Time and Defense: The History of Defense Systems and Remarks on the National Missile Defense (NMD)

Gert G. Harigel
CERN, Geneva, Switzerland

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> ‘Our scientific power has outrun our spiritual power.
> We have guided missiles and misguided men.’
>
> Martin Luther King, Jr.

1 Introduction

The United States is in the process of building a National Missile Defense (NMD) system to counteract a possible attack by a small number of (intercontinental) ballistic missiles (ICBMs) against its mainland and to protect its allies. In this paper *political aspects* and consequences for arms control, entailed by such an NMD system, *will not be discussed*. Readers who are interested in this general aspect are referred to an earlier paper by the author [1].

Some major historical defense systems are described briefly in Section 2. Their efficiency and lifetimes may help one to draw conclusions for any future efforts to counter aggression. This study does not cover the cost of building and maintaining such structures, but the context could become a complementary and rewarding topic for an historian. Section 3 deals, on an elementary level, with defense in the boost, post-boost, mid-course, and re-entry phase against the attacking missiles, the way an incoming ballistic missile could or may be intercepted, and what kind of warheads play a role (nuclear, chemical, and biological). These warheads can be delivered on land- or sea-launched intercontinental ballistic missiles, or on land-, sea-, or air-launched cruise missiles. NMD does not aim, at least at the present stage, at the interception of cruise missiles. The objective of NMD is to explode the incoming warhead (or to change its course), by a head-on or peripheral collision or with a near-by explosion. Section 4 is linked to the main topic of the workshop, namely timing for a successful intercept, including the speed of incoming missile and the kill vehicle, and the correction of the latter's final trajectory. Section 5 evaluates a few of the many countermeasures that can be easily and cheaply implemented and would make the mid-course defense system impotent: jamming of ground-based radar systems, deployment of decoys, cooling of the missile, change of its trajectory during mid-course, and overwhelming the defense by building and using more missiles. As in any other modern development, aspects of classical physics for the success of the NMD play an important role.

There are no new technologies involved in NMD. All main ingredients are based upon what has been known and developed during the second half of the twentieth century. The problem in achieving the objective is rather the error-free handling of an enormous amount of data to determine the flight trajectory of incoming missiles and of the kill vehicle with sufficient precision during a short time interval. Firstly, geo-stationary satellites for optical/infrared recognition of the launch time and site are required to help to determine roughly the ICBM trajectory. Then, ground-based X-band radar, and a huge number of satellites in low orbit take over, equipped with heat sensors, to determine the missile's trajectory with precession and provide information for course correction of the kill vehicle in the final stage of approach. Experience gained in high-energy physics with tracking detectors can give a taste for the complexity of the task.

Proponents of NMD overlook the obvious possibility that an aggressor could transport warheads by cruise missiles or clandestinely on boats or aeroplanes much more cheaply to almost any target, making the NMD defense system worthless.

2 Lifetime and efficiency of defense systems throughout history

This is a timeless subject, for there has never been a time in history when some tribe or nation has not been contemplating actions and policies that lead to war or peace. Throughout history, struggles arose frequently between families, clans, small and large population groups, first about hunting ground for animals, then possession of arable land, and finally about mineral resources. Local fights spread with time to larger areas. First, fists and teeth were the main weapons, soon humans learned to prepare special tools for fighting each other. With the help of catapults, large stones were thrown at a target, and large flaming arrows became the predecessors of missiles. In parallel they developed means of body protection by armour, and surrounded their living quarters with fortifications. Each advance in offensive weapons was countered by defensive structures, mostly in this time sequence. At first all developments stretched over longer periods, but intervals became smaller and smaller with progress in technologies and science. It is the aim of this Section to describe briefly the major defense systems, culminating in the proposed Strategic Defense Initiative (SDI) popularly known as Star Wars, developed by President Reagan, who claimed that it would make all other weapons obsolete. This claim had already been made for other weapons at earlier times in history. Will the National Missile Defense idea do what is advertised, or will it lead only to a new arms race? Are we willing to learn from historical precedents?

The build-up of defense systems is as old as any offense activity. There is no defense system that could withstand attack forever, and no defense system is perfect at the start. To quote Hellmuth von Moltke: *Offence is the straight way to the goal, whereas defense is the long way around.*

A few such systems will be briefly discussed.

2.1 The Great Wall of China

The Great Wall of China can be considered as the longest-lived defense system. It stretched over a length of 6300 kilometres from the Yalu River (Gulf of Chihli) to Jiayuguan (Central Asia). It has been built and rebuilt over a period of almost 2000 years, beginning with the interconnection of walls which surrounded small kingdoms. The major construction periods start with the 4th century BC, were accelerated by the first Chinese Emperor Qin 220–206 BC, using almost one million compulsory labourers including some 300 000 soldiers. Maintenance work in the 7th century caused the death of half a million workers within ten days. A major upgrade was made during 1368–1644 in the Ming Dynasty (5660 km). The fortification consisted of a 9-metre high wall and about twenty-five thousand alarm towers 13 metres high. Signals could be transmitted over a distance of 2000 kilometres in 24 hours. During the Qin reign 180 million cubic metres of rammed earth provided the core of the wall (10 metres thick, 5 metres high). The aim of the Wall was to protect against the Huns. However, this fortification never performed properly as a defense line. In 1208 Genghis Khan broke through the Wall and China was liberated again only in 1368. In 1644 the Wall was opened by the treason of a general near Shanghaiguan, where it had the formidable height of 16 metres and a width of 8 metres. The Wall degraded and its remains are now only a tourist attraction.

2.2 The Roman *limes*

In comparison the Roman *limes* was a much less ambitious defense building. The best known part was in the western part of Germany spanning between the Rhine and Danube rivers. Building had been started in 9 AD, and it was reinforced between 117–161 AD. It had a length of 480 kilometres, and consisted of 3-metre high palisades and watch towers. It fulfilled its intended function only until 260 AD, when the Alemanni broke through. The Romans built similar *limes* in Great Britain, Anatolia, and Syria in the 2nd century AD, again with relatively short lifetimes.

2.3 Castles and city walls

Castles and city walls were the preferred fortifications for small city-states. Their efficient lifetime was at the best a couple of hundred years, before they were destroyed with the help of gunpowder, canons, and fireballs.

The metallic armour of mercenaries turned out to reduce mobility, could not protect the horses of the horsemen, and soon went out of fashion.

2.4 Defense lines in the 20th century

The lifetime of fortifications built in the first half of the 20th century decreased rapidly.

- The French Maginot Line connected some modern fortresses, which had held out during World War I. Built in the 1930s, it presented a tremendous advance over previous fortifications and offered all imaginable comfort for the defenders. It was built along the Franco–German border, but not extended to the Franco–Belgian border, the builders assuming that the Germans would respect the neutrality of Belgium and The Netherlands in any conflict. Germany did not behave as expected in World War II and its troops marched through the northern flank into France in 1940, attacking the fortifications from the rear side.

- The counterpart of the Maginot Line was the German Western Wall, a much less elaborate defense structure. It was not needed at the very beginning of World War II, but demonstrated some efficiency towards its end in 1945.

- Following the occupation of France in 1940 Germany built up the Atlantic Wall. Its major fortifications were built near the narrowest part of the English Channel, where it was expected that Allied troops would try to land. This turned out to be a miscalculation by the German headquarters combined with an underestimation of air-borne troops who could land behind the Atlantic Wall.

- Anti-aircraft canons, developed between the two World Wars, became increasingly worthless due to countermeasures in the form of chaff (aluminized paper) used in World War II, that distorted radar images and simulated planes where there were none. High-flying planes could only be reached with insufficient accuracy.

- Reagan's Star Wars programme did not get beyond a preliminary design study, since scientists showed that laser canons could neither produce nor send the desired energy density towards incoming missiles to destroy them.

The above examples show that time intervals are getting shorter between the building of new defense systems and the lifetime of their efficient use. This preliminary study of some major defense systems and their 'effective' lifetime has been made in order to find out if there is a pattern that might help to predict the performance of future developments. Any such development starts slowly, rises to maturity, and then declines in its efficiency. Rise and decline time may vary considerably from case to case, may have a steep rise and a slow decline, or vice versa, or may be Gaussian. A reasonable scientific description could be made by fitting the data by a Gaussian-like curve and defining the efficiency by the full-width at half-maximum (fwhm). This has not (yet) been done for the present study. Instead best estimates for the start-up and complete demise are given.

