required for such a cooled shroud is very low relative to that required to build a long-range missile or a nuclear warhead. Such shrouded warheads would prevent hit-to-kill homing by exoatmospheric interceptors using infrared seekers and would thus defeat the planned US National Missile Defense (NMD) system.

The Design Details

Liquid nitrogen boils at the low temperature of 77.4 Kelvin (K) (–196 degrees Celsius). A metal shroud in contact with liquid nitrogen will thus remain at about 77 K until all the nitrogen has boiled away. Liquid nitrogen is widely used in research and engineering applications to maintain materials at a low temperature and is readily available (it can be produced by cooling air, which is about 78 percent nitrogen).

A warhead shroud that could be cooled to liquid nitrogen temperature could readily be made from aluminum. A simple design would be a double-walled cone-shaped shroud containing liquid nitrogen coolant in the cavity between the inner and outer walls. Since the warhead would give off heat, the designer would thermally isolate the warhead from the shroud to minimize the heat transfer to the shroud. The shroud could be attached to the warhead with pegs made of a material with low thermal conductivity, such as Teflon.

Multilayer insulation would be placed in the gap between the warhead and shroud to greatly reduce the heat transfer by radiation from the warhead to the shroud. Multilayer insulation, sometimes referred to as "superinsulation," consists of many layers of metallized plastic (such as thin sheets of mylar with aluminum evaporated onto the surface) with very thin spaces between the layers. (To the human eye, it appears similar to aluminum foil.) Multilayer insulation is available commercially and is a very effective insulator.[1]

A first generation nuclear warhead deployed by an emerging missile state would likely be large. We assume here that such a warhead could be contained in a cone with a base diameter of one meter and a height of three meters. The shroud would then be slightly larger than the warhead, which would be inserted through the open back end of the shroud.

Within this design concept, there would be many design choices available to the engineers building a shrouded warhead. For this discussion, we will assume that a pressure release valve in the base of the shroud would be used to control the gas pressure between the walls of the shroud as liquid nitrogen boils off into gas. One side of the pressure release valve would be attached to a tube that vents expended nitrogen gas through the shroud-base to space. To prevent this venting gas from producing a thrust, a simple T-shaped outlet nozzle could be used. The net force from gas leaving one end

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[1] The highly reflective metallized surfaces reduce the heat transfer by radiation with an effectiveness that increases geometrically with the number of layers. Multilayer insulation is punctured with many small holes to permit air to escape quickly in a vacuum, and the vacuum between layers greatly reduces heat transfer by conduction.

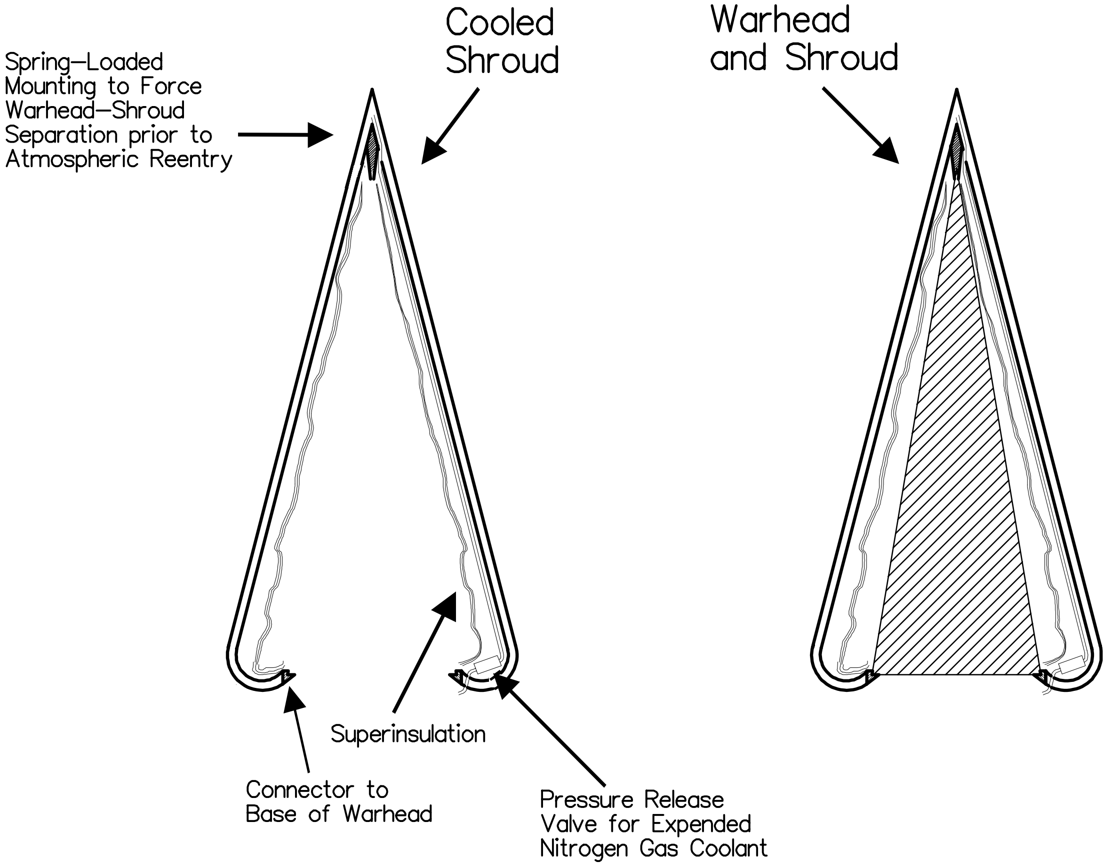

Figure 9-1. Schematic diagram of liquid-nitrogen cooled shroud.

of the T opening would be offset by the force from gas leaving the opening that points in the opposite direction. The other side of the valve is connected to a tube that transfers expended gas-phase nitrogen coolant from the shroud nose area. A schematic of such a cooled shroud is shown in Figure 9-1.