Figure 1 shows a plot (for convenience on a double logarithmic scale) of the useful lifetime of defense installations/methods over two-and-a-half thousand years as defined above. In this plot is indicated how each system became obsolete by whom or by which technical development. A straight line can represent the data. No effort has yet been made to evaluate error bars, to define the slope, and to represent this line by an equation.

Since this eyeball-fitted line represents so well the events during a very long period of human history, the temptation is great to extrapolate it into the future. Doing so leads to the conclusion that defense mechanisms will become obsolete almost immediately after having been put into place. Taking an extreme view, it could mean that the National Missile Defense would not even see the light of the day before being made obsolete by countermeasures. Only time will show the validity of our extrapolation.

2.5 Shift of warfare from ground to air

A change in theory and practice of warfare becomes obvious during the later part of the 20th century. Whereas the practice in earlier epochs was mainly composed of political, economic, and military elements, it is now increasingly influenced by technological, scientific, and psychological elements. In previous centuries the theory of warfare had been subdivided into a strategic part, considering wide spaces, long periods of time, large numbers of forces as a prelude to battlefield, and the tactical part, which was just the opposite to the former. The distinction between strategy and tactics has blurred since World War I (WW I) and especially during World War II (WW II). Surprisingly to the author, this distinction between strategy and tactical is still kept for nuclear weapons, and finds expression in the Strategic Arms Reduction Treaties (START I, START II) and in the Intermediate Nuclear Forces (INF) treaties.

Whereas warfare during WW I was mainly on the ground and at sea, and aeroplanes played only a secondary role for reconnaissance purposes, a dramatic shift occurred during WW II. Weapons systems reached further and beyond front lines.

Defense systems crumbled, anti-aircraft canons became militarily impotent during massive air raids. German V1 and V2 rockets reached their targets almost unimpeded on the British mainland. The only defense against these rockets in the forties was to bombard their launch pads. The recent Kosovo war demonstrated even more vividly that defense against planes, now flying at considerably higher altitudes, by anti-aircraft canons is a hopeless enterprise.

The second half of the 20th century witnessed a dramatic improvement in the rudimentary German WW II rocket technology, promoted on the other side of the Atlantic and now common knowledge in most industrialized countries. These missiles can transport nuclear warheads, and

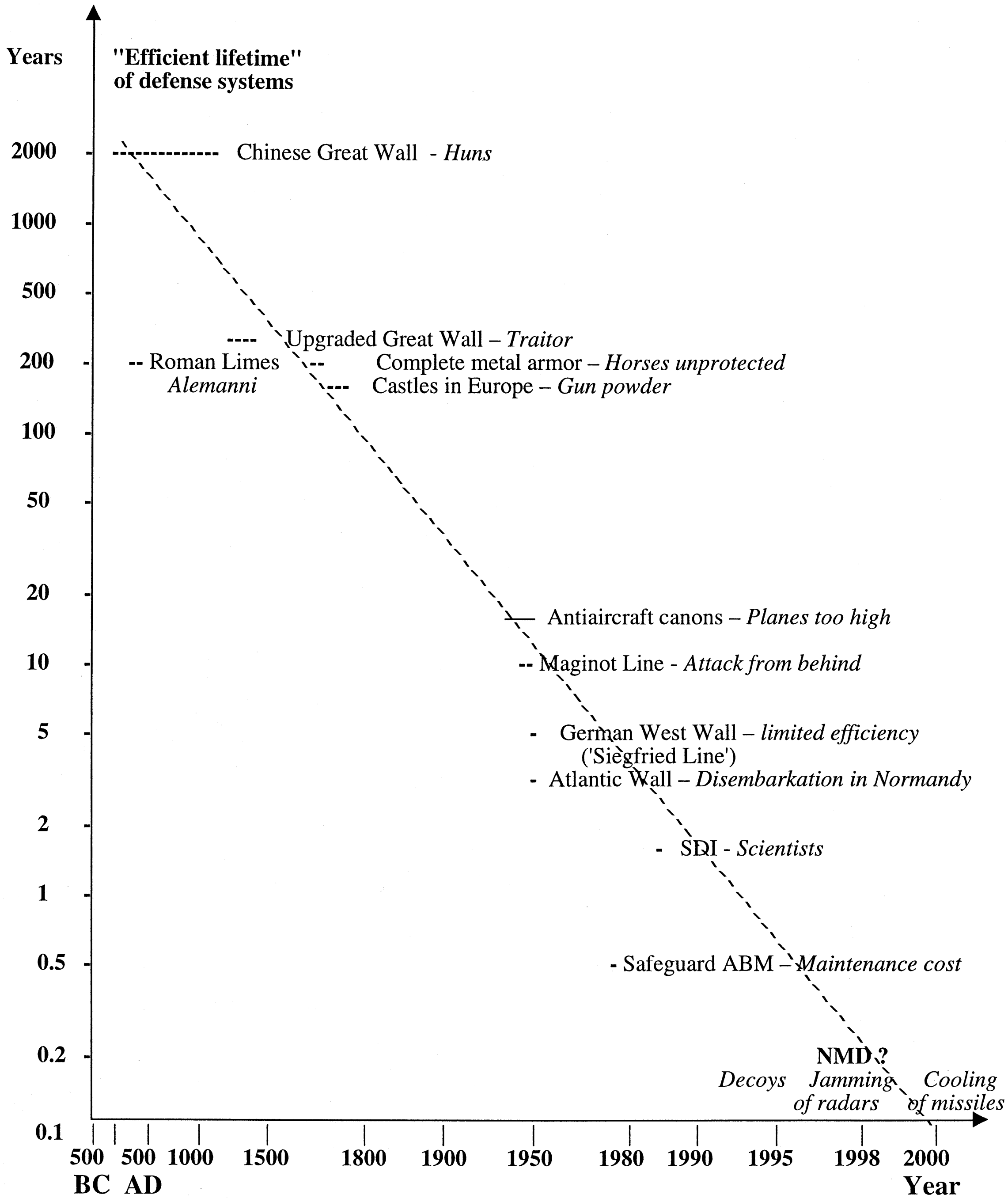


Figure 1: Efficient lifetime of defense systems throughout history [1]

of less military value, chemical and biological weapons [2]. A majority of people condemn these weapons, called Weapons of Mass Destruction (WMD), and demand their elimination. However, some countries believe they need WMDs, mainly nuclear weapons, for deterrence, but deny their possession for others. The escalation of the arms race during the Cold War led to the planning for comprehensive antimissile defense systems for both super powers. Fortunately, the Anti-Ballistic Missile Treaty (ABM), concluded in 1972, limited drastically, and still does, such an out-of-control development.

2.6 Missile defense activities since the 1980s

President Reagan's speech on 23 March 1983 was the starting point for the Strategic Defense Initiative (SDI).

Concerned, eminent scientists made feasibility studies, culminating in the 'Report to the American Physical Society of the study group on Science and Technology of Directed Energy Weapons' [3]. Soviet scientists made a similar study [4]. Both groups came to the conclusion that most of the systems would not work as advertised or even not at all. The latter is the case for space-based laser canon [5]. The software aspects cause another tremendous hurdle [6]. A discussion of the results of these two documents is beyond the scope of the present paper. The reader is referred to the original literature, which remains valid today.

A considerable amount of money was wasted during the years following Reagan's proposal. Deception of the public about supposed successes played a role in promoting SDI [7, 8]. However, for several years the topic no longer made any headlines. Public awareness was reawakened only during the first Gulf War (Desert Storm). Unfounded success stories and tests were then sold to the general public, who for the most part do not understand the basic science and technology behind such claims. During CNN broadcasts, the military commanders claimed a widely exaggerated success rate of the Patriot missile in shooting down Scud missiles coming from Iraq. The General Accounting Office found that only nine per cent of the Patriot–Scud engagements were supported by the strongest evidence that an engagement resulted in a warhead kill. The Patriot's supposedly near-flawless performance may be one of the greatest myths in weapons history. As Winston Churchill once said 'In war truth is such a precious good that it has to be surrounded by a strong bodyguard of lies.'

The Patriot was originally designed to shoot down aircraft. In the 1980s, it was given an upgrade and a modified warhead to give it a limited capability to defend against short-range ballistic missiles. The Scuds were flying over 3 600 km per hour faster than the Patriot had been designed to deal with. The Patriot must detonate when it is within a few metres of the Scud to have a high probability of destroying the warhead [9, 10, 11].

During the Clinton presidency SDI was revived, now under another name, as National Missile Defense (NMD). An excellent description of all aspects of NMD, written for the general public, can be found in Ref. [12]. NMD's task is advertised as a defense against a small number of missiles coming from rogue states (nowadays called countries of concern). NMD consists actually of two components: the Theater High Altitude Area Defense (THAAD) and the Ballistic Missile Defense (BMD). A shift of SDI from Directed Energy Weapons (DEW) to Kinetic Energy Weapons (KEW) occurred [13, 14].

NMD relies only partially on space-based laser canons, thus becoming more realistic than SDI. NMD is supposed to destroy warheads in mid-course by impact, but this policy may still change to the, in some respects easier, boost-phase intercept (BPI) [15, 16] but which might require an excessive amount of aeroplanes [17, 18]. Directed energy weapons are – again! – under development: Air Borne Lasers [19] and Space Based Lasers (SBL) [20].

NMD is planned to protect against both so-called theatre missiles and strategic (intercontinental) missiles.

3 The task of NMD: ICBM detection, launch of kill vehicle, engagement

General background information on missiles is given in ‘The Last 15 Minutes: Ballistic Missile Defense in Perspective’ [21].

The National Missile Defense Program against ballistic missiles launched from countries of concern faces challenges similar to those of a defense against an attack from the Former Soviet Union on the United States during the Cold War as far as timing and distances are concerned.

The boost phase of an ICBM typically lasts between 200 and 300 seconds. After the missile has achieved the required terminal velocity, the bus separates from the booster in the vacuum of space and begins to dispense its contents: the so-called post-boost phase of the missile’s flight once the boost is complete. By the end of this phase (between 400 and 700 seconds into the flight), the objects have an elliptical trajectory, influenced only by gravity. The payload travels at about 7 kilometres per second ($\sim$24 000 kilometres per hour), about 10 times faster than a rifle bullet, at an altitude of between 300 and 400 kilometres, far above the atmosphere. That relatively quiescent part of the flight lasts about 1000 seconds (roughly fifteen minutes). The fourth, so-called re-entry phase lasts only about forty seconds.

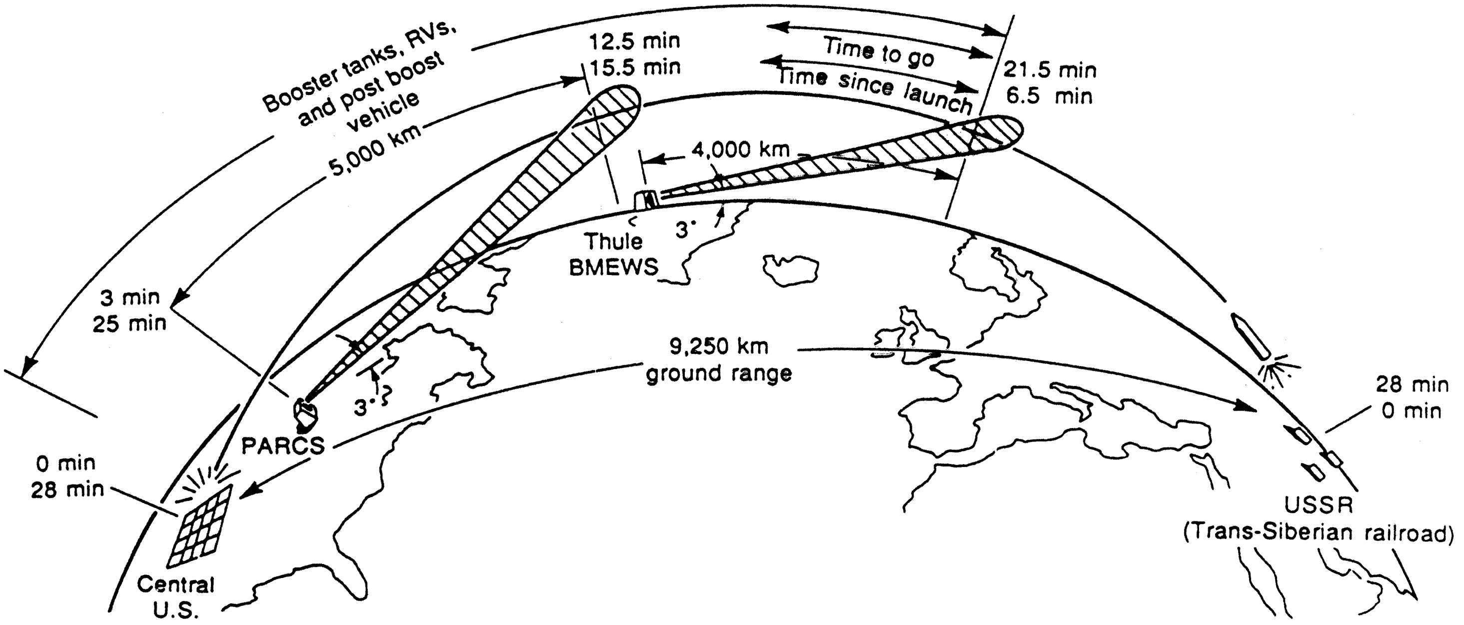
Figure 2 shows the main ICBM warning time lines and ranges, Fig. 3 the first 30 minutes in the standard scenario for an attack [22].

Intercept can be attempted in the boost (BPI), the mid-course (MCI) or re-entry (REI) phase. The present NMD aims at the mid-course destruction of the ICBM and will be the main topic of our discussion. The boost phase intercept might be cheaper, faster to realize, and a more reliable method against launches from small countries of concern [15]. However, it aims only at the destruction of the booster, leaving the harder to penetrate skin of the missile warhead intact. This warhead will follow closely the original trajectory. It would still do harm elsewhere and perhaps not far from the original target.

Ballistic missile warheads can reach altitudes of more than 1000 kilometres, and are very small (U.S. nuclear warheads are typically about 180 centimetres long and 45 centimetres wide at the base and resemble a large artillery shell). To successfully intercept a warhead, the kill vehicle (KV) must travel through the same 45-cm wide area of space during the same three-thousandths of a second. Since the collision speed of the interceptor with the missile exceeds 10 kilometres per second, the energy communicated in such a collision by the 50 kilograms or so of the interceptor seeker and structure is equivalent to the detonation of about 500 kilograms of high explosive [15]. Contact anywhere on the warhead would probably destroy it, not only knock it off course. If the kill vehicle contains an explosive, the space and time-condition for successful intercept is slightly relaxed for the defense. The use of nuclear explosives in the kill vehicle, as had been contemplated in the long ago abandoned Safeguard System, is no longer seriously discussed [16]. This system was intended to provide protection to Minuteman ICBM missile fields, Strategic Air Command bases, and the National Command Authority in Washington, DC.

The kill vehicle should come preferentially from a direction opposite to the flight path in order to have a reasonable chance of intercepting. If both are advancing in almost the same direction, the kill vehicle is at the disadvantage of time lapse between detection and its own launch. It would need a higher speed (10 km/s) than the attacking missile to reach its goal.

Approximate ICBM Warning Time Lines and Ranges[a]



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a. Assumes a 9,250-km ICBM flight of twenty-eight minutes, nominal 20° reentry angle, 3° elevation of beams above horizontal, and no limits on detection because of radar sensitivity (all objects within line of sight and more than 3° above the local horizon are detected).