For this design, when powered flight was completed, standard techniques would be used to deploy the shrouded warhead so that it would be spin stabilized, rotating slowly around its axis of symmetry, and oriented in the desired direction. We discuss later in this chapter what orientations the attacker could use to control reflected infrared radiation from the Earth. The 1999 NIE concludes that countermeasure technologies such as “separating RVs, spin-stabilized RVs, and RV reorientation” are “readily available” to countries such as North Korea, Iran, and Iraq.

Since the shroud would be attached to a rotating stabilized warhead, centrifugal forces would confine the liquid-phase nitrogen coolant to the outer and lower regions of the shroud (see Figure 9-2). There would only be gas-phase nitrogen coolant in the tip of the shroud—where gas would be released through an aluminum tube connected to the pressure release valve in the base of the shroud. This design would therefore avoid the complicating problems of dealing with mixed phases of liquid nitrogen and gas in an environment with no gravity.

The shroud could be designed so that it could be removed from the warhead prior to reentry by a spring-loaded device or small gas generator behind the shroud-nose, which would be activated by a timer. Such a separation process is shown in Figure 9-3.

As noted above, a reasonable estimate for the size of such a conical shroud would be a base diameter of one meter and a height of three meters. Thus, the inner and outer walls of the shroud would each have a surface area of approximately 5 square meters—for a total surface area of 10 square meters. If we assume the walls of the shroud are a generous 1.5 millimeters thick (roughly 1/16 of an inch), then an aluminum shroud (with a density of roughly 2.7 grams per cubic centimeter) will weigh some 40 kilograms.

Such a shroud would require at most a roughly equal weight of liquid nitrogen coolant (40 kilograms) to chill it from room temperature (300 K) to liquid nitrogen

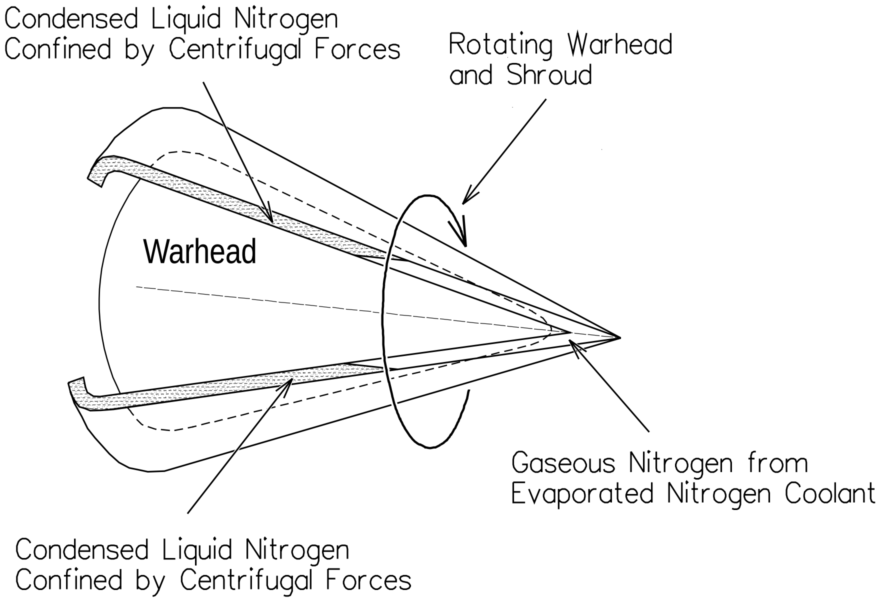

Figure 9-2. Spinning motion of warhead and shroud will confine liquid-phase nitrogen to outer and lower regions of the shroud.

temperature of 77 K.[2] As we calculate in Appendix I, about 200 grams of coolant per minute would then be required to maintain this temperature while the shroud is exposed to direct sunlight, sunlight reflected from the Earth, infrared radiation radiated by the Earth (earthshine), and heat radiated from the warhead through the superinsulation and the Teflon supports. Thus, about 6 kilograms of liquid nitrogen would be required to keep the shroud cool for 30 minutes, which is the flight time of an intercontinental-range ballistic missile. (If part or all of the warhead trajectory were not in sunlight, then less coolant would be required to maintain the shroud at a temperature of 77 K.) As we discuss below, the attacker would likely choose to use cooled shrouds on trajectories that are partially or completely in the Earth's shadow; for a trajectory completely in the Earth's shadow the amount of nitrogen required to maintain the shroud at 77 K would be about one kilogram.