Figure 2: Approximate ICBM warning time and ranges [22]

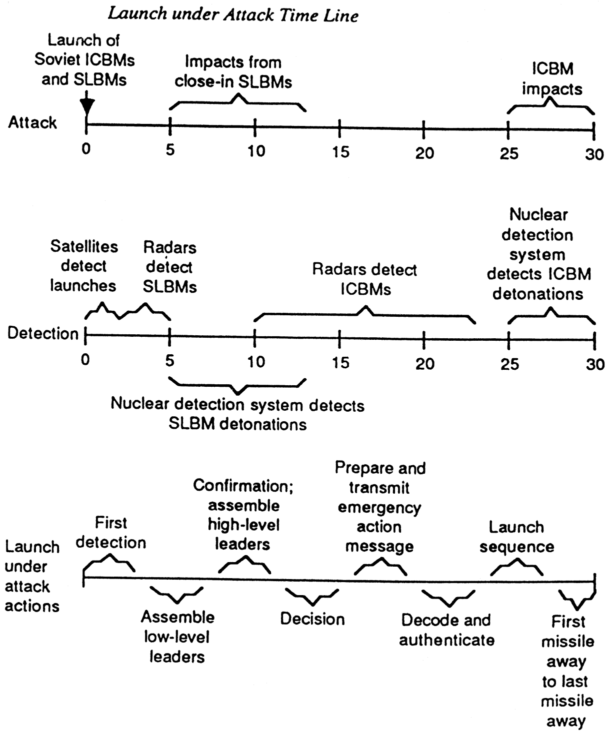
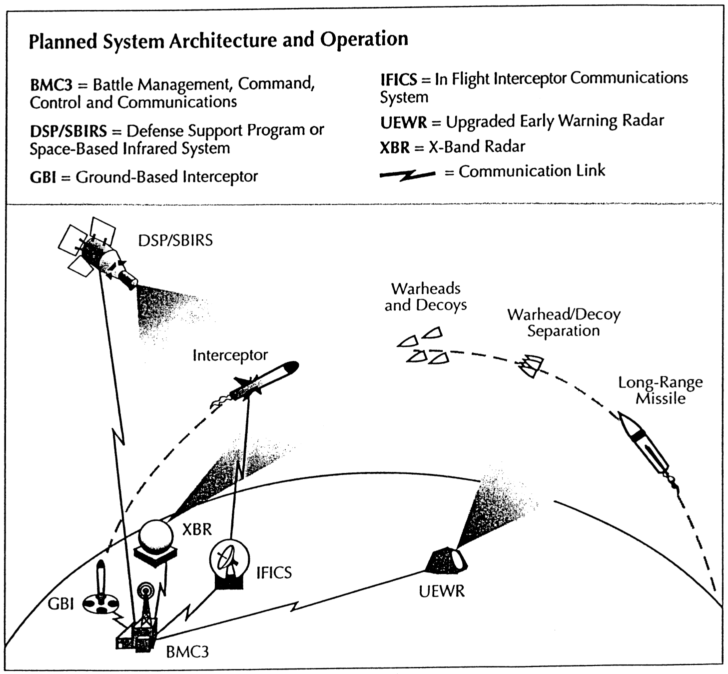


Figure 3: Launch under attack time line [22]

Figure 4 [23] shows schematically the planned system architecture and operation for the intercept.



Note: Locations in this figure are for illustrative purposes only and are notional.

Figure 4: Planned system architecture and operation [23]

3.1 Detection constraints: Geometry and time

Since an aggressor can launch a missile from anywhere on the Earth at any given time, a surveillance system is required that is permanently operational and covers the entire surface of land, sea, and even air space. The primary way to fulfil this task is to observe the light/heat signal coming from the rocket booster when the missile is launched. Only geostationary satellites are – or may be – up to this task. The sensor, which is at an altitude of almost 40 000 kilometres above the Earth's surface, consists of a line of thousands of light-sensitive spots that performs a rotary sweep in just 10 seconds. The sensor operates in the mid-wave infrared band, which is absorbed by water vapour in the atmosphere, so as to have the least interference from heat sources on the planet's surface. It is claimed that 'three detections at 10-second intervals are enough to provide a very accurate track in azimuth – that is in the direction of travel of the ICBM – and that there are enough DPS (Defense Support Program) satellites now in orbit that the states of concern could be viewed in stereo, by two satellites. This improves the timeliness by five seconds on average and provides greater reliability' [15]. Such an observation would provide the first – relatively precise – measurement of the ballistic trajectory. However, a particular target of the ICBM would not be known until after the ICBM burnout. The last 10 seconds of burn of a nominal ICBM with 250 seconds of burn time makes a difference of some 5 000 kilometres in the impact point. Figure 5 shows typical burn times for single-stage rockets, which depends on the intended range [24].

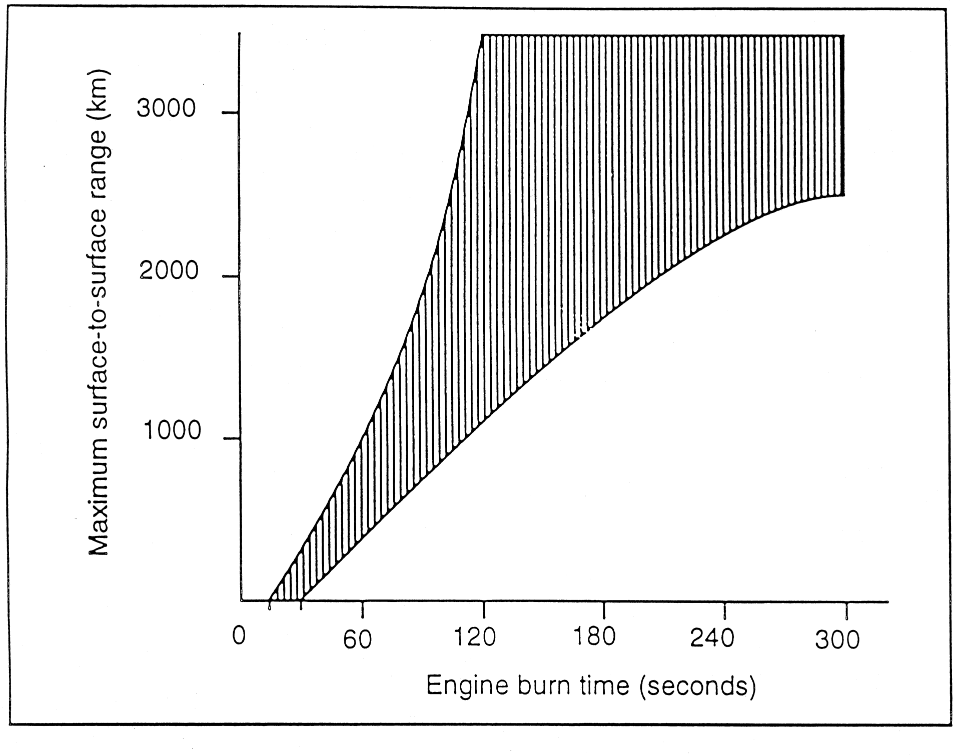


Figure 5: Typical engine burn times for single-stage rockets [24]

A number of ground-based, X-band radar stations would then have to take over to give further information on the trajectory and speed of the missile. Since these radar stations can not look beyond the horizon, additional information has to be provided from low-orbit satellites, equipped with various detector systems, among them radar and heat-sensitive devices (Satellite-based infrared sensors in low-Earth orbit, SBIRS-Low). The reconstruction of a curve in space needs at the minimum a system built from three observation points. More points give better redundancy, and they should not all be in one plane. The geometrical constants of such a system, where satellites move relative to each other with high velocity, have to be known with high precision at any given time.

3.2 The intercept, when and where? The consequences

An intercept can be envisaged during the boost, the post-boost, the mid-course (1000 seconds, about 15 minutes), or the re-entry phase. The first three options for intercept are retained by the U.S. Whatever the load the warhead contains, an encounter with a kill vehicle can cause two effects, which are rarely discussed in detail. Firstly, it can destroy the propulsion part in the boost phase, or – during the mid-course – a thruster. It can also destroy the warhead itself. Secondly, it could leave the warhead intact, but give an additional momentum to it, causing a deviation of its trajectory.

Can warhead destruction always be considered to be an advantage or can it have detrimental effects?

The destruction of the warhead will leave debris behind, which will essentially follow the original trajectory in exo-atmospheric space. The parts will hit ground somewhere. Since an intercept will happen at high altitude, chemical or biological material will be distributed over a wide space, irrespective of whether it is in a single warhead or still contained in a bunch of bomblets. These agents will probably not have severe effects on humans, since their density at ground level will not attain the critical value to cause adverse health effects. An exception might be made with plutonium, where negative long-term effects at ground level can be expected.

In case the warhead remains intact and its trajectory is changed in an unpredictable way, effects during landing at other than the originally targeted place may be advantageous or not for the attacked country.

3.3 Threat from type of warheads

Weapons attain more destructive power over time, as was the case with the switch from TNT to nuclear explosives. There is no longer a strong relation between power and number of weapons as in a classical war. In addition, the vulnerability of populations increases due to denser agglomerations.

NMD is advertised as an efficient means to protect the United States and its allies from weapons of mass destruction (WMDs). It assumes that the main threat will come from missiles, which could transport nuclear, chemical, or biological warheads. The author has argued that delivery of chemical and biological agents by ICBMs is inefficient and highly improbable [2]. There seems to be some convergence on this opinion regarding chemical weapons. However, there is still wide disagreement on the efficient use of biological weapons. It has been stated: 'Delivered to a typical U.S. city, which has 3000 people per square kilometre, a payload of 100 bomblets, each containing two kilograms of anthrax slurry, could be expected to kill some 100 000 people – compared with about 60 000 for a first-generation nuclear weapon, such as those used on Hiroshima and Nagasaki' [15]. Technological details of efficient delivery are kept secret. Figure 6 [25] shows that bomblets can be protected against excessive heating during the re-entry phase. This topic will be further discussed below in the section on countermeasures.

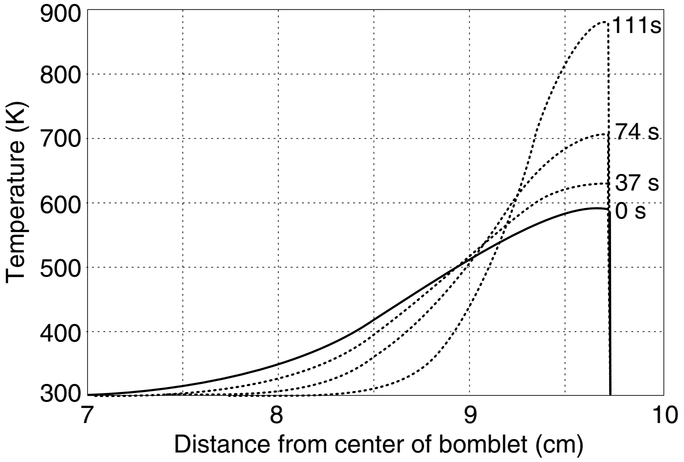


Figure 6: Re-entry heating of bomblets [25]

ICBMs that can transport nuclear warheads present a potential danger. However, the nukes are becoming so compact that countries of concern or terrorists can choose many other ways for their transportation.

4 Determination of trajectories and timing of intercept

The NMD complex currently planned has six distinct parts, all of which must perform perfectly if the system is to succeed [26, 27]. These elements are:

1) The initial launch detection and tracking system.
2) Five ground-based early warning radars (GBRs).
3) Four X-band (high-frequency, short-wavelength) radars whose function is to discriminate between incoming real warheads and decoy missiles (about 10 locations are envisaged in the full configuration by 2011, Table 1, [25]).
4) Interceptor booster, a very fast rocket which carries the exo-atmospheric kill vehicle (EKV).
5) Exo-atmospheric kill vehicle, whose on-board computer processes updates on the location of the hostile missile after the EKV has separated from the booster. The combined closing speed of the target and the interceptor is some 24 000 kilometres per second.
6) The Battle Management, Command, Control, and Communication (BMC^3) network. A critical sub-element of BMC^3 is the In-Flight Interceptor Communications System (IFICS).

A seventh element, a constellation of 24 low-orbit SBIRS satellites, is to be added later to improve launch detection and warhead–decoy discrimination.

Assuming that the trajectory of the ICBM has been determined during the boost phase and the end of the post-boost phase has been established with high precision, then the direction and speed of the ICBM are known to the laws of ballistic movement. They will remain known provided the warhead does not have a thruster to change the mid-course direction and speed.

During this approximatly 10 minute flight time the interceptor will have been launched, without having the final data, so it has a minimum chance to intercept if it does not have in-flight manœuvrability.

The endgame phase of an intercept begins when the infrared (IR) sensor built in the interceptor's kill vehicle (KV) acquires the target. The distance between the KV and the target at the beginning of the endgame is the so-called acquisition range (AR). During the whole endgame phase, the KV manœuvres according to the target's trajectory information provided by the IR sensor in order to put itself on a path that leads to a direct hit with the target. To make a hit, enough endgame time, which is to say large enough acquisition range, is needed for the KV to correct its current velocity and position errors.

Table 1: Preliminary NMD architectures [25]

	Initial configuration	Full configuration
Planned deployment date	2005–7	2011
Number of interceptors deployed in Alaska	100	125
Number of interceptors deployed in North Dakota	0	125
Upgraded early warning radars	Beale (Marysville, Calif.) Clear (Alaska) Cape Cod (Massachusetts) Fylingdales (England) Thule (Greenland)	Beale Clear Cape Cod Fylingdales Thule South Korea
X-band radars	Shemya (Alaska)	Shemya Clear Fylingdales Thule Beale Cape Cod Grand Forks (N. Dakota) Hawaii South Korea
Satellite-based infrared sensors in low-Earth orbit (SBIRS-Low)	No	Yes

5 Countermeasures

First tests of the Ballistic Missile Defence (BMD) were very far from successful [28]. Will the BMD system be effective? The question can only be answered in the form 'Will it work against what?' The answer will depend among many other questions to be solved on the effect of countermeasures. Comprehensive studies are being made by a Study group organized by the Union of Concerned Scientists and the Security Studies Program at the Massachusetts Institute of Technology [29, 30].

The kill probability (KP) is one of the key technical parameters for evaluating the effectiveness of a missile defense system. The higher the kill probability, the more effective the defense system will be. Inevitably, a missile defense system will be challenged by countermeasures, which may decrease the kill probability. There are three different kinds of them against a THAAD system: infrared stealth, radar interference, and decoys.

5.1 Infrared stealth, aerosols

There may exist several kinds of countermeasures against IR sensors. Amongst these is a common one known as IR stealth to shorten the acquisition range to an unacceptable level. For a given IR sensor and background noise, the acquisition range depends mainly on temperature, material, and sizes of the target. The most effective way of realizing IR stealth is to chill the target to a low temperature since IR radiation decreases quickly with temperature. Dry ice (195 K), liquid nitrogen (77 K), or various Freons can do the job by being filled into the space between the shroud and thermally insulated layers [29, 31].

The effect of IR stealth on KP on the acquisition range can be calculated [29, 31]. This acquisition range of an IR sensor can be approximated by [32]

$$R = \left(\frac{A_{\text{optics}}}{4\pi F_{\text{L}}} \cdot \frac{\Phi_{\text{source}}}{\Phi_{\text{D}}} \right)^{1/2}$$

where:

A_{optics} is the area of the optical system, F_{L} the loss factor of IR radiation,
Φ_{source} the radiation power in the sensor detectable spectrum emitted by the target, and
Φ_{D} the radiation power detected by the IR sensor.

Φ_{source} is given by:

$$\Phi_{\text{source}} = \epsilon A \int_{\lambda_1}^{\lambda_2} \frac{2\pi hc^2}{\lambda^5} \frac{1}{\exp(hc/k\lambda T) - 1} d\lambda \ ,$$

where:

ϵ is the emissivity of the target, A the area of the target's IR radiation,
λ_1, λ_2 the lower and upper limit of wavelength for the sensor, respectively,
h the Planck constant, k the Boltzmann constant,
c the speed of light, and T the temperature of the target.

The maximum acquisition range RD is achieved when Φ_{D} is the minimum detectable power of the IR sensor:

$$R = \left(\frac{A_{\text{optics}}}{4\pi F_{\text{L}}} \frac{\Phi_{\text{source}}}{NEP \cdot SN_{\text{min}}} \right)^{1/2}$$

where:

SN_{min} is the minimum detectable signal-to-noise ratio,
NEP the noise equivalent power, which can be approximated by:

$$NEP = \frac{(A_D \cdot B)^{1/2}}{D^*}$$

where:

A_{D} is the effective area of a sensor's detector element [33], B the bandwidth,
D^* the detectivity, which represents the performance of the sensor.