For this discussion, we will assume that the attacker would begin to cool the shroud only after the missile was launched and was above the atmosphere in the vacuum of space. Although it would be possible to cool the shroud prior to launch, by waiting until the warhead is above the atmosphere, the attacker would avoid any potential problems associated with water freezing on the inside and outside of the shroud.[3] Once the warhead is above the atmosphere, the liquid nitrogen could be pumped into the space between the two walls of the shroud using gas pressure or a small pump. Until then, the nitrogen could be stored in a flat, cylindrical tank attached to the bottom of the warhead. While it would

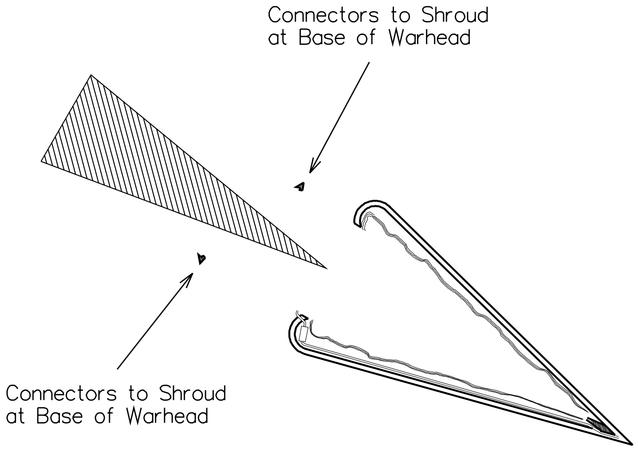

Figure 9-3. Prior to reentry, the shroud could be separated from the warhead using a spring-loaded device.

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[2] The specific heat of aluminum at room temperature is approximately 900 J/kg-K (Ray E. Bolz and George L. Tuve, eds., *Handbook for Tables of Applied Engineering Science*, Cleveland, Ohio: The Chemical Rubber Company, 1970, p. 96). Thus, to cool a shroud weighing M kilograms from a temperature of 300 K to 77 K would require (900)(223) $M = 2\times10^5\ M$ joules. Since the heat of vaporization of liquid nitrogen is approximately 2×10^5 J/kg (ibid., p. 74), then the amount of liquid nitrogen required to cool the shroud would be M. However, this calculation somewhat overestimates the amount of nitrogen required, since it neglects the decrease in the specific heat of aluminum as the temperature is decreased as well as any cooling effect of the gas-phase nitrogen. For example, the specific heat of aluminum at 77 K is about 330 J/kg-K (Y. S. Touloukian and E. H. Buyco, *Thermophysical Properties of Matter, Volume 4: Specific Heat–Metallic Elements and Alloys* (New York: IFI/Plenum, 1970), pp. 1–3.)

[3] If the attacker wanted to cool the shroud prior to launch, in order to prevent water from freezing on the shroud, the attacker would need to control the humidity in the warhead environment while the warhead remained in the atmosphere. One way to do so would be to house the warhead in an aerodynamic fairing flushed with or containing dry nitrogen.

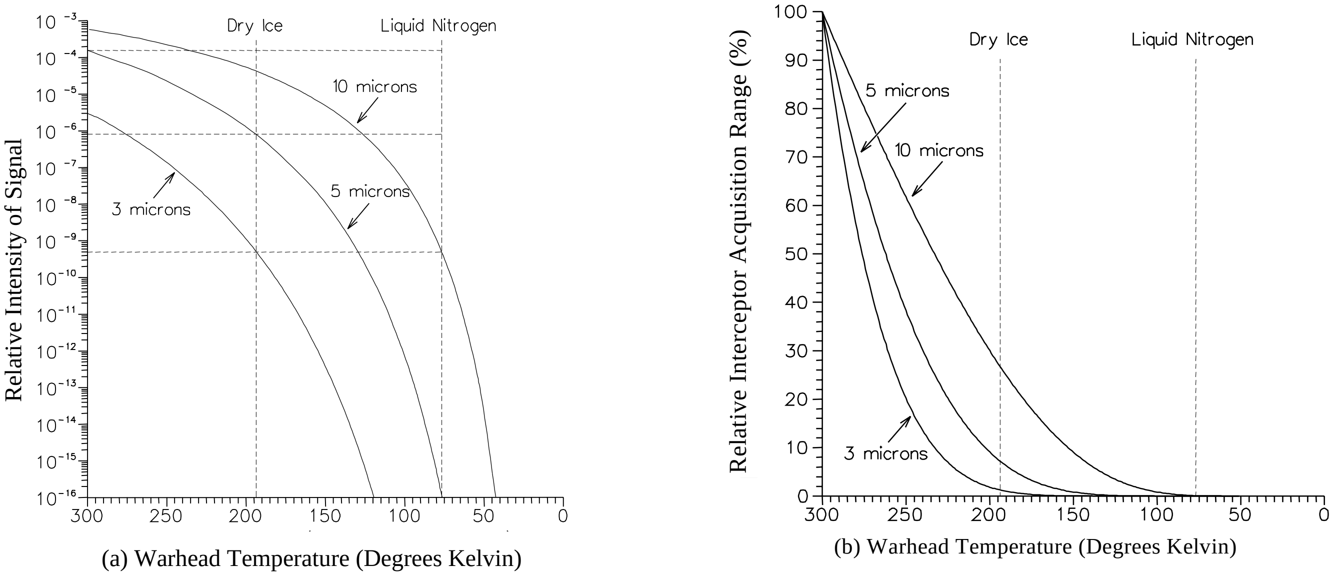

Figure 9-4. (a) Relative emission of a blackbody at three different wavelengths as a function of its temperature (b) The detection range as a function of warhead temperature, relative to the detection range of a warhead at room temperature.

take some minutes for the shroud to cool down to 77 K, it would be fully cooled before an interceptor could reach the shrouded warhead. (Although the SBIRS-low sensors would be able to detect the shrouded warhead until it had cooled somewhat, this would not help the defense.)

The total amount of liquid nitrogen needed to cool the shroud down to 77 K and maintain it at that temperature would be less than 46 kilograms, or about 58 liters of liquid nitrogen. This amount of liquid could be contained in a double-walled tank with a base diameter of 1 meter (to match that of the warhead) and a height of 8 centimeters. If made from 1.5-millimeter-thick aluminum, such a cylinder would weigh about 14 kilograms.[4] Thus, the total weight of the shroud, the liquid nitrogen coolant, and the nitrogen storage container would be roughly 100 kilograms. This would add about 10 percent to the payload for a first generation warhead weighing 1,000 kilograms. Thus, an existing missile could deliver a shrouded warhead of the same weight to a somewhat shorter range or a somewhat smaller and lighter warhead to the same range. For example, a missile that could carry an unshrouded warhead weighing 1,000 kilograms to a range of 12,000 kilometers could instead deliver a shrouded warhead to a range of roughly 10,000 kilometers.

Reduced Infrared Detection Range

The exact wavelength of the radiation that the infrared sensors on the kill vehicle will use is not publicly known. However, sensor arrays that detect infrared radiation at wavelengths of 3 to 5 microns (µm) that would be suitable for use on a kill vehicle are currently available, and sensor arrays that operate at a wavelength of 10 microns may now be available or may become available in the future. A shrouded warhead at liquid nitrogen temperature would radiate a 5-micron infrared signal roughly a trillion times (10^{12}) less intense than that of an unshrouded warhead (see Figure 9-4a). This means that if a kill vehicle's 5 µm sensor allowed it to begin homing on a room temperature warhead at a range of 1,000 kilometers,[5] it could only begin to home against a warhead with a cooled shroud at a range of about one meter! As Figure 9-4a shows, even if the NMD kill vehicle uses a sensor that can operate at a wavelength of 10 microns, the signal from the cooled shroud would be roughly a million times (10^6) less intense than that from an unshrouded warhead. In this case, the kill vehicle acquisition range would be reduced from 1,000 kilometers to 1 kilometer.

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[4] The surface area of a cylinder with a base diameter of 1 meter and a height of 8 centimeters is roughly 18,000 square centimeters. Aluminum has a density of 2.7 grams per cubic centimeter.

[5] This detection range may be generous to the defense. For the second sensor fly-by test, the Raytheon kill vehicle reportedly acquired the targets at a range of 700–800 km. (William B. Scott, "Data Boost Confidence in Kill Vehicle Performance," *Aviation Week and Space Technology*, 8 June 1998.)

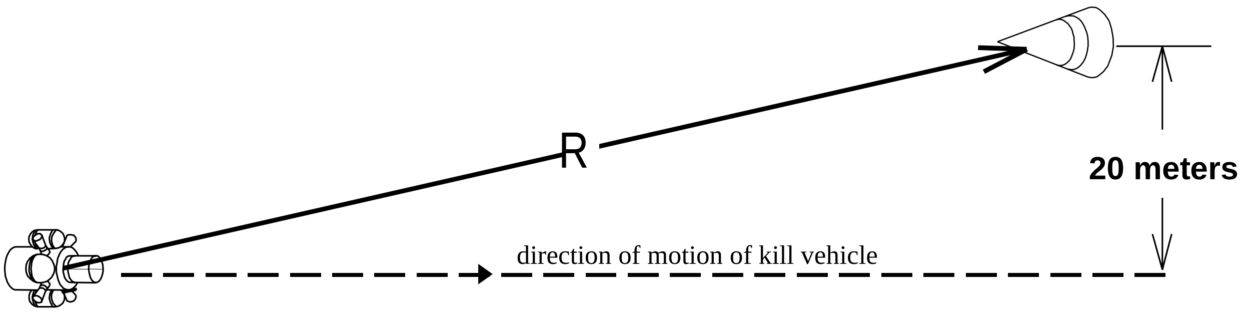

Figure 9-5. Assumed intercept geometry. Here the kill vehicle is moving in the horizontal direction to the right. When the kill vehicle first detects the warhead at a range R, we assume the lateral miss distance would be only 20 meters if the kill vehicle did not maneuver.

The implications of such a reduction in kill vehicle acquisition range are dramatic, as shown in Table 9-1. We assume that the NMD system—using data from the ground-based radars and SBIRS-low—is able to guide the interceptor booster to its basket with near perfect precision. Thus, we will assume that the lateral miss distance the kill vehicle would have to correct for once it acquires the target is only 20 meters. (See Figure 9-5).

An interceptor that begins to home on its target at a range of 1,000 kilometers will have roughly 100 seconds to maneuver laterally if the target and interceptor have a closing speed of 10 kilometers per second. Under these conditions, a lateral movement of 20 meters would require only a very small average lateral acceleration of 0.0004 g (where g is the acceleration due to gravity, which is approximately 10 m/sec^2). This is easily managed by the kill vehicle, which would likely have a lateral acceleration capability of a few tens of gs.[6] However, if the kill vehicle instead detects the target at a range of only 1 kilometer, the required average lateral acceleration would be 400 g, well beyond the capability of the kill vehicle, even assuming the interceptor responds instantaneously after detecting the target.