Thermal noise is mainly IR radiation coming through the window [34]. Since THAAD IR sensors work in a low temperature environment

$$D^* = \lambda_2/2hc \cdot (\eta/\pi c)^{1/2} \left(\int_{\lambda_1}^{\lambda_2} \frac{\epsilon_1}{\lambda^4} \frac{\epsilon_1}{\exp(hc/k\lambda T) - 1} d\lambda \right)^{1/2} \cdot \sin^{-1} \Theta$$

where:

η is the quantity effectivity, Θ the view angle of the sensor, and
ϵ_1 the emissivity of the window material.

For the THAAD IR sensor and a target of 1 metre in diameter, the following parameters were used for the simulation: $A_{\text{optics}} = 7.85 \cdot 10^{-3}$ m^2, $F_{\text{L}} = 2, \epsilon = 0.8$, $A = 1$ m^2, $\lambda_1 = 4$ μm, $A_{\text{D}} = 11 \cdot 10^{-8}$ m^2, $B = 100$ Hz, $SN_{\min} = 10$, $\eta = 0.6$, $\epsilon_1 = 0.2$, $\Theta = 3$ degrees.

Figure 7 [31] shows the acquisition range as a function of warhead for an infrared wavelength of 4 μm, which goes down from 120 kilometres at 300 K to not more than 1 metre at liquid nitrogen temperature. The total time of flight (TOF) to cover this range is less than 1 ms for a target with 5 km/s velocity if the KV's speed is 2.7 km/s. The TOF gets proportionally smaller for ICBMs and their intended KVs. Figure 8 [25] shows the detection range as function of warhead temperature, relative to that of a warhead at 300 K, for three other infrared wavelengths (3, 5, and 10 microns) that might be used by NMD sensors.

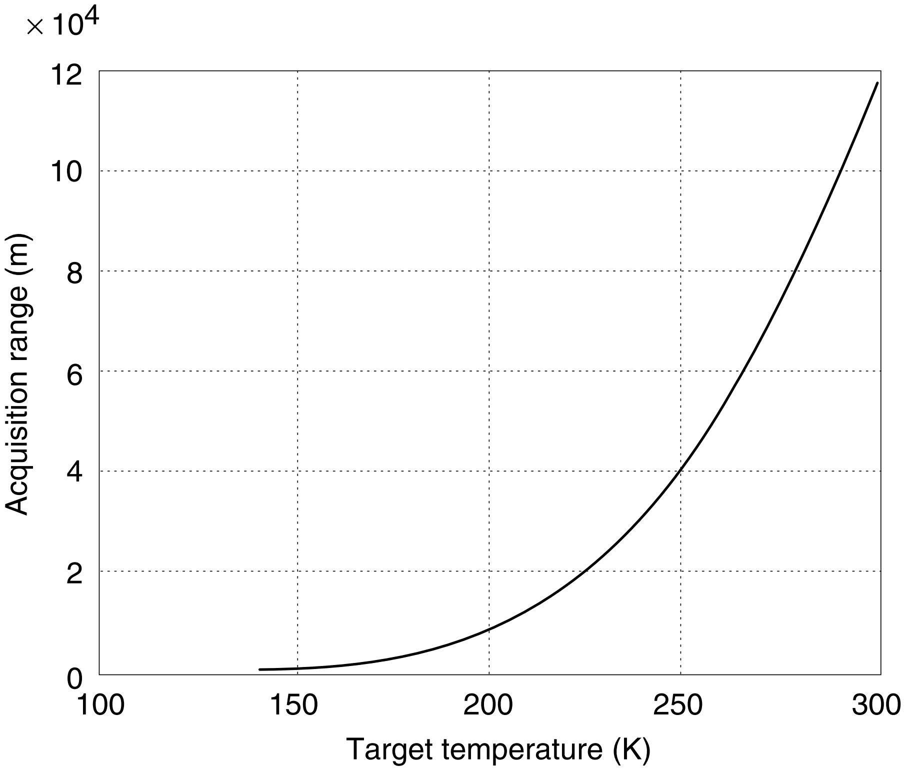
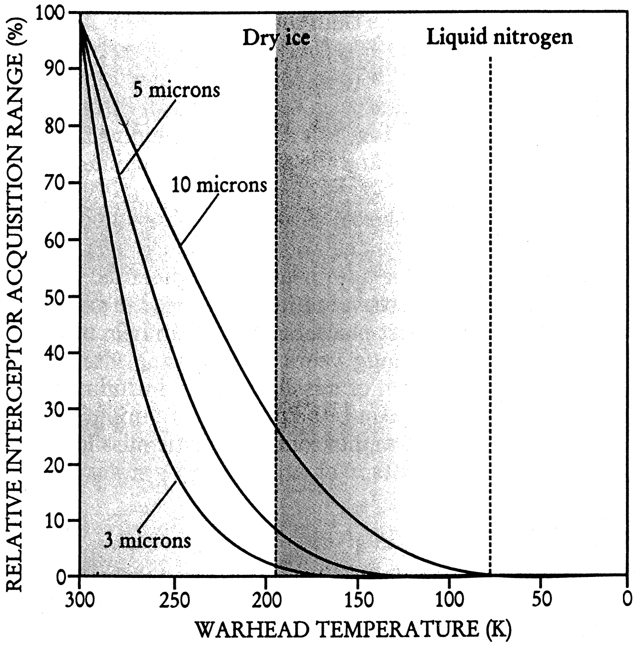


Figure 7: Acquisition range versus target temperature [31]



Reducing temperature reduces visibility of an attacking warhead. This graph shows the detection range as a function of warhead temperature, relative to that of a warhead at 300 K, for three infrared wavelengths that might be used by NMD sensors.

Figure 8: Relative interceptor acquisition range versus warhead temperature[25]

The kill probability (KP) can then be studied with the help of Monte Carlo simulations. They have been performed for low speed KVs of 2.7 km/s to intercept a target at 5 km/s or 7 km/s. Results are shown in Fig. 9 [31]. The KP is above 90% at room temperature and decreases quickly from about 70% to 1% for 5 km/s target as the target's temperature goes down from 273 K to 200 K.

The surface of a conical shroud around a nuclear warhead is estimated to an area of 5 square metres, for a total surface of 10 square metres, taking its base diameter of 1 metre and a height of 3 metres. 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 temperature of 77 K. About 200 grams of coolant per minute would then be needed to maintain this temperature while the shroud is exposed to direct sunlight, sunlight reflected from the Earth, infrared radiation radiated by Earth, and heat radiated from the warhead itself.

5.2 Radar interference, radar absorbing metals

Whereas the satellite-based detectors are of absolute necessity for NMD for initial tracking of ICBMs, the X-band ground-based radar (GBR) is one of the most important components of the THAAD system. The GBR detects, acquires, and tracks targets before interceptors could launch. When a certain tracking accuracy is achieved, interceptors are committed to their targets and launched, then the GBR continues to track the targets and issues updated target information through BMC^{4}I system to the interceptors and KVs to guide their boost phase flights and mid-