Table 9-1. The average lateral kill vehicle acceleration required for the kill vehicle to hit the target as a function of kill vehicle detection range (labeled "R" in Figure 9-5).
We assume a closing speed of 10 km/sec, and a lateral miss distance of 20 meters at kill vehicle acquisition.

Interceptor Acquisition Range	Closing Time	Average lateral interceptor acceleration required ($g \approx 10$ m/sec^2)
1,000 kilometers	100 seconds	0.0004 g
100 kilometers	10 seconds	0.04 g
10 kilometers	1 seconds	4 g
1 kilometer	0.1 seconds	400 g

If the shrouded warhead reduces the kill vehicle detection range to even several kilometers, for all practical purposes the probability of an intercept will be reduced to zero. With infrared sensors that detect radiation of 3–5 microns, the detection range would be reduced to about a meter; for 10-micron sensors, the detection range will only be about a kilometer. In either case, it is clear that the kill vehicle will have no chance of intercepting the target.

Detection Using Reflected Radiation

In addition to an infrared signal radiated by the shrouded warhead, there may also be a signal from infrared radiation or visible light that is reflected off the shroud. Such reflections from the shroud could be due to visible light coming directly from the sun or from sunlight that is reflected off the Earth. Since the Earth is an intense emitter of infrared radiation, the shroud could also reflect infrared radiation from the Earth. However, as we will show, an attacker can take measures to

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[6] Based on the kill vehicle's mass and fuel, we estimate its total ΔV to be about 1 km/sec. If we assume that it must have enough fuel for 10 seconds of thrust, the average acceleration would be 10 g.)

essentially eliminate the possibility that the kill vehicle could home on these signals.

Reflected Infrared Radiation. If the cooled shroud reflected all the Earth's infrared radiation that impinged on it, then the reflected infrared radiation would be comparable in intensity to that emitted by a warhead at room temperature.[7] Since the infrared absorptivity of aluminum is 0.03, the shroud would reflect almost all the infrared radiation that strikes it. If some of this radiation were reflected toward the kill vehicle, it might be adequate to permit the kill vehicle to home on it. However, a shroud made of polished aluminum would be a specular reflector. Like a mirror, it would reflect radiation at the same angle relative to the surface of the shroud that the incident radiation strikes the shroud.[8] As a result, for the type of shroud we consider here, there would be a broad range of directions into which the shroud will reflect no infrared radiation from the Earth.

To see this, consider a shroud with half-angle α at an altitude h above the Earth's surface and pointed straight down toward the Earth. In this case, it is straightforward to show that this shroud would not reflect radiation into a conical volume of half-angle θ, where

$$\theta = 180 - 2\alpha - \arcsin[R_e/(R_e+h)] \text{ degrees} \quad (9\text{-}1)$$

and R_e is the radius of the Earth (6,370 kilometers). This region lies below the warhead and is symmetric around the vertical direction. For a shroud with a base diameter of 1 meter and a height of 3 meters, the half-angle α would be 9.5 degrees. The region of no reflections would change with altitude since the angle at which radiation approaches the warhead from the Earth depends on altitude. For example, at an altitude h of 370 kilometers, the half angle θ would be 90 degrees and no infrared radiation would be reflected into the half space below the shroud, bounded by a horizontal flat plane. For a warhead at an altitude of 1,000 kilometers, the half angle θ would be 101 degrees (in this case, it is easier to think of the infrared radiation being reflected into a cone of half-angle 180 – 101 = 79 degrees, with the tip of the cone pointing down toward the Earth. For a warhead at 130 kilometers—the goal for the minimum intercept altitude of the NMD kill vehicle—the half-angle θ would be 82 degrees.

By tipping the shroud so that its axis is no longer vertical, the attacker could shift the orientation of the region of no reflected infrared radiation. In particular, the region could be rotated up so that it was no longer symmetric around the vertical and more of its volume faced in directions from which an interceptor might approach. Detailed calculations show that the shape of the region would distort somewhat from conical, but the region would remain very broad for tip angles of a few tens of degrees. For example, Figure 9-6 shows the boundary of the region of no reflection for a case in which the warhead is at an altitude of 1,000 kilometers and the axis of the warhead is rotated 10 degrees from the vertical. The warhead will reflect infrared radiation from the Earth only into directions lying in the region above this surface. When releasing the warhead

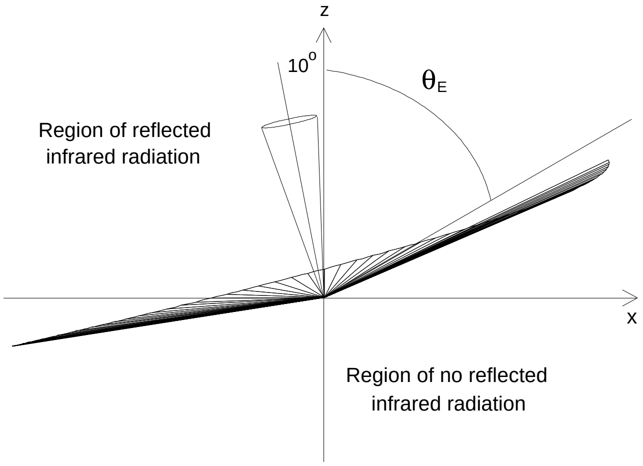

Figure 9-6. The region of no reflection for a tipped warhead.