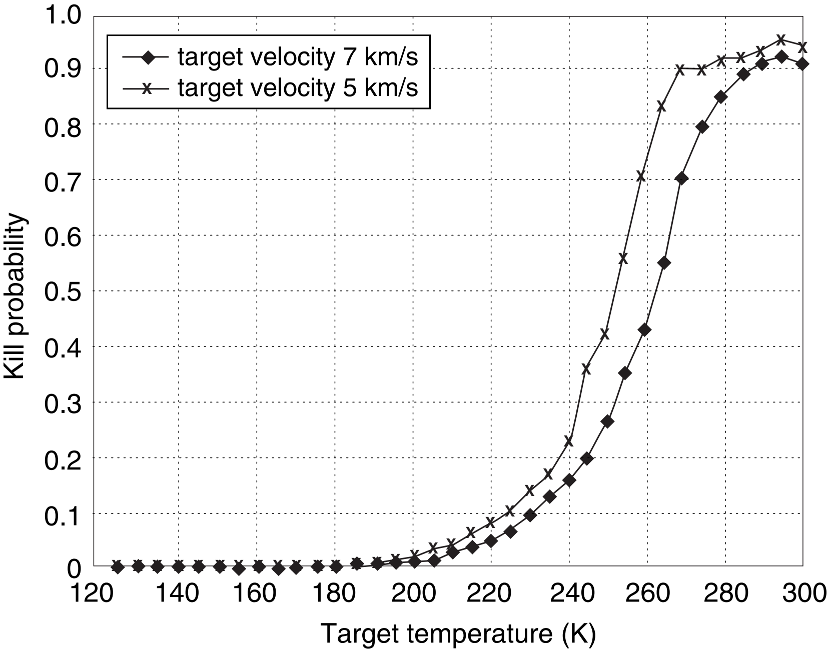


Figure 9: Kill probability versus target temperature [31]

course flights respectively. When a KV's mid-course flight finishes and its endgame flight begins, the KV is delivered to the handover point where the IR sensor of the KV is expected to acquire the target. The so-called handover point is actually an error basket in space. To achieve a successful intercept, the basket has to satisfy two conditions: (1) at the handover point, the KV is at the position where it can acquire the target, (2) the KV's position and velocity vector at the moment ensures that the resulting zero effort miss distance (ZMD) error is within the KV's manœuvring capability. On the one hand, the above two conditions depend mainly on the GBR's capability to accurately predict the trajectory of the target. On the other hand, the KV's capability of removing ZMD error is limited by the amount of fuel it carries and the total time of flight (TOF) during the endgame that is available for the KV to manœuvre. Table 2 (Fig. 10) gives the amount of acceleration needed as a function of the acquisition range [29].

Table 2: The average lateral kill vehicle acceleration required for the kill vehicle to hit the target as a function of kill vehicle detection range (labelled 'R' in Fig. 10) [29][1]

Interceptor acquisition range (km)	Closing time (s)	Average lateral interceptor acceleration required ($g \approx 10$ m/s^2)
1 000	100	0.0004 g
100	10	0.04 g
10	1	4 g
1	0.1	400 g

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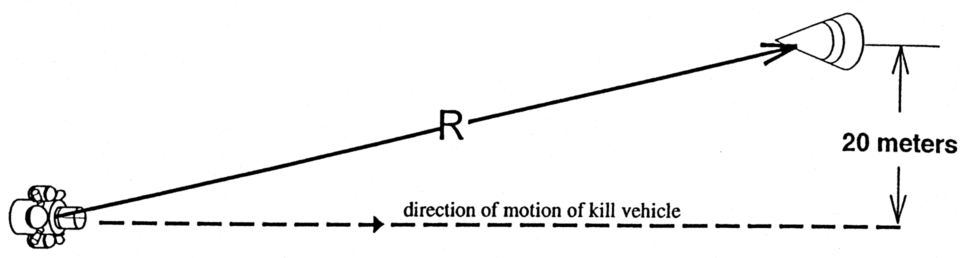
[1] We assume a closing speed of 10 km/s, and a lateral miss distance of 20 metres at kill vehicle acquisition.



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.

Figure 10: Average lateral kill vehicle acceleration required for a kill vehicle to hit a target as a function of kill vehicle detection range [29]

Using all the parameters from the previous paragraph except acquisition range, which is set to 100 km, results from Monte Carlo calculations are shown in Fig. 11 for the relationship between KP and ZMD error [31]. KP decreases with ZMD error. In addition to GBR, information obtained from satellites may be used for tracking. Their jamming could then also be an effective countermeasure.

Typical velocities of strategic targets are 7 km/s, and for theatre targets 5 km/s. Calculations show that the KV with a speed of about 5 km/s will have nearly the same kill probability against strategic missiles as against theatre missiles. It strongly suggest that a defense system with the same performances would be nearly as capable in intercepting strategic missiles as in dealing with theatre missiles if its performances and reliability are proved in testing against theatre missile targets.

The KV should explode when it is not more than about 4 metres away from the target. This requires timing within a fraction of a millisecond.

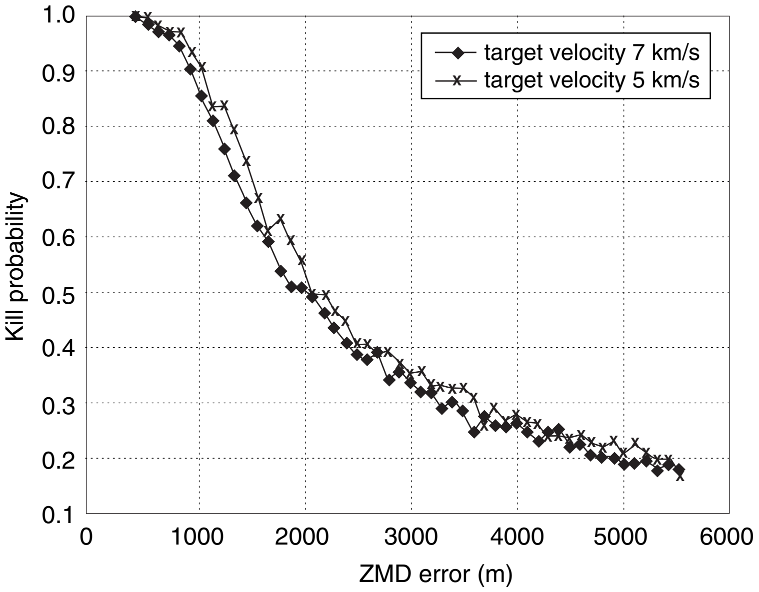


Figure 11: Kill probability versus ZMD error [31]

5.3 Anti-simulation balloon decoys for nuclear warheads, chaff, and heat-absorbing aerosol

Decoys or false targets are a most commonly used countermeasure and had already been developed by all Nuclear Weapon States (NWSs). They are required to simulate some physical characteristics of the real re-entry vehicle (RV), like size, shape, temperature, and speed etc., according to their task. The discrimination distance plays an important role. KP drops as discrimination distance decreases. The problem is that if the discrimination distance is too small, the KV may not have enough time to put itself on the flight path of the real target, resulting in very low KP.

With a ZMD error of 1000 metres results are shown in Fig. 12 [31]. KP drops as discrimination distance decreases. The KV's KP is over 90% as the discrimination distance exceeds 65 km. Then it drops quickly from about 90% to zero when the discrimination distance decreases from 65 km to 30 km.

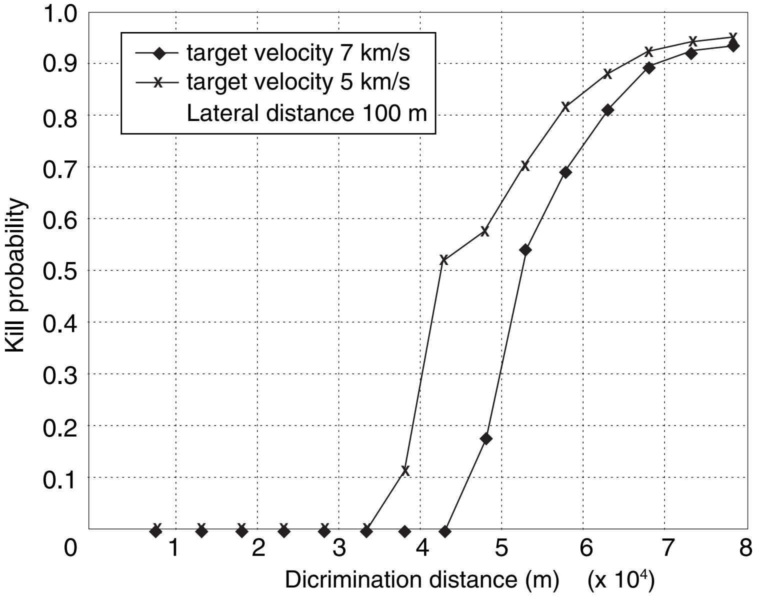


Figure 12: Kill probability versus discrimination distance [31]

The most effective method for delivering chemical or biological (CB) weapons by ballistic missile – if this will be attempted at all – is to divide the missile's payload into 100 or more bomblets, or sub munitions, each carrying up to a few kilograms of CB materials. Shortly after the missile booster burns out, these bomblets would be released from the warhead in a way that makes them spread out in a cloud as they travel through space toward the target. The atmosphere would slow bomblets to aircraft speeds at low altitudes. There would be no defense against this kind of attack. Weight for weight, biological agents are hundreds to thousands of times more potent than chemical weapons. The United States has developed bomblets [30]. However, the manufacturing of CB ammunition may be not as easy as some sources claim. The US had a nerve gas programme in the 1950s, when 400 000 M-55 rockets were manufactured, each containing a 5-kg payload of Sarin (GB). Because of leaks, 51 180 nerve gas rockets had to be discarded by dropping them off the coast of New York State and Florida.