This figure assumes the warhead is at an altitude of 1,000 kilometers, and the axis of the warhead has been rotated around the y-axis by 10 degrees from the vertical. The warhead will reflect infrared radiation from the Earth into those directions lying in the conical region above the surface shown.

At this altitude, a kill vehicle looking down at the warhead at angles less than θ_E = 59.8 degrees from the vertical would see the earth rather than space as a background.

Along the positive x-axis, the lower boundary of the region of no reflection lies at an angle that is less than 5 degrees greater than θ_E. Thus, a kill vehicle approaching the warhead from the right side of the figure would be able to see reflected radiation against a space background only if its direction of approach happened to fall within this narrow range of angles. This range of angles could be further reduced by using a tipping angle greater than 10 degrees.

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[7] The Earth infrared flux is about 240 W/m^2, and a 300 K blackbody emits about 280 W/m^2 over the 3 to 16 µm band.

[8] The attacker could easily cover the shroud with a thin layer of another material, such as polished gold, if it was concerned that the surface of the aluminum might not be sufficiently specular.

from the missile after boost phase, the attacker could orient the warhead to point the region of no reflection toward the directions from which interceptors would be approaching as they neared the warhead. The 1999 National Intelligence Estimate noted that emerging missile states must be expected to be able to spin stabilize warheads, which would allow such orienting.[9] Since the region of no reflection is very broad, the attacker would not need to orient the shroud with high precision.[10]

Reflected Visible Light. Although the kill vehicle will have a visible sensor to aid in target detection, as the system is currently configured, the final homing (during the last tens of kilometers) must be done using the infrared sensors.[11] In this case, any visible light reflected from the shroud could not be used to home on the warhead. We do not know if the current design can be modified to permit final homing using the visible sensor, but to eliminate the chance that the kill vehicle could home on visible light reflected from the shrouded warhead, the attacker can simply choose to attack at night (or more precisely, when the missile's trajectory would be in the Earth's shadow), much as Iraq chose to launch nearly all of its Scud missiles at night during the Gulf War. Since the attacker would presumably initiate the conflict with the United States, it would have considerable flexibility in choosing the timing of the attack.

Since the Earth's axis of rotation is inclined 23 degrees relative to the Earth's orbital plane, an emerging missile state would be able to attack some cities using trajectories that are entirely in the Earth's shadow at only certain times of the year, whereas other cities could be attacked year round using such nighttime trajectories. However, the entire trajectory would not need to be in the Earth's shadow, only the part where an intercept could occur.

For example, Figure 9-7 shows that in midwinter, North Korea could attack the entire United States using trajectories that are never sunlit, although attacking the east coast would require it to use trajectories that are depressed slightly below normal (about a 17-degree, rather than a 23-degree, loft angle).

Flying missiles on the kinds of modestly depressed trajectories considered here would not be difficult for a country that had a missile capable of flying on standard trajectories. Atmospheric forces during boost phase are not a problem since the missile can be flown on a standard trajectory until it is high enough that the atmospheric density is low and can then be turned onto a depressed trajectory.[12] Indeed, in its 31 August 1998 missile test, North Korea successfully launched its missile onto a significantly depressed trajectory.

Since the reentry vehicle on a depressed trajectory travels a longer path through the atmosphere during reentry, there are two other potential concerns: that the accuracy will degrade and that additional heating may be a problem. However, missiles deployed by emerging missile states would have very poor accuracy even on a standard trajectory, and the additional loss of accuracy would not be significant. Moreover, detailed calculations show that heating would also not be a problem.[13]

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[9] National Intelligence Council, "National Intelligence Estimate (NIE): Foreign Missile Development and the Ballistic Missile Threat to the United States Through 2015," unclassified summary, September 1999, p. 16.

[10] Even if the kill vehicle approached the warhead so that it viewed the warhead against the background of the Earth, the warhead would not be detectable as a cold spot against the warm Earth background. Until the kill vehicle was close to the warhead, the warhead would fill only a small fraction of a pixel on the kill vehicle seeker array, and thus would not produce a detectable reduction in the Earth background seen by that pixel. For example, if the seeker had a one-degree field of view and a 256 x 256 seeker array, a warhead would only fill about 2 percent of a pixel at a range of 100 kilometers and about 10 percent at a range of 50 kilometers (which would be about 5 seconds before a possible intercept).

In addition, at all angles of approach over which the kill vehicle could view the warhead against the Earth background, the warhead would reflect earthshine toward the kill vehicle. As Figure 9-6 shows, for a warhead at an altitude of 1,000 kilometers, a kill vehicle looking down at the warhead at angles less than θ_E = 59.8 degrees from the vertical would see the Earth rather than space as a background. Since the warhead reflects into those directions, this would further reduce the possibility that the kill vehicle could detect the warhead as a cool spot against the warm earth background.

[11] In the 18 January, 2000 intercept test, the kill vehicle failed to hit its target because the infrared sensors were not functioning properly. In this test, the final homing began at 6 seconds before the predicted impact time, and the closing speed between the kill vehicle and the mock warhead was 6.7 kilometers per second (Defense Department Background Briefing on Upcoming National Missile Defense System Test, 14 January 2000). Thus, the final homing—to be performed by the infrared sensors—began at a distance of roughly 40 kilometers from the target.

[12] This is discussed in detail in Lisbeth Gronlund and David Wright, "Depressed Trajectory SLBMs," *Science and Global Security,* Vol. 3, 1992, pp. 101–159.

[13] Calculations of reentry heating were conducted on 10,000-kilometer-range trajectories with reentry angles of

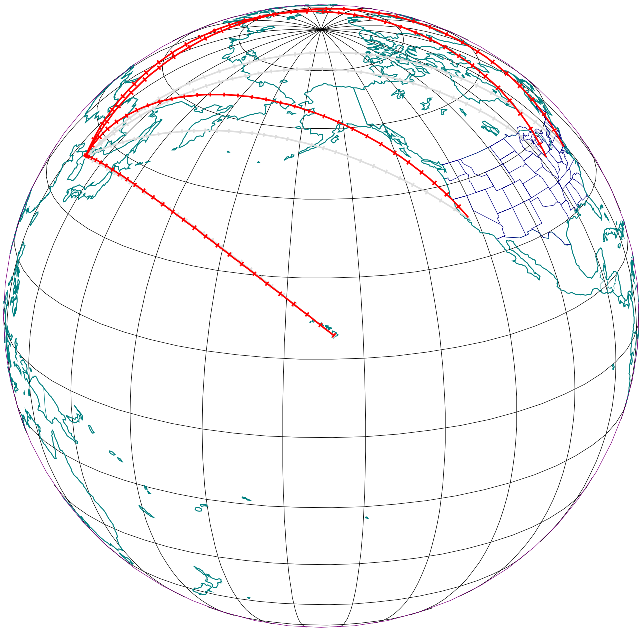

Figure 9-7. Trajectories from North Korea to New York, Chicago, San Francisco and Hawaii during midwinter (23 degree Earth inclination).
This shows the night side of the Earth (viewed from the same distance as the sun). This figure demonstrates that at this time of year all of these cities could be attacked by North Korea on trajectories that were entirely in the Earth's shadow. Keeping the trajectory to New York entirely in the Earth's shadow would require depressing its trajectory to a loft angle of 17 degrees. (The gray curves under the trajectories show the ground tracks of the missile.)

Finally, we note that the modest depressions of trajectories we consider here would lead to minimal loss of range.[14]

Figure 9-8 shows that during midspring or midfall, the west coast of the United States, as well as Hawaii and Alaska, could be attacked by North Korea on trajectories that are never sunlit, although a slight depression (20-degree loft angle) would be needed for the west coast.

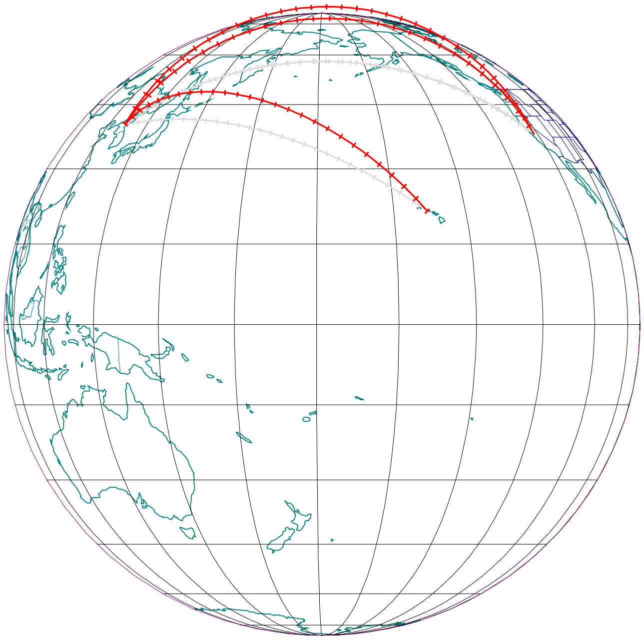

Figure 9-8. Trajectories from North Korea to San Francisco and Hawaii during midspring and midfall (zero degree Earth inclination).
Two trajectories are shown for San Francisco, one at a standard loft of 23 degrees (which will be partially sunlit), and one slightly depressed to a loft angle of 20 degrees (which would be entirely in the Earth's shadow).

Figure 9-9 shows that with some depression of trajectory (roughly a 19-degree loft angle), North Korea could attack Hawaii on a trajectory that is not sunlit even in midsummer.

Thus North Korea could attack Hawaii on nonilluminated trajectories at any time of year. With some depression of the trajectories, North Korea could attack San Francisco on nonilluminated trajectories for more than six months a year, and North Korea could even attack Washington, D.C., on a nonilluminated trajectory by using a more depressed trajectory (15-degree loft angle) for about one month a year during midwinter.