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. For the planned NMD X-band radars, the appropriate length of a piece of chaff is about 1.5 centimetres, whereas chaff effective against the early-warning radars would be 35 centimetres.

The United States is not planning to discriminate the warhead from empty balloons during reentry. In principal the position change due to drag could be used for discrimination (Figs. 13a,b). The atmospheric drag would affect the total velocity and displacement along the trajectory of an incoming balloon. 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 measurement of the balloon's radial velocity and its less accurate measurements of the balloon's cross-range velocity.

5.4 Course change of incoming missile

If the ICBM is still equipped during mid-course with a thruster (popular with the MIRVs), the warhead can change its trajectory and would pose for the defense an almost insurmountable difficulty. Thrusters may produce small kinks in the trajectory or might be artifacts caused by turbulence. Similar effects have been observed during the evaluation of bubble chamber pictures. Track measurements needed repeated analysis. However, in this type of experiment time did not play any significant role, quite different from NMD demands.

5.5 Attack with increased number of missiles

NMD can eventually be made inefficient by an increase in the number of attacking missiles.

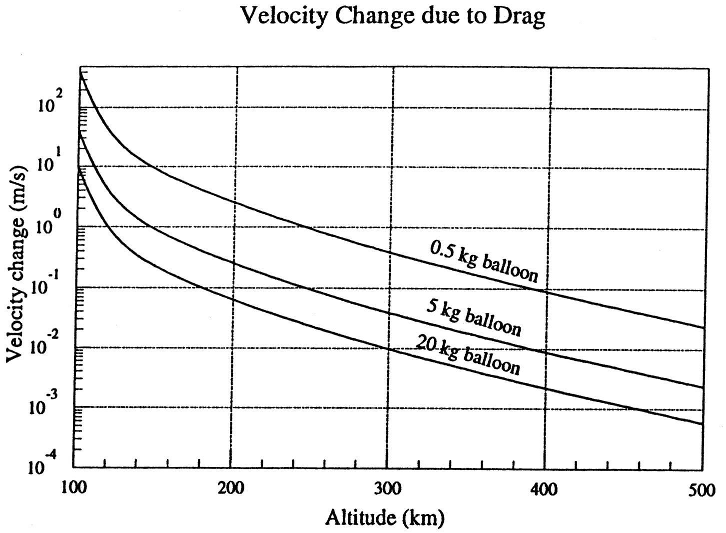
6 Conclusion

A fundamental question can be raised: Is there a ballistic missile threat and from whom? The ballistic missile arsenal is declining [35] (Fig. 14), however, this tendency may be reversed in several countries by the envisaged deployment of NMD. The present danger for the U.S. and its allies lies more in the increasing number of short and medium range rather than intercontinental, ballistic missiles.

The attacker has a clear advantage over the defense by using innumerable possibilities to disguise his warheads against radar or infrared detection, and overwhelm the defense by sheer numbers or submunition and too many real targets. Furthermore, countries of concern may not possess the technology to spin-stabilize the warheads to obtain higher precision of targetting. Tumbling of the warhead increases the difficulty for the defense to distinguish it from a decoy.

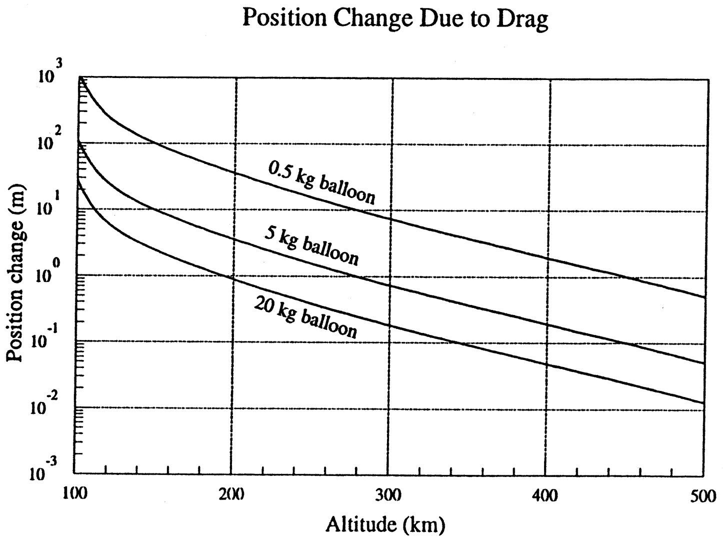
Defense has to work the first time and can not be seriously tested against all known or newly developed options or countermeasures that the aggressor may have available well ahead of time, before the defense has manufactured its system.

There are an infinite number of better and necessary actions to be taken by any responsible government than to build the equivalent of a 'National Missile Defense', that has a high chance of not working at all. Not long ago a well-known physicist had to testify on the feasibility and efficiency of such a system during a hearing of an U.S. Senate Committee. He had been asked if NMD would work. It is reported that he thought for a short while, then came up with a resounding 'YES', and after a pause he added, 'provided the adversary collaborates.' Even such an answer seems still too optimistic.



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.



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.

Figure 13: a) Velocity change due to drag; b) position change due to drag [29]

Scientists should re-evaluate, if deemed necessary, their assessment of SDI and extend it to NMD. Those working in weapons laboratories should be given tasks that address more urgent problems of society, such as changes in means of energy production, protection of the environment, to name a few challenging tasks. Scientific evaluation, like the one that had been done by a group of prominent experts in the case of SDI, should carry more weight than judgement by the military establishment. There is already an excellent study on countermeasures. It will soon be complemented by a new APS study on National Missile Defense in the boost-phase [36].

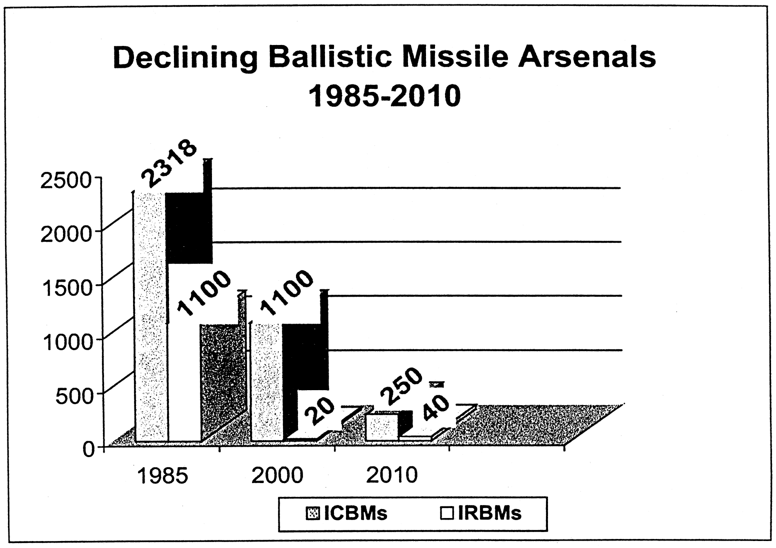


Figure 14: Declining ballistic missile arsenals 1985–2010 [35]

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Expected to be available at the end of 2001, co-chaired by Daniel Kleppner of MIT and Frederick K. Lamb of the University of Illinois at Urbana/Champaign. Other members of the Advisory Committee on NMD are John F. Ahearne, W. R. Frazer, Steve Koonin, Kumar C. Patel, Roberta P. Saxon, Jeremiah D. Sullivan, and, *ex officio,* James S. Langer, George H. Trilling, and Judy Franz.