20° and 15°, and were compared to similar calculations on a standard, minimum-energy trajectory of the same range with a reentry angle of 23°. (These calculations used the method described in Appendix F.) The peak heating rate and total heat absorbed per area were calculated at the nose of the RV and on the wall of the RV at a point one meter behind the nose. These calculations show that the peak heating rates are actually less on the depressed trajectories than on the standard trajectory (by approximately 4% and 15% at the nose for the 20° and 15° cases, respectively, and by approximately 8% and 24% on the wall of the RV) since the RV's speed on the depressed trajectories is lower at the altitudes of peak heating. The total heat absorbed is somewhat higher on the depressed trajectories (by approximately 7% and 24% at the nose for the 20° and 15° cases, respectively, and by approximately 4% and 9% on the wall of the RV), since the duration of heating is somewhat longer. An emerging missile state could easily accommodate these increases by a modest thickening of the heat shield.

[14] Flying a missile with a maximum range of 10,000 kilometers on a depressed trajectory with a reentry angle of 20° rather than a standard trajectory with a reentry angle of 23° would only reduce the range by a few tens of kilometers, or by a few hundred kilometers for a trajectory with a reentry angle of 15°.

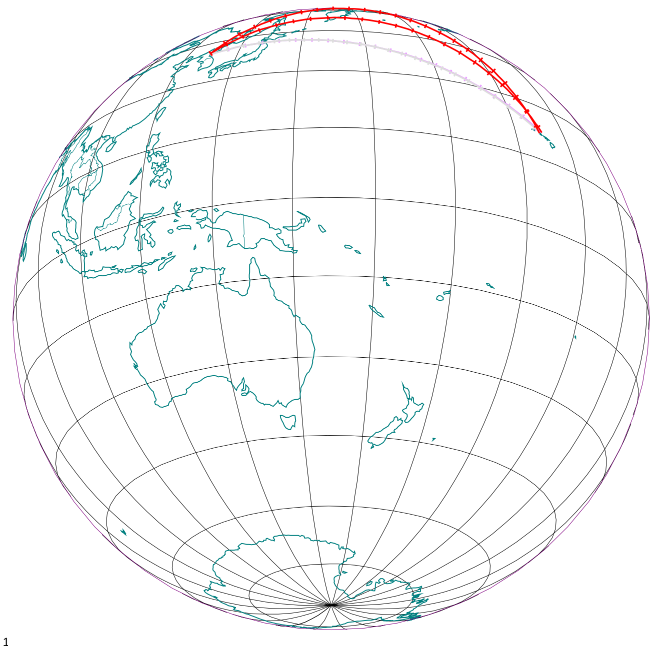

Figure 9-9. Trajectories from North Korea to Hawaii during midsummer (23 degree Earth inclination). Two trajectories are shown.
A slightly depressed trajectory with a 20-degree loft angle will be briefly sunlit, while one with a smaller loft angle of 15 degrees will never be sunlit.

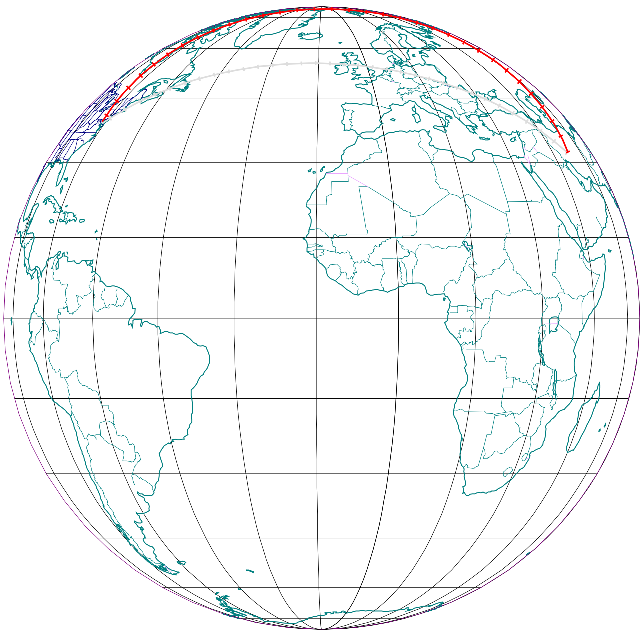

Figure 9-10. Trajectory from Iran to Washington, D.C., during midfall or midspring (zero degree Earth inclination).
A standard (loft angle of 23 degrees) trajectory will never be sunlit.

Figure 9-10 shows that Iran or Iraq could attack Washington, D.C., on trajectories that are not sunlit in midfall or midsummer, using standard trajectories (23-degree loft angle). With some depression of trajectories, these countries would be able to attack Washington, D.C., on trajectories that are not sunlit at least 8 months out of 12.

Reflected moonlight could, in principle, also be a source of visible light, although it is unlikely that this source is bright enough to be exploited by a homing kill vehicle.[15] However, if an attacker is sufficiently concerned about this source of illumination, timing the launch so that the moon is also below the horizon would address this concern.

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[15] The full moon is about 1/400,000 as bright as the sun, so its flux is about 0.0034 W/m^2. MSX's visible sensor (Appendix B) is said to be able to detect targets with reflectivity-area products of 0.1–0.35 m^2 viewed against a dark space background at ranges of "several times" 6,000 km. Since the kill vehicle's detection capability is likely to be at least several times poorer, assume it would be 6,000 km against such targets. If illuminated by full moonlight, this would correspond to a detection range of about 10 km. Thus we can make a very rough estimate of the kill vehicle's visual detection range as ranging from about 10 km for a very high emissivity (low reflectivity) shroud to about 30–40 km for a low emissivity shroud.